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Fire-on-Fire Interactions in Three Large Wilderness Areas

Casey Teske
The University of Montana

FIRE-ON-FIRE INTERACTIONS IN THREE LARGE WILDERNESS AREAS

By

Casey C. Teske

M.S., Forest Resources, University of Idaho, Moscow, Idaho, 2002
B.S., Chemistry, University of Idaho, Moscow, Idaho, 1999

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Approved by:

Sandy Ross, Associate Dean of The Graduate School
Graduate School

LLoyd P. Queen, Chair
Department of Forest Management

Carl A. Seielstad
Department of Forest Management

Ronald H. Wakimoto
Department of Ecosystem and Conservation Sciences

Anna Klene
Department of Geography

Colin Hardy
Department of Forest Management

Teske, Casey, Ph.D., Spring 2012 College of Forestry and Conservation

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Chairperson: Dr. LLoyd P. Queen

Current knowledge about wildfire occurrence is not complete. Fire researchers and managers hold the assumption that previous wildfires affect subsequent wildfires; however, research regarding the interactions of large wildfires at their common boundaries is missing from the literature. This research focuses on understanding the influence of previous large wildfires on subsequent large wildfires in three wilderness areas: The Greater Bob Marshall, the Selway-Bitterroot, and the Frank Church. Data from the Monitoring Trends in Burn Severity (MTBS) project, which mapped large wildfires in the western United States occurring since 1984, are used for the research. The combination of using wilderness areas and remotely sensed images allows an objective and consistent analysis of fire-on-fire interaction that is extensive in both time and space. Standardized methods for analyzing fire interactions do not currently exist, therefore methods were developed, tested, and refined to describe, quantify, and compare once-burned and re-burned locations within a subset of ten fires in terms of size, location, timing between fires, and severity. These methods were then used to address the question of whether re-burns occur within each of the three wilderness areas. Edge and re-burn characteristics were also derived and quantified. Results were statistically and empirically compared to randomized fire intersections and to published fire history research for each area. Although a low proportion of each study area burns or re-burns, when a new fire encounters a previous fire it re-burns onto the previously burned area approximately 80% of the time. Current large wildfires are behaving in a typical fashion, although on some landscapes the amount of re-burn is not different from what would be expected due to chance. Lastly, the complexity of the post-fire landscape was assessed using texture metrics. Pre-fire and post-fire landscapes were shown to be different, with post-fire landscapes exhibiting greater diversity than pre-fire landscapes. When re-burned areas were compared to those locations that had only burned once, however, landscapes generally became less complex. Although wildfires and wildfire effects in each wilderness area differ, the overall results of this study confirm that previous fires do affect subsequent wildfires.

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Chapter 1 – Introduction

OVERVIEW

This dissertation examines the interactions of multiple large wildfires with each other in three wilderness areas: the Frank Church, the Selway-Bitterroot, and the Greater Bob Marshall. Although anecdotal evidence is abundant, formal documentation on the effects of multiple wildfires interacting with each other is scarce. Therefore, this research is inductive and exploratory in nature. The dissertation consists of five related chapters. Chapter one provides background information, some terminology, and overall context for the research. Chapters two through four detail three distinct research areas, provide additional relevant background information, and define new terms. Chapter two describes the curiosity-driven approaches to formulating tractable research questions and methods. In chapter three, large wildfire interactions in each of the three large wilderness areas are quantified and described using methods derived specifically for this research. Chapter four investigates the effects of large wildfires on the landscape using metrics derived from remotely sensed imagery. Chapter five summarizes the overall findings from this dissertation research and re-integrates the analyses presented in chapters two through four.

RESEARCH CONTEXT

As a result of several active wildfire seasons, especially in the Northern Rockies, much research has focused on further understanding wildfire events. Conventional wisdom is that recent wildfires are larger and occurring more frequently than was characteristic in the past (Eidenshink *et al*., 2007). In the western United States, the effectiveness of fire suppression over the past century is blamed for fuels accumulations that result in larger, more frequent, and more destructive wildfires; this accumulation occurs faster than ecosystems have adapted (Pyne, 1995; Arno and Fiedler, 2005; Keeley, 2006). The scarcity of literature on the interactions of multiple large wildfires in the same location suggests that current knowledge about large wildfires is not complete, especially in the context of broad landscapes.

To advance current knowledge, characteristics of large wildfires that burned between 1984 and 2007 are examined quantitatively for three wilderness areas in the Northern Rockies using products from the Monitoring Trends in Burn Severity (MTBS) dataset (Eidenshink *et al*., 2007). The MTBS dataset is a national dataset that was developed to assess the environmental impacts of large wildfires (Eidenshink *et al*., 2007). It is comprised of remotely sensed data products derived from images acquired by LANDSAT sensors since 1984, and allows for a systematic and objective analysis of wildfire effects across large spatial areas and through time. Thus, MTBS data are conducive to answering questions about wildfire occurrence and extent.

Consistent with the MTBS project, this research defines large wildfires as those wildfires greater than 405-ha (*i.e.,* 1000 acres; Eidenshink *et al*., 2007) and focuses on large wildfires that occur in wilderness areas. Wilderness areas are a product of the 1964 Wilderness Act. This Act established a national wilderness preservation system consisting of land areas greater than 5000-ac in size to be protected and managed in such a way that they remained "untrammeled by man." Because wilderness areas remain undeveloped to this day, natural processes are the primary catalysts for change in these environments. As such, conditions in wilderness areas typically serve as a baseline of what is natural in terms of wildfire occurrence and extent. The three wilderness areas were selected because of the availability of MTBS data for the areas. Additionally, they each cover an extensive area in the Northern Rocky Mountains, have a management history of allowing fires to burn in order to benefit resources (Arno and Fiedler, 2005; Wells, 2009; Zimmerman *et al*., 2011), and have well-documented fire occurrence (Arno, 1980; Barrett and Arno, 1988; Brown *et al*., 1994; Kipfmueller and Swetnam, 2000). In this dissertation, each of the three large wilderness areas – the Greater Bob Marshall, the Selway-Bitterroot, and the Frank Church – are considered individual landscapes. The term *landscape* is flexible: It can be applied to extensive land areas, and it can be characterized by the set of disturbances that form the patterns in and on it (Forman and Godron, 1986).

Although large wildfires are a small percentage of fire occurrences, they account for the majority of area burned annually (Calkin *et al*., 2005; Running, 2006) and have ecological consequences, some of which cannot be known immediately (Keane *et al*. 2008). Undeniably, wildfires influence the behavior and effects of future wildfires by creating variability in vegetation types and arrangements through space and time (Finney *et al*., 2005; Falk *et al*., 2007; Thompson *et al*., 2007; McKenzie *et al*., 2011). The primary focus of this research is to understand the influence that large wildfires have on subsequent large wildfires. Specifically, it addresses large wildfires in wilderness areas with a focus on:

1) the appropriate methods with which to analyze if large wildfires interact with each other, and how (chapter two);
2) whether large wildfires propagate onto, or are stopped by, locations previously burned by other large wildfires, and whether this behavior differs from the recent past, from what is expected due to chance, and among study areas (chapter three); and,
3) whether areas that burned once differ from areas that have burned more than once, in terms of patterns and arrangement, using metrics derived from the remotely sensed MTBS data (chapter four).

The remainder of this chapter reviews literature on the overarching areas of the three distinct research pieces. The research theme is placed into context, terms specific to all of the research sections are defined, and the study areas and datasets are described.

LITERATURE REVIEW

Fire Regimes

Wildland fire is a key ecosystem process in landscapes across much of the western United States. Perturbations caused by this natural disturbance play important roles in the formation of the vegetation complex, creating multiple states of continually changing patches, patterns, and arrangements of vegetation that influence the behavior and effects of future wildfires (Sousa, 1984; Sprugel, 1991; Perry, 1995; Weatherspoon and Skinner, 1995; Morgan *et al*., 2001; Rollins *et al*., 2004; Finney *et al*., 2005; Moritz *et al*., 2005; Raymond and Peterson, 2005; Folke, 2006; Groffman *et al*., 2006; Falk *et al*., 2007; Thompson *et al*., 2007; McKenzie *et al*., 2011). Both topography and climate influence predominant vegetation and fuels of a location, and daily weather patterns cause fluctuations in fuel moistures (Collins *et al*., 2007). Interactions between these factors influence fire behavior and its effects at a given location, and over time produce vegetation and fire characteristics that typify the geographic area or ecosystem. A fire regime describes the "nature of fires occurring over an extended period of time" (Brown, 1995; Morgan *et al*., 2001) and is often defined in terms of the rotation, frequency, severity, intensity, shape, and size typical of fires in a specific geographic area (Pickett and White, 1985; Agee, 1993; Morgan *et al*., 2001; Lentile *et al*., 2006; NWCG, 2006; Kellogg *et al*., 2008). As such, fire regimes provide context for the historical role of fire in that location (Agee, 1993; Rollins *et al*., 2004). Quantifying characteristics of a fire regime is important for future management of the landscape, especially when trying to maintain fire as a natural process (Attiwill, 1994; Landres *et al*., 1999). Area-based measures, such as fire rotation, and unbiased sampling are required to reconstruct fire regimes accurately across landscapes (Baker, 2009).

One aspect of fire regimes that has received little research attention is the interaction of multiple fires at their common boundaries. *Fire-on-fire interactions* occur when a fire encounters another recently burned area. Either the previous burn stops the fire, or the fire burns across it. When a fire burns onto a previously burned portion of the landscape, it is called a *re-burn*. Re-burns may be the rule in forests that are affected frequently by fires (Halofsky *et* *al.,* 2011), although this phenomenon was assumed to be ecologically harmful (see USDA, 1988) in the past. Fire managers and ecologists accept that old fires interact with and influence the behavior and effects of new fires at these boundaries (USDA, 1988; Agee, 1993; Thompson *et al.,* 2007; van Wagtendonk, 2007). There are several documented examples of fires re-burning portions of previously burned areas (e.g., the Tillamook Burn [Neiland, 1958], the Silver and Biscuit Fires [Thompson *et al.,* 2007]). However, few rigorous evaluations of the intersections of old wildfires and new wildfires exist (but see Collins and Stephens, 2007; Collins *et al.,* 2009; Halofsky *et al.,* 2011), especially across large landscapes. Edges, patches, and the resultant patterns created by wildfires and other disturbances are considered ecologically important, as many studies show (Finney *et al.*, 2005; Haire and McGarigal, 2010; Turner *et al.,* 1994). However, many contemporary studies largely focus on the effects of fuels treatments, such as prescribed fire and thinning, on wildfire behavior and severity (Finney *et al.,* 2005; Moghaddas and Craggs, 2007; Ritchie *et al.,* 2007; Stephens *et al.,* 2009) as opposed to the ecological effects of past fires. Thus, a systematic analysis of the interactions of previous wildfires on subsequent wildfires can further knowledge of the short- and long-term ecological implications of wildfire occurrence, presuming that landscapes burning multiple times in a short period confer different fire behavior and effects characteristics than once-burned landscapes.

Researchers can better understand how landscapes might have evolved to their present condition and what processes drove this evolution by studying the relationships between various landscape components, and combining this information with the disturbance history of a location. Much information about fire regimes has been assembled from fire history studies created exclusively from point sources such as fire reports, tree rings and dendrochronology, fire-scar and age-class sampling, and charcoal sedimentation in water bodies (Morgan *et al.*, 2001; McKenzie *et al.*, 2004; Lentile *et al.*, 2006). Although point-source data have allowed researchers to trace fire histories back hundreds to thousands of years, spatially explicit information is not available except by interpolation, thus making precise rendering of fire perimeter locations, frequencies, and distributions elusive. Recent technological advancements have provided many additional sources of fire history data that contain spatially explicit information, including GPS-based fire perimeters and a host of remote sensing products that span much of the electromagnetic spectrum. The result is a plethora of data and techniques with which to explore fire regime characteristics, including shapes, sizes, extents, frequencies, and severities across large areas (Morgan *et al.*, 2001; Rollins *et al.*, 2001; Holden *et al.*, 2005). Syntheses and analyses of these data enhance information about the inter-relationships of wildfires on the landscape, as well as identify gaps in knowledge.

The use of remotely sensed data to explore spatial patterns and relationships of disturbances such as wildfire across the landscape has become increasingly common. Satellite imagery is one of the more useful sources of remotely sensed information, given that both spatial and temporal extents, although limited historically, are easily derived (Brewer *et al.*, 2005; Holden *et al.*, 2005; Lentile *et al.*, 2006). Another benefit is that many satellite-based data products contain information in the non-visible portion of the electromagnetic spectrum not captured by other techniques like aerial photography. Portions of the infrared spectrum are useful for monitoring changes in the biophysical properties of healthy green vegetation, specifically in the near-infrared (NIR) and shortwave-infrared (SWIR) portions (Lopez-Garcia and Caselles; 1991; Jensen, 2005; Key and Benson, 2006; Thompson *et al*., 2007). The NIR and SWIR portions of the spectrum are sensitive to light absorption by chlorophyll, cell wall reflectance, and water content of vegetation; as vegetation characteristics change, the spectral response in both the NIR and SWIR changes. Datasets capturing information in these portions of the spectrum help researchers understand and quantify fire-induced vegetation change (Jensen, 2005; Brewer *et al*., 2005; Key and Benson, 2006; Eidenshink *et al*., 2007; Thompson *et al*., 2007). Consequently, fire history studies that utilize remotely sensed data supplement an extensive fire history reconstructed from field measurements.

Because of its utility, remote sensing is useful for delineating, mapping, and analyzing burned areas in many different regions and vegetation types across the world (Cocke *et al.*, 2005; Epting *et al.*, 2005; Holden *et al.*, 2005; Lentile *et al.*, 2006; Roy *et al.*, 2006; Eidenshink *et al.*, 2007). It has been used at multiple spatial and temporal scales, which is advantageous for assessing large areas and monitoring vegetation responses to disturbance (Jensen, 2005; Morgan *et al.*, 2001; Brewer *et al.*, 2005; Lentile *et al.*, 2006; Eidenshink *et al.*, 2007). Remote sensing is one source of data in many fire history databases in which spatial and temporal analyses of fire regime characteristics have been examined (Morgan *et al.*, 2001; Bolliger *et al*., 2003; Rollins *et al.*, 2001; Salvador *et al.*, 2005; Dickson *et al.*, 2006; Eidenshink *et al.*, 2007).

One challenge with remote sensing studies of fire history is replication of standardized processes for producing maps and analytical products, especially when large areas covering multiple administrative jurisdictions are involved or when comparisons through time are desired (Brewer *et al.*, 2005; Lentile *et al.*, 2006). Many image-based change detection techniques, such as supervised classification, are subjective; other techniques, such as unsupervised classification, are objective and repeatable but applied in ways that make comparisons between jurisdictions and over time difficult (Jensen, 2005; Brewer *et al.*, 2005; Lentile *et al.*, 2006), in spite of the fact that sensors do not differentiate between ownerships. This yields valuable but inconsistent and subjective results that are difficult to quantify and replicate (Brewer *et al.*, 2005).

Dataset

The recent Monitoring Trends in Burn Severity (MTBS) project is aimed at overcoming issues of replication and repeatability, and establishing an information base from which to assess trends in wildfire severity nationally (Eidenshink *et al.*, 2007; USGS, 2008). The MTBS project uses LANDSAT mission data to characterize all fires west of the 97th meridian larger than 405-ha that have occurred between 1984 and the present. Research estimates that large fires comprise less than 5% of annual fire occurrences, but account for more than 95% of the annual area burned (Knapp, 1998; McKenzie *et al.*, 2004; Calkin *et al.*, 2005; Running, 2006). Thus, these large fires have a substantial impact on ecosystems, landscapes, and future fires, although the extent of these impacts into the future cannot be known for some time (Keane *et al.*, 2008).

The MTBS dataset is considered a census dataset (Brewer, 2011) for large wildfires between 1984 and the present and provides a unique opportunity to study the effects of multiple wildfires through time across the landscape using a systematic, objective approach. The data products derived from LANDSAT 5 TM and LANDSAT 7 ETM+ imagery include burned area delineations, otherwise known as fire perimeters, and remotely sensed images with 30-m spatial resolution. Additionally, change maps derived from continuous data using differenced normalized burn ratio (dNBR) methods (Key and Benson, 2006), and thematic maps representing five classes of fire severity are included. Burned area mapping of individual large wildfires is complete for the three wilderness study areas (described in the following section) between 1984 and the present. Information about fire occurrence is stratified on an annual basis, thus both spatial and temporal distributions of wildfire can be obtained using this dataset. Eidenshink *et al*. (2007) present a complete description of the MTBS project. Limitations of the MTBS project are addressed in chapters two and three.

Study Areas

The wilderness areas used in this study are the Greater Bob Marshall Wilderness Area (GBMWA, or the Bob Marshall) in Montana, the Selway-Bitterroot Wilderness Area (SBWA, or the Selway-Bitterroot) in Idaho and Montana, and the Frank Church River of No Return Wilderness (FCRONRW, or the Frank Church) in Idaho. The relative locations of each wilderness area, and the burned areas within each of the wilderness areas, are shown in Figure 1. Wilderness boundaries were buffered by three kilometers (outside) in order to contain the entirety of each large fire that occurred both within and proximate to them. Due to buffering, the study areas for this research are slightly larger than the actual areas encompassed by administrative boundaries. In this study, the Selway-Bitterroot area is nearly 876,000-ha, the Bob Marshall is just over 1,748,200-ha, and the Frank Church is just over 2,367,400-ha. These numbers include unburnable lands within the study areas, such as water and rock.

Figure 1: The Bob Marshall (a), Selway-Bitterroot (b), and Frank Church (c) Wilderness study areas. Figures 1a, 1b, and 1c show the locations of large wildfires as mapped by the MTBS dataset between 1984 and 2007 within the respective wilderness areas.

<u>Greater Bob Marshall Wilderness Area</u>

The Greater Bob Marshall Wilderness Area is located in the Northern Rocky Mountains of Montana (Figure 1), and consists of four administrative areas: Glacier National Park, the Bob Marshall Wilderness, the Great Bear Wilderness, and the Scapegoat Wilderness. These four contiguous areas encompass one million hectares, are managed by multiple agencies, and are part of the larger Crown of the Continent Ecosystem (Selkowitz *et al.,* 2002).

The Bob Marshall shares similar topographic, climatic, and vegetative characteristics across its landscape. Elevations range between 970-m and 3200-m. The Continental Divide, which bisects the area from north to south, adds to the climatic and vegetative diversity within the area (Keane *et al.*, 1994). The diverse topography contributes to a rain-shadow effect, with more precipitation reaching the western side than the eastern side of the Divide. The climate on the west side can be characterized as a modified maritime climate, with annual precipitation ranging from 50-cm in the valleys to 350-cm in the mountains (Keane *et al.*, 1994; Selkowitz *et al.*, 2002). The east-side climate is continental, with precipitation amounts ranging between 40-cm in the valleys to over 150-cm in the mountains (Keane *et al.*, 1994; Selkowitz *et al.*, 2002). Western slopes are generally comprised of forested areas, with climax species including subalpine fir *(Abies lasiocarpa)*, western redcedar *(Thuja plicata)*, western hemlock *(Tsuga heterophylla)*, Douglas-fir *(Pseudotsuga menziesii)*, and some remnant ponderosa pine *(Pinus ponderosa)*-bunchgrass prairie communities (Arno, 1980; NPS, 2010). Eastern slopes are comprised of forested-bunchgrass ecosystems, including subalpine fir and Douglas-fir forests, and bunchgrass prairies (Arno, 1980; Keane *et al.*, 1994; NPS, 2010). At higher elevations, especially in flat areas above tree line, alpine meadows and rocky barrens are common.

Wildfires of many sizes and severities have been integral in shaping the Bob Marshall landscape through time (Keane *et al.*, 1994; Arno, 2000; Keane *et al.*, 2006). Most wildfires occur during the summer months, but September winds associated with the southward migration of the polar front occasionally cause quick, dramatic increases in fire sizes. As a result of natural disturbances including wildfire, seral community types such as western larch *(Larix occidentalis)*, lodgepole pine *(P. contorta)*, and aspen *(Populus tremuloides)*, as well as shrub fields, are found across much of the Bob Marshall (Arno, 1980; NPS, 2010). Prior to 1900, mixed severity fires and frequent non-lethal understory fires were common, although large stand-replacing fires were also prevalent with several notable occurrences in recent years (Barrett *et al.*, 1997; Baker, 2009). *Fire intervals*, the number of years between successive fires, range from approximately 25- to 75-years for non-lethal surface fires, 100- to 150-years for stand-replacing fires in moderate elevation dry forest types, and 140- to 340-year mean return intervals for infrequent stand-replacing fires in western larch-lodgepole pine forests (Arno, 1980; Barrett *et al.*, 1991; Baker, 2009). In subalpine forests, small fires are common although large fires can and do occur when conditions align. A range of low-intensity surface fires to high-intensity crown fires exemplify the subalpine forest fire regime (Barrett *et al.*, 1997; Baker, 2009). Re-burning in this forest type does happen, although the incidence of re-burns having less than 30 years between fires is low (Baker, 2009).

<u>Selway-Bitterroot Wilderness Area</u>

Located in the Northern Rocky Mountains of Idaho and Montana, the Selway-Bitterroot Wilderness Area totals just over 550,000-ha (Finklin, 1983; Brown *et al.*, 1994). The Selway-Bitterroot has an inland-maritime climate in the northwest that transitions into a continental climate in the southeast (Finklin, 1983; Kipfmueller and Swetnam, 2000). Precipitation ranges from 63-cm along the southern wilderness boundary, to 102-cm along the western portion of the Selway River, to over 178-cm in the Bitterroot Mountains (Finklin, 1983). The warmest and driest months are July and August. Although these months also have the most lightning activity, the fire season generally begins in mid-June and lasts through late September, with most of the area generally burning later in the summer (Finklin, 1983; Brown *et al.*, 1994; Kipfmueller and Swetnam, 2000). The topography of the Selway-Bitterroot is complex and supports a wide range of vegetation (Finklin, 1983; Cooper *et al.*, 1991; Kipfmueller and Swetnam, 2000). The primary drainage west of the Bitterroot Crest is the Selway River, which feeds into the Clearwater River; east of the Bitterroot Crest, numerous small creeks drain into the Bitterroot River (Finklin, 1983). Subalpine species dominate the area overall, followed by Douglas-fir, and grand fir *(A. grandis)*. Ponderosa pine dominates the lower elevation dry sites, and western redcedar-western hemlock mixtures are found in the wet sites. Middle elevations tend to be Douglas-fir and grand fir, but lodgepole pine and western larch are also common. Upper elevations are composed of Engelmann spruce *(Picea englemannii)* and subalpine fir, although whitebark pine *(P. albicaulis)* and subalpine larch *(L. lyallii)* can be found on the most harsh and exposed sites (Brown *et al.*, 1994; Kipfmueller and Swetnam, 2000). The uppermost elevations are often sparsely vegetated bedrock and talus slopes, especially along the Bitterroot

Crest. Elevations range from around 500-m at the lowest point along the Selway River to just over 2800-m at the highest peak.

No part of the SBWA has ever been commercially logged (Finklin, 1983). Many fires of all sizes and severities have burned throughout the SBWA during the past century. The area has been the subject of many fire history studies due to its pristine nature (see Barrett and Arno, 1988; Brown *et al.*, 1994; Shiplett and Neuenschwander, 1994; Kipfmueller and Swetnam, 2000; Rollins *et al.*, 2001). It was initially created as the Selway-Bitterroot Primitive Area in 1932, and a substantial prescribed natural fire program was initiated in 1975 and fully implemented in 1979 in order to restore fire to a more natural role (Brown *et al.*, 1994). The use of fire for resource benefit persists to this day in the Selway-Bitterroot, representing the oldest natural fire program on U.S. Forest Service ownership in the United States.

Generally, the fire regime in the Selway-Bitterroot is a mixed regime. Lower elevations are characterized by non-lethal frequent understory burning in the ponderosa pine forest types, patchy stand-replacing fires in the Douglas-fir forest types, and long fire intervals between mixed and stand-replacing fires in grand fir-western redcedar forest types. Upper elevations are characterized by large stand-replacing fires in the lodgepole pine forest types, long intervals between stand-replacing fires in the Engelmann spruce forest types, and mixed severity fires in the whitebark pine forest types. Rollins *et al*. (2001) calculated an overall fire rotation of 194-years with shorter rotations in lower elevation forests and longer rotations in upper elevation forests. *Fire rotations* are defined as the number of years necessary for an area equal in size to a specified area to burn; this measure includes re-burns, meaning some sites may burn multiple times, and others not at all (Agee, 1993; Rollins *et al*., 2001; Baker, 2009). Brown *et al*. (1994) found historic mean fire intervals of 81-years in the low elevations and 115-years in the upper elevations of the Selway-Bitterroot. Although the methods differ, these studies both suggest that fire intervals in the Selway-Bitterroot are currently longer than they were prior to Euro-American settlement and modern suppression techniques.

Frank Church River of No Return Wilderness Area

Designated as a wilderness in 1980, the Frank Church River of No Return Wilderness encompasses nearly 960,000-ha and is only narrowly separated from the Selway-Bitterroot by the 180-meter-wide Magruder Corridor. The topography of the area is diverse and rugged, with deep narrow canyons, ridges running in all directions, and some peaks surpassing 3,050-m (Finklin, 1988). Three major rivers run through the Frank Church: The Main Salmon River flows generally westward and is near the northern boundary of the wilderness, while the Middle and South Forks of the Salmon River flow generally northeastward from the south into the Main Salmon River (Barrett and Arno, 1988; Finklin, 1988). At 1920-m deep, the Main Salmon River canyon is deeper than many noteworthy canyons of the world, including the Grand Canyon in Arizona. The types of vegetation that cover the Frank Church reflect the climatic and topographic diversity of the area. Species include ponderosa pine and grass at lower elevations, spruce and fir at the highest elevations, and Douglas-fir and lodgepole pine covering a majority of the rest of the area (Barrett and Arno, 1988; Finklin, 1988). Average annual precipitation ranges from 38- to 43-cm in canyon bottoms to 130- to 150-cm or more in the western mountains, with snow contributing most of the precipitation in elevations above 1500-m (Finklin, 1988). Lightning and thunderstorms are generally active from May through September, with peak activity during June through August, and occur more often in the mountainous northeastern part of the study area.

Historically, lightning-caused fires were common in the Frank Church, with an annual average of 75 mostly small fires per year during 1960-1983 (Finklin, 1988). Barrett and Arno (1988) noted 31 fires in the Salmon River corridor that were larger than 4-ha during the 1939-1986 time period, while Finklin (1988) cites two fires larger than 4-ha and one fire larger than 40-ha during the period 1960-1983. Overall, the fire regime can be classified as a mixed regime, since the effects of fires differ by forest type (Arno, 1980). Lower elevations typically experience frequent fires which have the potential to become large given the flashy fuels and steep slopes of the area, while upper elevation fires are generally large but less frequent than the low elevation fires (Barrett and Arno, 1988). Barrett *et al*. (1997) estimated a 20-year mean fire interval (MFI) in ponderosa pine forests, a 52-year MFI for Douglas-fir-western larch forests, and a 112-year MFI for lodgepole pine forests across the Interior Columbia River Basin, of which the Frank Church is a part.

Although the fire regimes of each wilderness area can be classified as mixed regimes, there are differences between the wilderness areas. The sizes of the areas differ, terrain features are laid out in different ways, the types of vegetation differ, and their fire intervals differ. However, the areas do share similarities. Each wilderness is located in the Northern Rocky Mountains, covers an extensive area, has a management history of limited suppression, and has a well-documented fire history; also, MTBS datasets are complete and available for each area.

The MTBS dataset allows for exploration of the inter-relationships of time and space on wildfire occurrence, pattern, and arrangement over these large wilderness areas. The products of the MTBS dataset can influence current thinking about the interactions of multiple large wildfires, specifically how previous fires affect subsequent fires in wilderness areas. Strategic research on the effects of the interactions of multiple large wildfires in large wilderness areas has not been previously addressed. Additionally, using remotely sensed imagery for systematic fire history analyses with this level of detail and at this scale is a new concept. An objective, verifiable, and replicable investigation of wildfire interactions is possible using the MTBS dataset in combination with these wilderness areas, which act to filter confounding variables such as different land management objectives, fire suppression techniques, and differences in fire mapping techniques for non-forested locations. The next three chapters each describe research that uses the MTBS dataset to answer questions about wildfire interactions in these wilderness areas.

Chapter 2 – Initial Research Stage

The Influences of Space, Time, and Severity on Fire Intersections in Three Large Fire Sequences

OVERVIEW

In the first stage of this research, the interactions of multiple large wildfires are explored using the Monitoring Trends in Burn Severity (MTBS) dataset and various image processing and geographic information system (GIS) tools and methods. This chapter focuses specifically on determining the appropriate methods with which to analyze the MTBS dataset to investigate if and how large wildfires interact with each other. It briefly summarizes the data exploration leading up to the research, then describes the first stage of the dissertation research, detailing the development of the techniques required to answer the research questions in chapters three and four.

The MTBS data are conducive to answering the question of whether or not re-burns occur, as long as re-burns are 1) large enough to meet the re-burn size criteria, 2) occur within the period covered by the MTBS project, and 3) are detectable by MTBS methods. The MTBS data include fire perimeters for large wildfires in the United States. The locations of these perimeters can be analyzed through time to characterize re-burns in terms of size, frequency of occurrence, and location. A better characterization of re-burns might be achieved if a sufficient number of re-burns from a broad area were analyzed, thus the wide-ranging Pacific Northwest region was selected. The MTBS-defined Pacific Northwest (PNW) Mapping Zone is a large area, encompassing Washington, Oregon, Idaho, western Montana, and parts of northern California and northern Nevada. The PNW Mapping Zone is large, ecologically diverse, includes a variety of vegetative species in both forested and non-forested areas, encompasses lands owned and managed by multiple agencies and private landowners, and much of the area regularly experiences wildfires. The MTBS project has completely mapped large wildfires occurring between 1984 and the present in this Mapping Zone. These data characteristics ensure that a variety of analyses on re-burns can be explored.

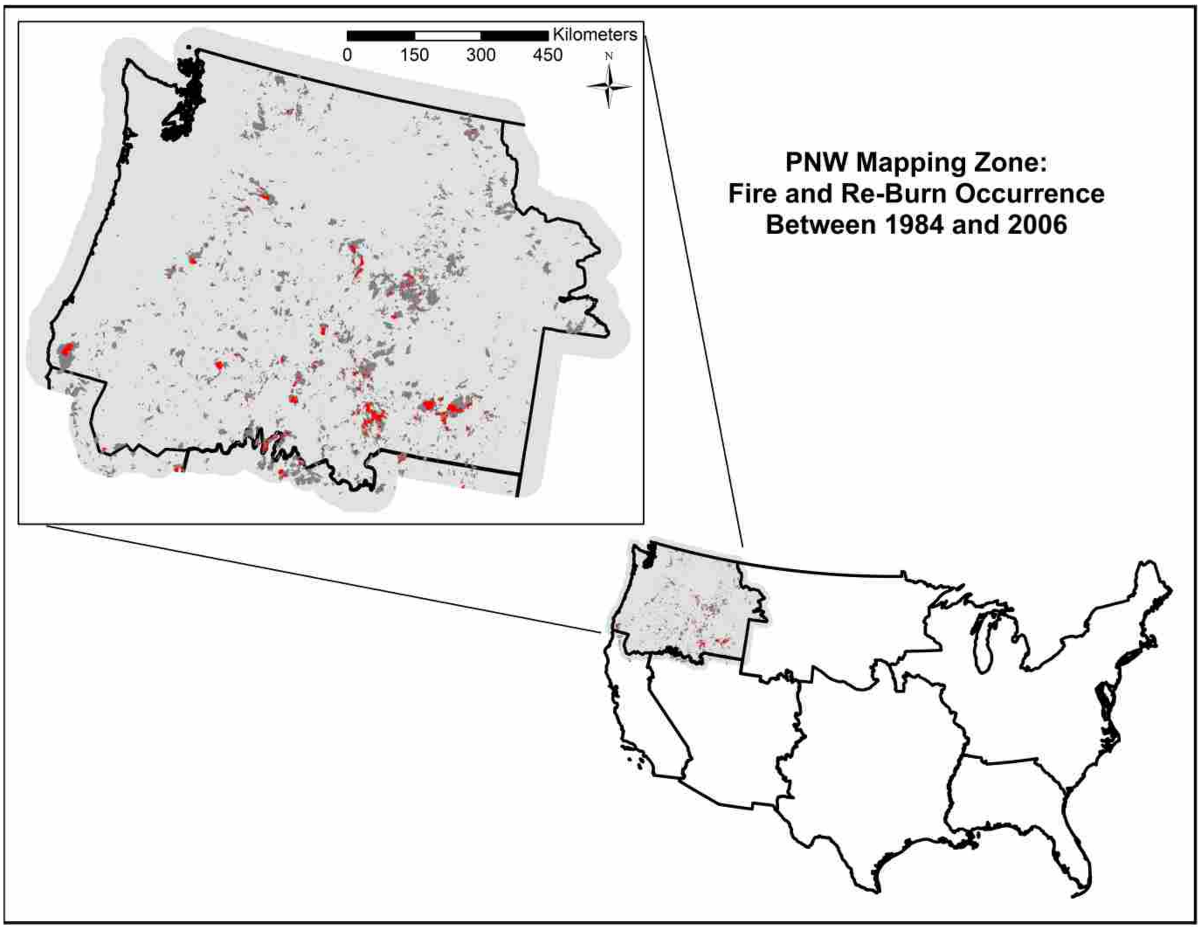


Figure 2: The MTBS Mapping Zone delineations for the United States. The PNW Mapping Zone is highlighted, with burned areas in grey and re-burned areas in red.

The MTBS data for all wildfires mapped in the PNW Mapping Zone between 1984 and 2006 were compiled and analyzed. At the time of this portion of the analysis, fires beyond 2006 were not completely mapped yet. There were 2,827 instances of re-burn in these data. While it was expected that re-burns would occur, the abundance and sizes of re-burns are unexpected: 20% of the re-burned areas are larger than 500-ac (203-ha) while 14% of the re-burns are larger than 1000-ac (405-ha; Figure 2). Many of the fires and re-burns are in non-forested areas; post-fire analyses in these areas are inherently problematic, which will be discussed later. The original concept of framing questions, and characterizing and comparing of re-burns across an entire mapping zone is illogical, given that the broad context of the Pacific Northwest is an area much larger than the scale at which wildfires function, and specific literature regarding the re-burn phenomenon is scarce.

These results impact further analyses in several key ways. First, they demonstrate that fire-on-fire interactions involving large wildfires do exist on the landscape, so the MTBS dataset appear to be a rational dataset to exploit the characteristics of these interactions. Second, there are known issues in the MTBS data for grassland ecosystems due to the nature of these lower productivity ecosystems and the MTBS methodology. To resolve this problem, the research analyzes only the mapped large wildfires occurring in forested areas. Third, highly variable fire environments and fire regimes complicate the comparison of fire-on-fire interactions in the widely diverse forested ecosystems across the entire PNW Mapping Zone. Therefore, this research reflects refined study areas and more precise research questions.

The next step in this stage of this research focuses on a subset of fires mapped by the MTBS project that occur within the Greater Bob Marshall Wilderness Area, a region much smaller than the PNW Mapping Zone. Fire perimeters and post-fire images from the MTBS dataset area were used to study the fires. Once-burned and re-burned areas are differentiated and analyzed with respect to timing between fires and severity using this data. Although this step decreases the number of fire-on-fire interactions that are available to analyze, it allows the methodological framework to be tested and refined. By refocusing on a smaller study area, the variability caused by regional differences is reduced, as are data processing and analysis time. This reduced study area gives a better perspective of how fires interact with each other within a localized area.

The work presented in this chapter yields a framework with which to carry out the research at multiple spatial scales and with various data formats. The methods developed in this stage can be applied at the forest, state, or regional level, as well as at the level of individual fires, with appropriate sub-groupings applied (*i.e.,* vegetation types). These methods can also be applied in other locations, and comparisons of fire interactions within and among these different locations can then be made. This was done in Chapter three: Using only the fire perimeter data, fire interactions in three distinct study areas were examined and compared. In chapter four, fire interactions are further explored in terms of post-fire landscape complexity using only MTBS image data.

In sum, the MTBS project is national in scope and broken into seven Mapping Zones for the contiguous United States. The Pacific Northwest Mapping Zone was initially selected to analyze fire interactions for this dissertation. As a result of the preliminary findings just mentioned, combined with a lack of literature on re-burns as a process, a subset of ten fires within a single wilderness area (the Greater Bob Marshall) were selected to facilitate methodological development and to help define and refine questions and methods for the research presented in this dissertation. This chapter focuses specifically on these ten fires, and the methods with which they are analyzed.

Subsequent chapters focus on three large wilderness areas selected from within the PNW Mapping Zone – the Bob Marshall, Selway-Bitterroot, and Frank Church. These wilderness areas contain a variety of vegetation types, but are predominantly forested; each wilderness encompasses a large land area, but is manageable both computationally and ecologically as an individual study area; large wildfires and re-burns occur in each wilderness; and the history of fire in these areas has been well documented. The use of the three wilderness areas provides an objective filter with which to study the interactions of large wildfires. A focused study of fire-on-fire interactions is executed within the frame of the landscape scale at which large wildfires function, and comparisons between the areas are made.

The methodological framework described in this chapter is used to explore fire interactions in these three wilderness areas, using the MTBS dataset in two distinct ways in subsequent chapters. The re-burn process is analyzed using the vector data (*i.e.*, fire perimeters) in chapter three, and the complexity of the post-fire landscape is explored using the raster data in chapter four.

BACKGROUND

Normalized Burn Ratio and Differenced NBR

The normalized burn ratio (NBR) is a band ratio that was developed in the early 1990s (Lopez-Garcia and Caselles, 1991) and subsequently modified and named the NBR by Key and Benson (2006; Brewer *et al.,* 2005). The NBR exploits the sensitivities of photosynthetically active green vegetation in the near- and short-wave infrared (NIR and SWIR) portions of the electromagnetic spectrum. On LANDSAT5 TM and LANDSAT7 ETM+ sensors, the NIR and SWIR portions of the spectrum are represented in band 4 (B4, 0.76-0.9µm) and band 7 (B7, 2.08-2.35 µm) respectively. The differenced NBR (dNBR), or delta NBR, is the difference between the pre- and the post-fire NBR. Delta NBR differentiates burned and unburned areas of vegetation, and is also used to discern the different levels of burn severity found within a previously burned area (Brewer *et al.,* 2005; Cocke *et al.,* 2005; Key and Benson, 2006; Eidenshink *et al.,* 2007; Thompson *et al.,* 2007; Safford *et al.,* 2007).

Pre- and post-fire image pixel values are converted to the at-satellite reflectance values, and the NBR is then calculated for both pre- and post-fire images using the reflectance values in the respective bands according to Equation 1 (Lopez-Garcia and Caselles, 1991; Key and Benson, 2006). The differenced NBR (dNBR) is calculated according to Equation 2.

$$NBR = \frac{(\mathbf{NIR} - \mathbf{SWIR})}{(\mathbf{NIR} + \mathbf{SWIR})} \qquad \textit{Equation 1}$$

$$dNBR = \mathbf{NBRpre} - \mathbf{NBRpost} \qquad \textit{Equation 2}$$

The spectral response of vegetation in these two regions of the infrared spectrum differs following a fire. Reflectance in the SWIR increases following a fire while reflectance in the NIR decreases (Lopez-Garcia and Caselles, 1991; Key and Benson, 2006; Thompson *et al.,* 2007). The magnitude of the difference between the NIR and SWIR is higher than the difference between any of the other regions of the spectrum (Lopez-Garcia and Caselles, 1991; Key and Benson, 2006). Dividing by the sum of the two bands normalizes the NBR such that spatial and temporal comparisons of the NBR values can be made. Burned areas can be differentiated from unburned areas by calculating the dNBR. Although the dNBR is not a direct measure of the severity of a fire, it is a useful index that can be mapped and is a quantifiable degree of change that occurs as a result of fire (Key and Benson, 2006). Some researchers have demonstrated that dNBR correlates well to field-based estimations of burn severity, although it is not a direct measure (Eidenshink *et al.,* 2007). Typical dNBR values range between +2000 and -2000, with negative dNBR values indicating vegetative growth and positive dNBR values indicating vegetative mortality. Larger degrees of change between pre-fire and post-fire plant canopies are implied as the dNBR values move further from zero in either direction.

Classified dNBR

The continuous dNBR can be thematically classified into discrete classes of burn severity. *Burn severity* is defined by the MTBS project as "the degree to which a site has been disrupted by fire" (Eidenshink *et al.,* 2007). Severity includes the mosaic of effects interior to the perimeter that occur within one growing season after a fire, and it relates principally to visible changes in biomass, soil exposure, and fire byproducts like ash (Eidenshink *et al.,* 2007). To classify burn severity, an image analyst determines where significant thresholds exist in the dNBR data value range and these thresholds are used to discriminate between severity classes (Eidenshink *et al.*, 2007). The threshold values may vary across ecosystems, although they are generally similar for a region (Eidenshink *et al.,* 2007). In the case of the MTBS project, no matter the ecosystem, the data products are classified into five burn severity classes: Unburned, Low Severity, Moderate Severity, High Severity, and Enhanced Greenness – a descriptor of increased post-fire response. Consistent classifications and terminology reduce confusion about severity. Although severity exists across a continuum, describing it using these five broad classes allows researchers and managers to more easily communicate about severity-related topics (Collins *et al.*, 2007; Eidenshink *et al.*, 2007; Miller and Thode, 2007). Classification can also compensate for data scaling differences between other fires or ecosystems.

METHODS

A subset of the MTBS dataset, consisting of ten large fires in the Northern Rockies that included areas that had re-burned between 1984 and 2007, was selected. Only the 2007 fires in these areas that had been completely mapped by the MTBS project were used. These fires occurred in three distinct regions within the Greater Bob Marshall Wilderness Area, and were placed into three groups based on this geography. Using the three different groups of fires as case studies, re-burned areas were identified and described in terms of severity, re-burn severity, timing between fires, and the redistribution of severity in re-burned areas.

Fire Sequences

For this research, a *fire sequence* is defined as the set of fires that includes an initial fire(s) and any subsequent fires that burn into or out of the area previously burned by the initial fire(s). In this chapter, the research focuses on how the fires interact when they intersect within a fire sequence. Each of the three case study groups of fires is considered a fire sequence: the Glacier Sequence, the Bob Marshall Sequence, and the Scapegoat Sequence (Figure 3).

These sequences consist of multiple large wildfires that occurred in forested areas of the Greater Bob Marshall Wilderness Area within the Northern Rocky Mountains of Montana. The initial fire(s) occurred at some point in the period 1984-2007, and part or all of one or more subsequent large fires burned into or out of the area previously burned by the initial fire(s). For the remainder of this chapter, all fires and results are discussed and reported in ‘acres’ as opposed to ‘hectares.’ This is the common practice in fire management and policy, and fire reporting systems in the United States use ‘acres’ as the standard of measurement for a burned area. One acre is equal to 0.405 hectares.

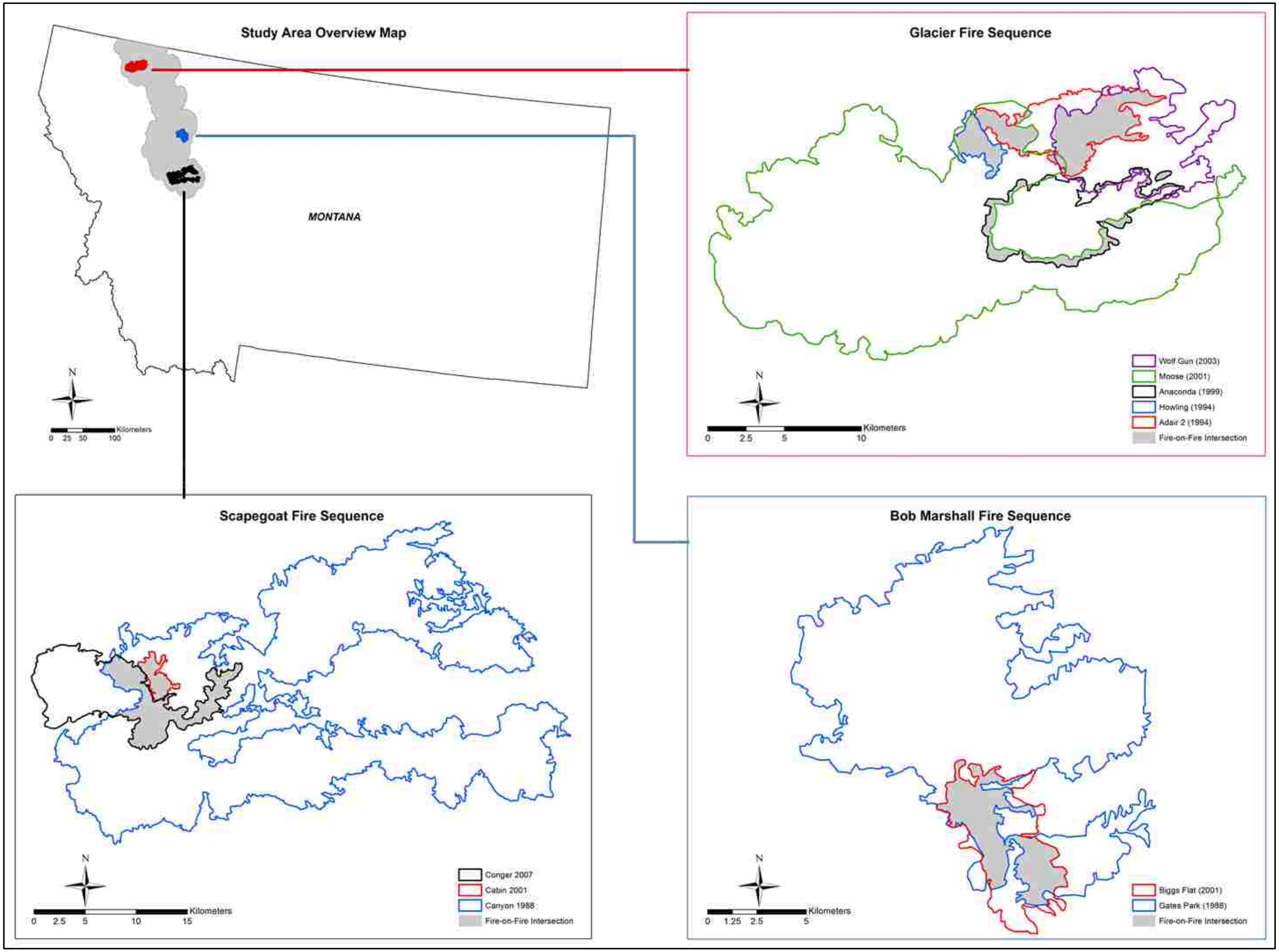


Figure 3: The overview map shows the study area (highlighted in grey, *top left*) relative to the state of Montana. Fire sequences are mapped individually and are associated with the overview map by color: The Glacier Sequence is framed in red (*top right*), the Scapegoat in black (*bottom left*), and the Bob Marshall in blue (*bottom right*). Shaded areas within each fire sequence represent fire-on-fire intersections.

<u>The Glacier Sequence</u>

The Glacier Sequence consists of five fires: Howling (1994), Adair 2 (1994), Anaconda (1999), Moose (2001), and Wolf Gun (2003).

- The Howling Prescribed Natural Fire was ignited by lightning on June 23, 1994, in Glacier National Park. It was the first fire the Park managed as a *prescribed natural fire* (PNF) – a naturally ignited wildfire that is allowed to burn within certain environmental parameters in order to achieve resource objectives – and little to no suppression action was taken. The fire burned less than one acre during a six-week period, and started to become active toward the end of July. Due to an active fire season nationally, resources were scarce and the decision was made to maintain this fire as a PNF. In the end, the Howling Fire burned just over 2,000 acres during four months (Kurth, 1996; Zimmerman *et al.,* 2011).
- The Adair 2 Fire began on August 12, 1994. It burned through mid-September and ultimately became part of the North Fork Complex, which consisted of the Howling Fire, the Adair 2 Fire, and the Starvation Fire (Boehle, 2002; Rodriguez, 2005). The Adair 2 fire burned until mid-September under high relative humidity conditions.
- On August 8, 1999, the Anaconda Fire was started by lightning on the west side of Glacier National Park. It was allowed to burn to accomplish resource objectives (Boehle, 2002), and most of the fire activity occurred under the hot and dry conditions of a high-pressure system in September (Rodriguez, 2005).
- The largest fire in this sequence, the Moose Fire, started by lightning on the Flathead National Forest near the western boundary of Glacier National Park on August 14, 2001. It was detected two days later and declared a wildfire. Conditions in the area were said to be “ripe for extreme fire behavior” (Barrett, 2002), and the fire repeatedly escaped control lines and eventually burned more than 70,000 acres over the course of several weeks (Rodriguez, 2005). The previously described Anaconda Fire and Howling Fire are both credited with influencing the behavior and growth of the Moose Fire (Boehle, 2002).

- The Wolf Gun Fire, a fire managed as part of the Trapper Creek Complex, was ignited by lightning on July 16, 2003, in the western part of Glacier National Park. The fire burned into September, primarily burning in mixed conifer with heavy dead and downed fuels.

The Bob Marshall Sequence

The Bob Marshall Sequence consists of two fires: Gates Park (1988) and Biggs Flat (2001).

- Detected on July 11, 1988, the Gates Park Fire burned in the North Fork drainage of the Sun River in the Bob Marshall Wilderness. Originally a PNF, the fire was eventually converted to a wildfire and suppression actions taken due to the possibility it might escape wilderness boundaries. However, direct suppression tactics were minimal as resources were scarce during the 1988 fire season. The fire burned through the end of October, many days without significant growth (Love and Watson, 1992; Rodriguez, 2005).
- The Biggs Flat Fire was started by lightning on September 27, 2001. It was managed to meet resource objectives using confine and contain strategies as opposed to direct suppression strategies, and much of the fire burned on top of the burn scar from the 1988 Gates Park Fire (Linse, 2002; Rodriguez, 2005).

The Scapegoat Sequence

The Scapegoat Sequence consists of three fires: Canyon Creek (1988), Cabin Creek (2001), and Conger Creek (2007).

- The Canyon Creek Fire was started by lightning on June 25, 1988, in the North Fork of the Blackfoot River drainage. It burned for 112 days and was the largest fire in the Northern Rockies that year. Between September 6 and 7, a wind-event caused the fire to grow over 117,375 acres in just nine hours (Rodriguez, 2005).
- The Cabin Creek Fire, also a lightning-caused fire, started on September 26 and burned until October 8, 2001, growing to just over 2,000 acres. The fire burned completely within the scar left by the Canyon Creek Fire in the Dry Fork of the Blackfoot River drainage. The average daily growth was 100 acres, with a maximum gain of 250 acres in one day.

- The Conger Creek Fire, yet another lightning-caused fire in the Blackfoot River drainage, started on July 17, 2007, near the North Fork of the Blackfoot River in Conger Creek. The fire burned through mid-September. On its largest growth day, July 29, the fire grew by approximately 10,000 acres during a plume-dominated event. During this event, the Conger Creek Fire spread onto the burn scar left by the Canyon Creek Fire, burning across it until reaching the burn scar from the Cabin Creek Fire. The burn scar left by the Cabin Creek Fire effectively reduced the fire behavior of the Conger Creek Fire, causing it to flank the area burned by the Cabin Creek Fire (Seielstad, 2010). Nearly half of the total acreage burned during the Conger Creek Fire was on top of the burn scar from the 1988 Canyon Creek Fire.

Image Processing Methods

After selecting fire sequences and acquiring the relevant datasets from MTBS data servers, the remotely sensed images were processed. Each of the steps in the five-step process is discussed below.

Quality Control

Quality control measures determined whether the data were adequate for use in analyses, and that the best available scenes had been used during MTBS processing. Two quality control issues addressed in this stage of research were the presence of clouds in the images and/or LANDSAT7 ETM+ (L7ETM+) scan line corrector (SLC) problems. If clouds were present in the images, either directly over the fire area or with shadows directly over the fire area, a suitable cloud-free replacement image was sought. MTBS provides a 'cloud mask' with the dataset, from which clouded areas can be masked from additional analyses. If a cloud-free image was not available, the MTBS cloud mask data were used. However, if a cloud-free image was available, it was used in place of the cloudy image for any image processing and analysis. This resulted in one post-fire scene replacement. Since 2003, L7ETM+ imagery has had a SLC problem, which results in stripes across an image (USGS, 2008). If a fire was mapped using a L7ETM+ image, and the SLC problems affected any of the fire area, a suitable LANDSAT5 TM replacement image was sought. If a suitable replacement image could not be found, the fire was dropped from this stage of analysis. The SLC-issue caused one fire to be dropped from this portion of the analysis, less than 600-ac of which were re-burned onto a previous fire.

Attribution of Burned Areas

To differentiate between once-burned and re-burned locations within a fire, some additional attributes were added to the fire perimeter attribute tables. Fire perimeters, called *burned area delineations* by the MTBS project, are derived by discriminating the outermost perimeters of areas that burned from unburned areas using a conventional change detection metric, the delta NBR (dNBR). This dissertation uses the term *fire perimeter* when referring to the burned area delineations.

Using the geographic information system (GIS) and remote sensing software packages ESRI ArcMap (ESRI, 2009) and ERDAS IMAGINE (ERDAS, Inc., 2009), and the MTBS fire perimeters, the intersections of multiple fires were determined. Intersecting areas greater than 100-ac were retained and attributed as re-burns. Fire perimeters that touched, as well as intersecting areas less than 100-ac and/or less than 60-m wide, were considered shared perimeters, or shared edges, between fires. These edges are what Collins *et al.* (2009) considered as *extent-constrained,* since a previous fire constrains the extent of a subsequent fire. The re-burn and edge parameters were ultimately selected based on mapping resolution, similar fire studies, existing fire size classification thresholds, and polygon chaining – when adjacent polygons overlap based on vertices and snap tolerance differences.

These new attributes were then used to select various parts of the fires that were used in the processing sequence described later in this chapter. For each fire in a fire sequence, an area of interest (AOI) was created and attributed based on the order in which the fires occurred and the number of times the area had burned, according to the following characteristics:

- First Fire Only (entire fire perimeter, burned once)
    - First Fire under Subsequent Fire (that portion of the initial fire that ultimately was re-burned by a subsequent fire, intersection)
- Subsequent Fire (entire perimeter of the subsequent fire, burned more than once in some places and only once in others)
    - Subsequent Fire Only (that portion of the subsequent fire that only burned one time)
    - Subsequent Fire on Previous Fire (that portion of the subsequent fire that burned on top of a previously burned area, intersection)

There were eighteen different AOIs created for the ten fires analyzed: The Scapegoat Sequence had four AOIs, the Bob Marshall Sequence had three, and the Glacier Sequence had eleven. From these AOIs, nine were identified as intersections that had burned more than once during the study period, and nine were identified as only burned once. The number of fires in a fire sequence does not necessarily determine the number of AOIs.

Burn Ratios and Severity Classification

Using the pre- and the post-fire reflectance images included in the MTBS dataset, both pre- and post-fire NBRs were calculated according to Equation 1. This was done for the entirety of each image containing a fire in a fire sequence, resulting in nine pre-fire NBR images and nine post-fire NBR images – the Adair 2 and Howling Fires were both derived from the same pre- and post-fire LANDSAT images. The dNBR for each fire was derived and then compared to the dNBR that was provided with the MTBS dataset. The numbers and images matched in every case, so future iterations will use the dNBR images included as part of the MTBS dataset. The classified dNBR images images that were provided as part of the MTBS datasets were also used.

Filters

For each classified dNBR image, a neighborhood filter was applied to reduce the effects of potentially spurious data (*i.e.,* noise). Examination of each classified dNBR image indicated that some of the images had possible noise issues. For example, otherwise large contiguous patches of a given severity class contained a single pixel of a different class. To reduce the local variation caused by these pixels, a neighborhood filter – specifically, a 3x3 majority filter – was applied to the classified dNBR images using the *Image Interpreter GIS Analysis* tools found in ERDAS IMAGINE (ERDAS, Inc., 2009).

Equation 3 demonstrates how the value of the pixel-of-interest is determined. Input raster cells (C1 through C9) are filtered with the 3x3 filter (F1 through F9) and the output raster pixel-of-interest (C) is assigned a valued based on the formula in Equation 3. In this instance, all values in the 3x3 filter were 1. In effect, this low-pass filter smoothed the classified data by applying the value of the majority of the 3x3 neighborhood pixels (C1 through C9) to the pixel-of-interest (C).

$$\mathbf{C} = (\mathbf{C1} * \mathbf{F1}) + (\mathbf{C2} * \mathbf{F2}) + (\mathbf{C3} * \mathbf{F3}) + \ldots + (\mathbf{C9} * \mathbf{F9}) \qquad \textit{Equation 3}$$

Processing Sequence

For each individual fire in each fire sequence, all six images were stacked into a single 5-band image (B1 through B5) as follows:

- B1 = Pre-fire NBR
- B2 = Post-fire NBR
- B3 = dNBR
- B4 = Classified dNBR
- B5 = 3x3 Majority Filter

Once the 5-band images were created for each fire, the data values were exported to an ASCII text file for use in statistical analysis packages using each of the AOIs as masks. For each 5-band image, the pixels that fell within a given AOI were extracted in table format. Each row represented a pixel. The columns were pixel attributes consisting of the pixel coordinates in latitude and longitude, and the value for each band at that location. Additional attributes in the text files included a numeric code identifying the AOI, the year of the fire, the number of times the location had burned, the difference in years between fires (*i.e.,* the *time-since-previous-fire* [TSPF]) at that location, and the order in which the pixel had burned (*i.e.,* first burn, second burn, etc.). In all instances, no more than two burns occurred in a single location. The resulting individual ASCII files were then combined into one file for use in the statistics software.

GIS Analysis

In a separate step, the classified dNBR images were combined using the *Combine* tool in ArcToolbox. This tool combines multiple rasters into one raster, with unique output values assigned to each unique combination of input values. Only those portions of the initial fire that were re-burned by the subsequent fire were used; once-burned locations were not used in this step. The values were exported to ASCII text files. This defined the order in which fire severity occurred, such that it was possible to compare the severity of an initial fire and a subsequent fire to each other, as well as how the proportion of area in each severity class changed.

Statistics

Statistical analyses were performed using Microsoft Excel and SPSS (PASW Statistics Release 18.0.0) software. To determine if those places that burned more than once differed from those places that only burned once, a one-way analysis of variance (ANOVA) procedure with four different dependent variables was performed. One-way ANOVA is a procedure used to test the hypothesis that the group means of dependent variables are equal. The groups were classified as Once-Burned and Re-burned. The four different dependent variables were *Post-NBR, dNBR, Classified dNBR,* and *Filtered Classified dNBR*. The ANOVA was run with a significance threshold of $\alpha=0.05$. Additionally, descriptive statistics for each fire sequence were compiled.

RESULTS and DISCUSSION

An ANOVA analysis was done to compare the means of those places that burned once and those places that burned more than once with respect to the post-fire characteristics NBR and dNBR (continuous, classified, and filtered). For each of the four variables in all ten fires in the three fire sequences, there was a significant difference ($P = 0.000$; $\alpha = 0.05$) between those places that burned once and those that burned more than once. These findings led to descriptions and analyses of the individual fires and the re-burned areas to try to understand if and how the severity of fires changes as places re-burn, whether this is the same in all fire sequences, and whether the timing between fires in places that have burned multiple times influenced re-burn sizes and severities.

Individual Fires and Severity

Between 1988 and 2007, ten fires in three fire sequences burned 347,569-ac. Two of the three largest fires occurred during the 1988 fire season, and account for virtually 60% of the total area burned by the three fire sequences (Figure 3, Table 1). Table 1 shows the area involved in each fire, by severity classification and overall. This table shows that a majority of the burned acres overall are classified as High Severity (141,421-ac; 41% of total burned area), followed by Moderate Severity (75,885-ac; 22%), Low Severity (72,715-ac; 21%), and Unburned (57,548-ac; 17%) categories. However, while the largest fires in each sequence follow this trend, the severity distributions do not necessarily follow this trend for every fire. For example, the Howling Fire has more acres classified as Unburned (52%), followed by Low Severity (43%), and Moderate Severity (6%), with nearly no High Severity (0%), while Wolf Gun and Adair 2 both have the highest proportion of area classified as Low Severity (46%).

Table 1: The proportion of total area burned (in parentheses) in each fire by severity class. Overall, the highest proportion of area is classified as High Severity, followed by Moderate, Low, and Unburned, and is influenced by the three largest fires (noted by *); other fires do not follow this trend.

Fire Sequence	Fire Name	Fire Year	Unburned	Low	Moderate	High	*Total Area*
Scapegoat Sequence	Canyon Creek*	1988	24,009 (14%)	26,672 (16%)	33,581 (20%)	84,594 (50%)	*168,856 (100%)*
	Cabin Creek	2001	542 (27%)	594 (29%)	648 (32%)	257 (13%)	*2,040 (100%)*
	Conger Creek	2007	4,716 (20%)	5,407 (23%)	7,224 (31%)	5,994 (26%)	*23,342 (100%)*
Bob Marshall Sequence	Gates Park*	1988	4,523 (12%)	4,890 (13%)	6,155 (16%)	22,726 (59%)	*38,294 (100%)*
	Biggs Flat	2001	1,483 (20%)	2,203 (30%)	2,358 (32%)	1,349 (18%)	*7,393 (100%)*
Glacier Sequence	Howling	1994	860 (52%)	710 (43%)	94 (6%)	3 (0%)	*1,667 (100%)*
	Adair 2	1994	2,333 (35%)	3,103 (46%)	1,134 (17%)	181 (3%)	*6,751 (100%)*
	Anaconda	1999	3,944 (35%)	4,235 (37%)	1,985 (17%)	1,241 (11%)	*11,405 (100%)*
	Moose*	2001	12,430 (17%)	18,242 (25%)	18,801 (26%)	23,938 (33%)	*73,410 (100%)*
	Wolf Gun	2003	2,709 (19%)	6,661 (46%)	3,904 (27%)	1,137 (8%)	*14,410 (100%)*
TOTAL ACRES by SEVERITY			*57,548 (17%)*	*72,715 (21%)*	*75,885 (22%)*	*141,421 (41%)*	*347,569 (100%)*

The fires within each fire sequence are listed chronologically in Table 2, with the earliest fires for each sequence listed first. The distribution of fire severity classifications for each fire individually, as well as those portions that burned more than once, and all fire sequences overall, were analyzed. For example, reading down the 'Fire Name' column for the Scapegoat Sequence, the Canyon Creek Fire is the first fire in the sequence, the Cabin Creek Fire is second, and the Conger Creek Fire burned third. All of Canyon Creek only burned one time; Cabin Creek burned completely on top of Canyon Creek and is all re-burn, indicated by ">1x"; and in the Conger Creek Fire, a portion burned only once ("Conger Only [1x]"), and a portion re-burned on Canyon Creek ("Conger on Canyon [>1x]"). Although none of Conger Creek burned on top of Cabin Creek (Conger on Cabin = 0% by category), it was influenced by the edges of Cabin Creek and is thus represented as "Conger on Cabin (>1x)" in Table 2. Fire-on-fire interactions in the other two fire sequences are represented similarly.

The proportion of area classified in each severity class for each fire is noted in the rows of Table 2. In the Glacier Sequence, 34% of the total area within the perimeter of the Adair 2 Fire is Unburned, 46% is Low Severity, 17% Moderate Severity and 3% High Severity. The majority of the area burned in the fires in the Scapegoat Sequence (SS) was in the High Severity category (Scapegoat Sequence All = 47%). The Bob Marshall Sequence (BMS) and the All Sequences Combined (ASC) groups also showed the majority of area burned in the High Severity category (BMS=53%; ASC=40%). The three largest fires – Canyon Creek, Moose, and Gates Park – had the highest percentage of area burned in the High Severity category (50%, 32%, and 59%, respectively), and these few fires highly influenced the overall severity distribution.

In every instance of re-burn, the proportion of area classified as Moderate Severity was higher than the proportion of area classified as High Severity (Table 2). For example, in the "Wolf Gun on Anaconda (>1x)" row, Moderate Severity accounted for 25% of the area re-burned, while High Severity was only 5%. In the Bob Marshall and Scapegoat Sequences, re-burns were primarily Moderate Severity (BMS=39%; SS=32% Cabin on Canyon, and 39% Conger on Canyon). In the Glacier Sequence, areas re-burned by the Moose Fire were primarily classified as Unburned (Moose Re-burns All, 58%), while those re-burned by the Wolf Gun Fire were primarily classified as Low Severity (Wolf Gun Re-burns All, 52%). The proportion of total area classified as High Severity was lower than any other severity class in every instance of re-burn except Biggs Flat on Gates Park.

Table 2: Proportion of total area burned by severity classification is listed for the once-burned (1x) and re-burned (>1x) portions of each fire. Re-burned areas have a low proportion of area classified as High Severity. The largest fires in each sequence are noted with a *.

Fire Sequence	Fire Name	Unburned	Low	Moderate	High
Scapegoat Sequence	Canyon Creek*	14%	16%	20%	50%
	Cabin Creek on Canyon Creek (>1x)	27%	29%	32%	13%
	Conger Creek	20%	23%	31%	26%
	Conger Creek Only (1x)	15%	18%	25%	42%
	Conger Creek on Canyon Creek (>1x)	27%	29%	39%	5%
	Conger Creek on Cabin Creek (>1x)	0%	0%	0%	0%
	Scapegoat Sequence	***15%***	***17%***	***21%***	***47%***
Bob Marshall Sequence	Gates Park*	12%	13%	16%	59%
	Biggs Flat	20%	30%	32%	18%
	Biggs Flat Only (1x)	35%	37%	19%	8%
	Biggs Flat on Gates Park (>1x)	12%	26%	39%	24%
	Bob Marshall Sequence	***13%***	***15%***	***19%***	***53%***
Glacier Sequence	Howling	52%	42%	6%	0%
	Adair 2	34%	46%	17%	3%
	Anaconda	35%	37%	17%	11%
	Moose*	17%	25%	25%	32%
	Moose Only (1x)	13%	24%	27%	35%
	Moose on Howling (>1x)	72%	20%	1%	0%
	Moose On Adair 2 (>1x)	57%	36%	4%	1%
	Moose on Anaconda (>1x)	50%	25%	16%	5%
	All Moose Re-burns (>1x)	*58%*	*27%*	*8%*	*2%*
	Wolf Gun	19%	46%	27%	8%
	Wolf Gun Only (1x)	13%	42%	33%	12%
	Wolf Gun on Adair 2 (>1x)	28%	54%	17%	1%
	Wolf Gun on Anaconda (>1x)	26%	44%	25%	5%
	Wolf Gun on Moose (>1x)	54%	44%	2%	0%
	All Wolf Gun Re-burns (>1x)	*28%*	*52%*	*18%*	*2%*
	Glacier Sequence	***21%***	***30%***	***24%***	***24%***
All Sequences		***16%***	***21%***	***22%***	***40%***

In places that burned more than once in the Scapegoat Sequence, much less of the area was classified as High Severity (Cabin Creek [>1x] = 13%; Conger Creek on Canyon Creek [>1x] = 5%) than other categories. In those places that only burned once, most of the area was attributed in the High Severity category (Canyon Creek All = 50%, Conger Fire Only = 42%). Of particular interest in this fire sequence is the Cabin Creek Fire. The Cabin Creek Fire burned completely within the area burned previously by the Canyon Creek Fire (Figure 3, Table 2), and is the only example of a large wildfire burning completely within another large wildfire in the three fire sequences. Although Conger Creek burned up to Cabin Creek, none of the area was re-burned as defined previously. Instead, the Cabin Creek Fire influenced the spread of the Conger Creek Fire, acting as an edge and buffering the movement of the Conger Creek Fire. As a result, Conger Creek burned around the Cabin Creek Fire. While shared perimeters between fires do exist, this is the only such example (in this stage of research) of a shared-perimeter situation that exhibits a lack of complete intersection. These findings suggest that previous fires affect subsequent fires in terms of spread and effects. Severity classifications in re-burned areas are lower than the same locations in previous fires. This may be due to the relationship that the length of time between successive fires has on vegetative succession, and what is available to burn at that location.

The characteristics of the once-burned areas of the two fires in the Bob Marshall Sequence are different from each other. The Gates Park Fire is primarily classified as High Severity (59%; Table 2), while the once-burned portion of Biggs Flat is largely Low Severity (37%) and Unburned (35%). Overall, the burned area is classified as High Severity (53%); the large proportion of High Severity in the Gates Park Fire influences this number. While the majority of the re-burned area is classified as Moderate Severity (39%), the percentage of area classified as Low Severity (26%) is nearly equal to High Severity (24%). Although the earlier Gates Park Fire likely influenced the severity of the subsequent Biggs Flat Fire in those places that re-burned, the once-burned attributes of the two fires are quite different. One reason that the fires in this sequence exhibit such different severities might be attributed to the seasonality of their occurrence: Gates Park started in July and burned during the hottest and driest months of the summer, while Biggs Flat ignited in September toward the end of fire season.

Overall, the area burned by fires in the Glacier Sequence can be characterized as Low Severity (Glacier Sequence All = 30%; Table 2), although the area classified in the other categories is rather evenly distributed. In the instance of the Moose Fire, the area burned overall is largely characterized by High Severity (Moose All = 32%) with the least amount of area in the Unburned class (17%). However, in areas re-burned by Moose, the highest proportion of area is classified as Unburned (58%), followed by Low Severity (27%), and just 2% of the re-burned area is classified as High Severity. As the Moose Fire is the largest fire in the sequence, it greatly influences the overall proportions attributed in each severity category. Also of interest in this sequence is the fact that both the Howling Fire and the Adair 2 Fire occurred in 1994, but exhibit somewhat different severity classification distributions. This can likely be attributed to the seasonality of their occurrences (June and August, respectively).

Tables 1 and 2 suggest that, although there are more small fires, a few large fires drive the overall distribution of severity classifications. Four of the ten fires are less than 10,000-ac (Cabin Creek, Biggs Flat, Howling, and Adair 2), and three fires are larger than 30,000-ac (Canyon Creek, Gates Park, and Moose). By the National Wildfire Coordinating Group (NWCG) standards, only two of the ten fires in this analysis are below the Fire Size Class G threshold. Fire Size Class G is used by fire managers to designate large wildfires, and only includes fires larger than 5,000-ac (NWCG, 2006).

Fire Sequences and Severity

Image processing methods yielded nine pairs of intersecting areas within the three fire sequences and one edge interaction (see Figure 3). Of the total area burned (347,569-ac; Table 1), just over 8% (27,885-ac; Table 3) is located in re-burned areas. The fires involved in fire-on-fire interactions are listed in Table 3. Each row represents the fires involved in a single type of interaction. The 'First Fire' column indicates the name of the fire that burned first in a location, and the 'Second Fire' column indicates the name of a subsequent fire that encountered the first fire. Additionally, the timing between fires (the *time since previous fire*, or 'TSPF,' column), the total area of the intersection (the 'Size of Re-burn' column), and the proportion of each fire involved in the interaction are listed. The 'Proportion of the 1st Fire that Re-burned in 2nd Fire'-column indicates the proportion of the total area of the first fire that was subsequently re-burned by the second fire. The 'Proportion of the 2nd Fire that re-burned onto 1st Fire'-column shows the proportion of the total area of the second fire that re-burned onto a previously burned area. For example, the 73,410-ac Moose Fire encountered the 6,751-ac Adair 2 Fire seven years after Adair 2 had burned. This interaction resulted in 1,686-ac re-burning – which is 25% of the total area of Adair 2 that was re-burned by the Moose Fire.

The Scapegoat Sequence spans nineteen years and includes three fires. The longest time between fires in those places that burned multiple times is nineteen years, and the shortest time is thirteen years. The total burned area is approximately 194,240-ac, of which nearly 12,320-ac is re-burned. Of particular interest in this fire sequence is the Cabin Creek Fire, which started and burned completely within the burn scar of the Canyon Creek Fire—the only such example in this portion of research. The total area burned by the Canyon Creek Fire was 168,856-ac. The entirety of the Cabin Creek Fire re-burned on top of Canyon Creek, burning 2,040-ac, or 1% of the total size of Canyon Creek. Additionally, the Conger Creek Fire and the Cabin Creek Fire interacted, but the interaction is considered an edge interaction as opposed to a re-burn. Conger Creek burned around the scar left by Cabin Creek, suggesting that the Cabin Creek Fire influenced the behavior of the Conger Creek Fire in this area by buffering its movement. As a result, zero acres of the Conger Creek Fire burned on top of the Cabin Creek Fire in spite of being adjacent to it spatially. Also of interest in this fire sequence is the fact that almost 20 years later, nearly half (44%) of the Conger Creek Fire burned within the area previously burned by the Canyon Creek Fire.

The Bob Marshall Sequence spans thirteen years, and includes two fires. The total burned area is nearly 45,690-ac, of which just over 4,750-ac are re-burned. The Biggs Flat Fire burned close to 7,400-ac, more than half of which were in the area burned thirteen years previously by the Gates Park Fire (64%, Table 3). In local fire management circles, this particular set of fires is notoriously talked about as the place "where we began to understand how old burn scars could significantly influence a current fire's behavior" (McBratney, 2010), as a result of watching fire behavior of the Biggs Flat Fire change as it encountered the scar from the Gates Park Fire. Although Biggs Flat appeared to stop at the High Severity areas of Gates Park, more than half of the Biggs Flat Fire did burn within a previously burned area, and much of the severity in this intersection is classified as Moderate Severity (39%; Table 2).

The Glacier Sequence is the most complex sequence in this portion of the research. This sequence only spans nine years, but includes five fires with various intersection and overlap situations (Figure 3). The longest time between fires in those places that burned multiple times is nine years, and the shortest time is two years. The total burned area is almost 107,650-ac, nearly 10% of which is re-burned by the two largest fires, Moose and Wolf Gun. The Moose Fire was the largest fire in the Glacier Sequence, burning just over 73,400-ac (Table 1), or 68% of the total area burned in this sequence (Table 3). The Moose Fire re-burned just over 5,100-ac of areas previously burned by other fires (Table 3). Just over 5,600-ac, or nearly 40%, of the total area burned by the Wolf Gun Fire (14,410-ac; Table 1) is in areas that burned for a second time during the study period, most of which (84%) was overlap with the Adair 2 Fire from nine years earlier (Table 3). The Adair 2 Fire was almost entirely re-burned; 95% of the original area burned by the Adair 2 Fire was re-burned by either the Moose Fire or the Wolf Gun Fire (25% and 70%, respectively; Table 3). The Howling Fire was also almost entirely re-burned by the Moose Fire (91%; Table 3). Although most of Howling and Adair 2 were re-burned, the subsequent fires in the areas of overlap were generally classified as Unburned or Low Severity (Table 2). In contrast, the Canyon Creek and Gates Park fires both had a small percentage of area re-burn, but these areas were predominantly characterized as Moderate Severity (Table 2).

Table 3: The fires pairs involved in fire interactions are listed, as well as the time between the two fires (time since previous fire, TSPF), the size of the re-burn, and the proportion of total fire area (for each fire) involved in the interaction. In general, the size of the area re-burned increases as TSPF increases.

Fire Sequence	First Fire (Total Acres)	Second Fire (Total Acres)	TSPF (years)	Size of Re-burn (Acres)	Proportion of 1st Fire that Re-burned in 2nd Fire (%)	Proportion of 2nd Fire that Re-burned onto 1st Fire (%)
Scapegoat Sequence	**Canyon Creek** (168,856)	**Cabin Creek** (2,040)	13	2,040	1	100
	Canyon Creek (168,856)	**Conger Creek** (23,342)	19	10,276	6	44
	Cabin Creek (2,040)	**Conger Creek** (23,342)	6	0	0	0
Bob Marshall Sequence	**Gates Park** (38,294)	**Biggs Flat** (7,393)	13	4,752	12	64
Glacier Sequence	**Adair 2** (6,751)	**Moose** (73,410)	7	1,686	25	2
	Adair 2 (6,751)	**Wolf Gun** (14,410)	9	4,732	70	33
	Howling (1,667)	**Moose** (73,410)	7	1,406	84	2
	Anaconda (11,405)	**Moose** (73,410)	2	2,075	18	3
	Anaconda (11,405)	**Wolf Gun** (14,410)	4	805	7	6
	Moose (73,410)	**Wolf Gun** (14,410)	2	113	0	1
TOTAL ACRES RE-BURNED				***27,885***		

It appears that the proportion of area involved in fire-on-fire interactions is loosely driven by the time-since-previous-fire, as well as the severity of the previously burned area. In general, the larger the TSPF value, the larger the area of the fire-on-fire intersection (Table 3). The different fire sequences also exhibit differences in the proportion of fire involved in intersections. The Glacier Sequence spans the shortest period, and the two largest fires in this sequence re-burned portions of smaller fires that had previously burned. In four of the six instances of overlap in this region, more than 15% of the area of the initial fire was re-burned by a subsequent fire (Table 3). The Scapegoat and the Bob Marshall Sequences spanned the longest period, and the largest fires in these sequences were subsequently re-burned onto by smaller fires. Fire-on-fire interactions in these sequences indicate that more than 40% of the second fire re-burned a previously burned area. Cabin Creek stands out as an interesting fire in the three sequences: It is the only case where the second fire burned completely within the first fire, and is also the only instance of a shared perimeter where no intersection occurred.

To briefly summarize the findings thus far, once-burned areas and re-burned areas have statistically different post-fire characteristics (NBR and dNBR – continuous, classified, and filtered), as shown by the ANOVA. Severity distributions are similar within fires within a sequence (Table 1), but the severity distributions differ between the Glacier, Scapegoat, and Bob Marshall fire sequences, as well as within the once-burned and re-burned components of a fire (Table 2). The size of re-burns generally increases as the amount of time between fires increases (Table 3). The next and final step in this stage of research is to isolate the re-burned areas to determine severity order in these locations.

Fire Intersections and Severity

The final step of the first stage of research examined the order of occurrence of fire severity in the fire sequences. That is, for each individual location that re-burned, how was the severity of the first burn classified and how was the severity of the second burn classified? The assumption was that if a location had burned previously, the prospect that a second fire would be classified as High Severity should be reduced. Figure 4 shows the proportion of the total area re-burned between initial fires and subsequent fires. The severity of the first fire is indicated on the *x*-axis, and the bars are coded according to the severity of the second fire.

In both the Scapegoat and the Bob Marshall fire sequences, the first fire generally predisposed subsequent fires to burn with effects in the Moderate Severity category, irrespective of the initial fire severity classification (Table 2; Figure 4). In the Scapegoat Sequence, the majorities of the re-burned areas classified as High Severity (HS) in the first fire are classified as either Low Severity (LS; 11%) or as Moderate Severity (MS; 13%) in the second fire (Figure 4). The distribution of severities within the re-burn of Cabin Creek on Canyon Creek is much more evenly distributed than the distributions of the Conger Creek on Canyon Creek intersection (Figure 4). In the Bob Marshall Sequence, most of the areas classified as Low Severity in the re-burns are classified either as Unburned (9%) or as Low Severity (7%) in the first fire (Figure 4).

The Glacier Sequence shows quite different trends in terms of severity class order (Figure 4). Most of the area involved in the fire-on-fire interactions in this Fire Sequence is classified as either Unburned or Low Severity for both the initial and the subsequent fires (UB-UB = 17%, UB-LS =18%, LS-UB = 23%, LS-LS = 15%; Figure 4). Most of the area classified as High Severity in the Glacier Sequence is not in places that re-burned. In fact, of the total area re-burned by the Moose Fire, only 2% is classified as High Severity (Table 2); similar proportions are exhibited in re-burned areas of the Wolf Gun Fire. Perhaps because of the short time period between successive fires in the Glacier Sequence, as noted in Table 3, the distribution of severity classes tends to be in the Unburned and Low Severity categories.

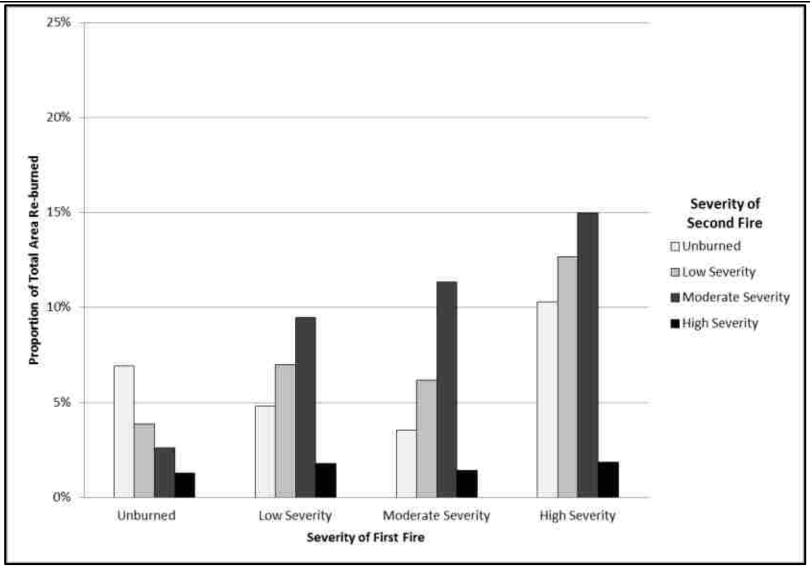
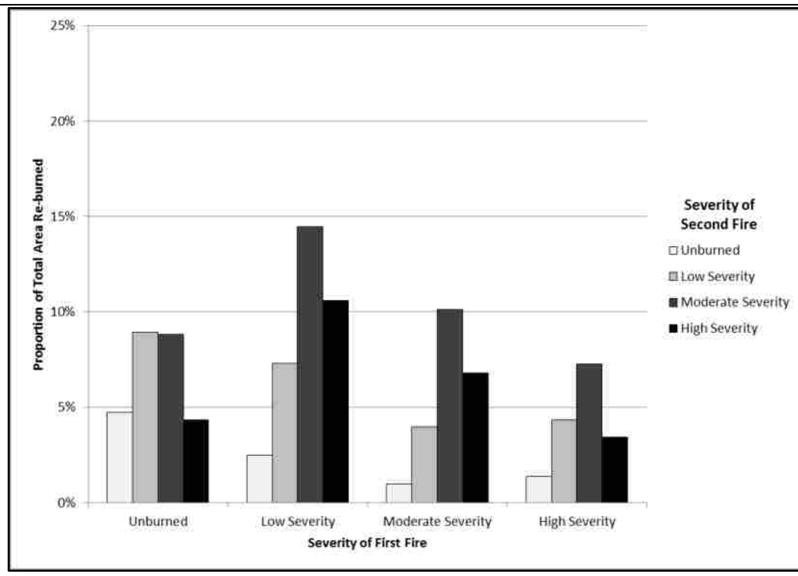
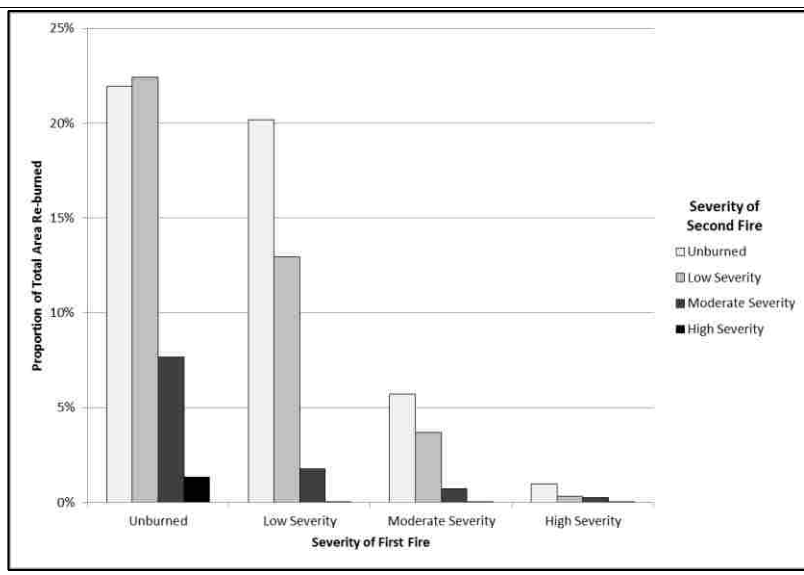
Scapegoat Sequence	
Bob Marshall Sequence	
Glacier Sequence	

Figure 4: Fire severity re-distribution for re-burned areas overall (as a proportion of total area burned). The severity of the first fire is indicated on the x-axis, and the bars are coded according to the severity of the second fire. Fires in the Glacier Sequence re-burned at lower severities than fire in the Scapegoat or Bob Marshall Sequences.

The persistence of unburned areas, whether these were islands interior to the fire or areas adjacent to the perimeter, is an interesting phenomenon. This is evident in all fire sequences and is mapped in Figure 5a-c. In the maps, any area where the severity classification remains the same is indicated by a color (green, orange, or red), while those areas with different severity classifications are indicated by grey for lower severity in the second fire or black for a higher severity in the second fire. For example, areas classified as Unburned in both the first and second fires (UB-UB) are shown as turquoise, while an area classified as moderate severity in the first fire and low severity in the second fire – which would be a reduction in severity – are shown in grey (Figure 5).

In Figure 5, notice how unburned islands persist within perimeters, and also how the direction of severity re-distribution (increased or decreased severity) differs in the Bob Marshall and Scapegoat Fire Sequences. In the Scapegoat Sequence overall, approximately 50% of the area classified as Unburned in the first fire remained Unburned after a subsequent fire. Generally, these unburned areas are interior unburned islands and edge locations and the area reduction between the first and second fires is from the edges of these islands being burned mostly by Low Severity fires (Figure 5a). In contrast, the Bob Marshall Sequence shows that Unburned classes are most often re-burned with Low and Moderate Severities almost equally (Figure 4), which would be an increase in severity (Figure 5b). In fact, only 20% of the areas classified as Unburned in the Gates Park fire remained Unburned when Biggs Flat re-burned over Gates Park. For the Glacier Sequence overall, 40% of the total area classified as Unburned remained Unburned. As pointed out in Table 2, for each separate fire pair, the percentage of area remaining Unburned ranges from 5% (Wolf Gun on Anaconda) to 72% (Moose on Howling). Figure 5c shows an example of the interaction of the Moose Fire with the Howling Fire, where a majority of the Unburned area remained Unburned and is shown in turquoise.

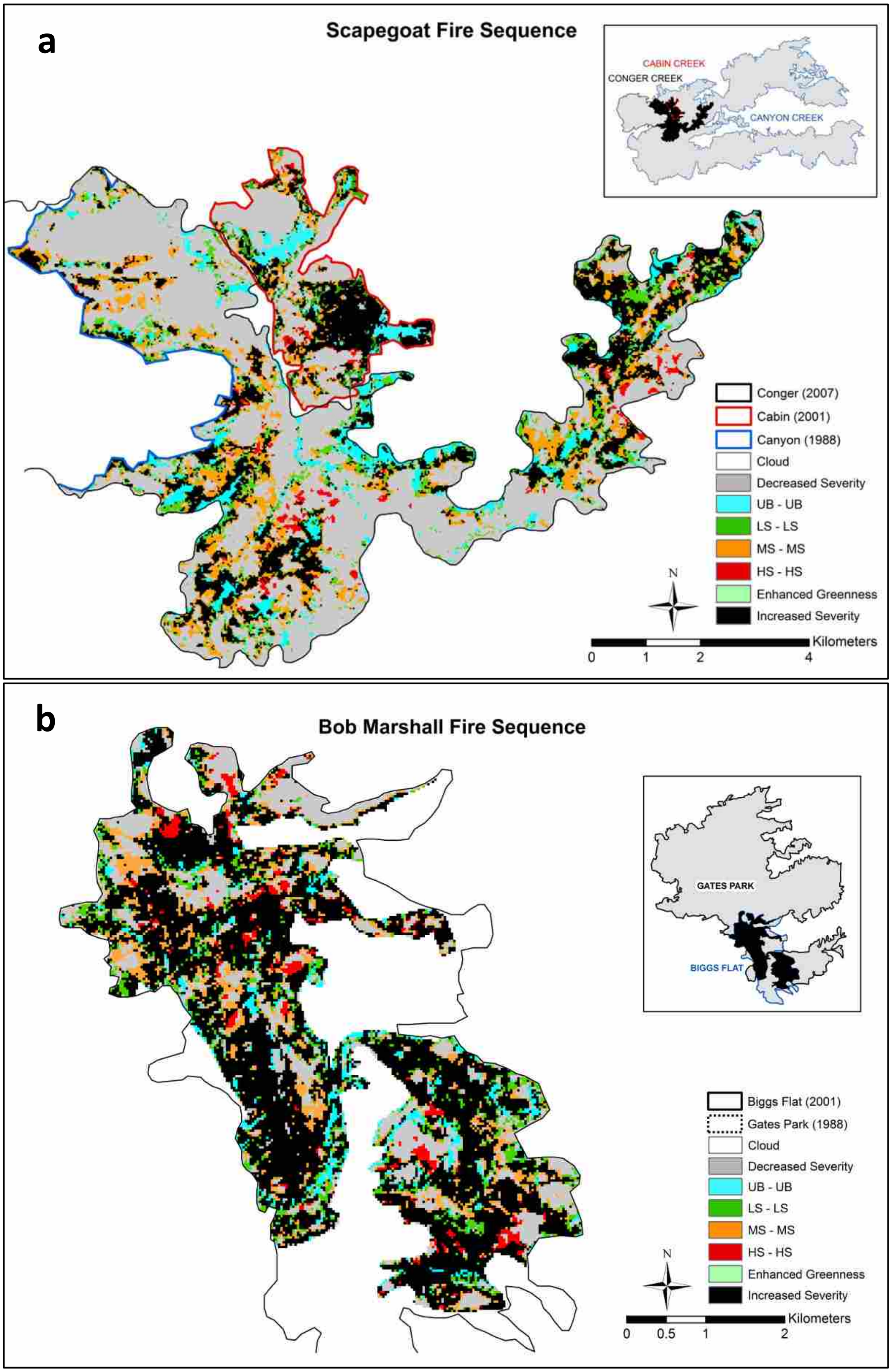
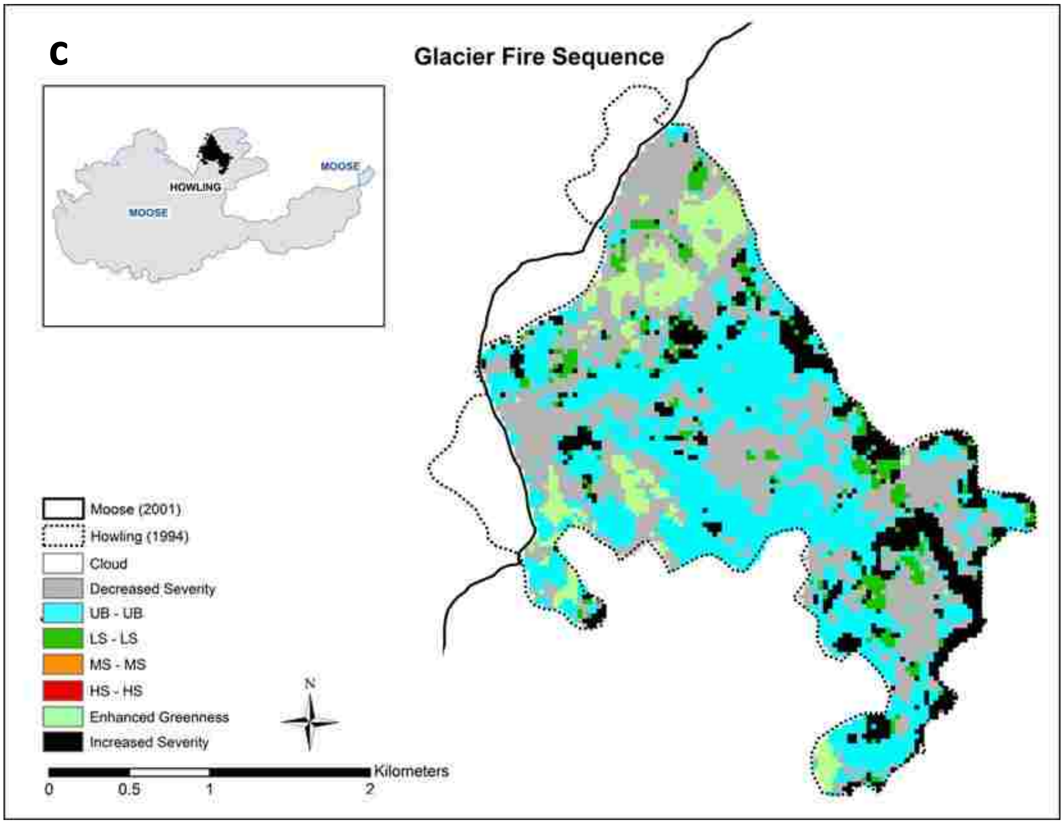


Figure 5: Severity classification maps showing direction of change in severity classifications between initial fires and subsequent fires for each fire sequence. *Note: Only the portion of the Glacier Sequence involving the Howling Fire re-burned by the Moose Fire is shown here*.


c
Glacier Fire Sequence
HOWLING
MOOSE
MOOSE
Moose (2001)
Howling (1994)
Cloud
Decreased Severity
UB - UB
LS - LS
MS - MS
HS - HS
Enhanced Greenness
Increased Severity
N
Kilometers
0
0.5
1
2

SUMMARY

This chapter focused on defining and refining objective and consistent methods to analyze fire-on-fire interactions. This developmental step was necessary because literature regarding the re-burn phenomenon is scarce, and as a result, standardized and replicable methods for analyzing re-burns do not exist. The variability of once-burned post-fire characteristics – NBR, dNBR, Classified dNBR, and Filtered Classified dNBR – were compared to re-burned post-fire characteristics, and all the groups were shown to differ statistically. Individual fires were then grouped into fire sequences, and the severity class distributions of the fires in the fire sequences were described in terms of their overall, once-burned, and re-burned components. Results from this step indicate that the majority of burned area was classified as High Severity, although this is not true for re-burned areas. Observations of the timing between fires and the severity classification order between fires both suggest that the size of a re-burned area is driven by the time-since-previous-fire and the severity of the first fire in that location. The existence of the MTBS dataset, coupled with the fact that fire-on-fire interactions have occurred with such different outcomes during the period 1984-2007, affords the opportunity to investigate this phenomenon more thoroughly. Information about these types of events is largely missing from the literature.

<u>Data Dimensions</u>

In this stage of research, multiple dimensions of the MTBS data were exploited, including analyses of vector data, continuous and thematic raster data, and multiple spatial and temporal scales. Initially, all fire occurrences in the large Pacific Northwest Mapping Zone between 1984 and 2006 were explored with regard to fire and re-burn occurrence using the fire perimeters. Although there are a number of fire-on-fire interactions mapped within the PNW Mapping Zone (Figure 2), there is a lack of literature regarding fire-on-fire interactions. Additionally, highly variable fire environments, regimes, and management issues are present across this broad area. Therefore, the research presented in this chapter focused on a sub-regional area in order to define methods and refine questions, and to minimize the potential effects of these broad-scale issues of variability on results. Ten individual fires, occurring between 1984 and 2007, were grouped into three fire sequences – the Glacier, Bob Marshall, and Scapegoat. These sub-regional fire sequences were analyzed in terms of the individual fires and the re-burned areas using fire perimeter data, and also looking at the timing between subsequent fires in re-burned areas. Additionally, post-fire characteristics in the once-burned and re-burned areas were examined using both continuous and thematic raster data.

Observations from this preliminary research show that previous fires affect subsequent fires, and that the severity and the time between subsequent fires is of importance when looking at fire effects in re-burned areas. The once-burned areas exhibit significantly different characteristics than those places that burned more than once for all factors as determined by the ANOVA. Once-burned areas are often larger and have larger areas more similarly classified (in terms of severity) than their re-burned counterparts. This supports the idea that the vegetation mosaic on the ground is partially a result of disturbances including large wildfires and fire-on-fire interactions, and is influenced by fire effects on the landscape. As demonstrated by the Glacier Sequence in those areas that re-burned, a shorter amount of time between fires yields smaller total area re-burned (Table 3), and proportionally more area classified in lower severity classes (Figure 4). This implies that previous fires do constrain subsequent fire spread, and reduce the effects of subsequent fires, for some time. As time between fires lengthens, the ways in which an initial fire influences the spread of a subsequent fire change as succession occurs. Although the study period is not long enough to predict severity characteristics in re-burned areas during the past twenty-four years, the probability that fire severity increases with time (in places burned more than once) likely increases through the years given the successional characteristics of these forests.

The interaction of fires is interesting to many researchers, in spite of the scarcity of literature about these interactions. The results from this study indicate that there are three characteristics of fire-on-fire interactions: Re-burning completely within a previous burn scar (rare); shared-perimeter or edge (rare); or complete overlap either burning into and across an old burn scar, or starting within a previous burn scar and burning out of it onto areas unburned during the study period. The mechanism for these types of fire-on-fire interactions cannot be explored using only MTBS data.

MTBS Limitations

While the MTBS dataset is used for answering the questions in this dissertation, it does have limitations. To further investigate how fires interact with each other using fire perimeter data, both temporal and spatial scale issues must be addressed. However, the MTBS data constrain the scales of fire-on-fire interactions that can be explored, both temporally and spatially. The fire sequences and individual fires are temporally limited; only those large wildfires that have occurred since 1984 can be analyzed with the MTBS dataset. In terms of spatial limitations, in the western U.S. only those fires greater than 1000-ac (405-ha) are mapped by the MTBS dataset. Temporal information on the start dates of fires is available in the dataset, but daily information such as fire behavior and spatial information such as fire growth are not included, although both the temporal and spatial information may be available from other sources for some of the fires. The short historical perspective coupled with fire size thresholds may be a limiting factor when attempting to fully explore the ecology of an ecosystem whose lifecycle and disturbances have a temporal scale of centuries rather than decades and that includes disturbances occurring on a spatial scale less than 1000-ac. Finally, the MTBS dataset itself is constrained by the availability of suitable imagery for analyses. A few limitations specific to the data include scan-line-corrector (SLC) issues and clouds in the images. These limitations are mitigated, as discussed in the Image Processing-Quality Control section of this chapter, in this stage of the research as well as in the next stages of research. In spite of its shortcomings, the MTBS dataset is an appropriate tool for exploring questions similar to those presented in chapters three and four because of its dimensionality in terms of data types and content.

CONCLUSIONS

This initial stage of research was critical for shaping future research questions, especially given the lack of literature and standardized methods for analyzing fire-on-fire interactions. Subsequently, the research focused on a sub-regional scale that explored three large fire sequences within the Greater Bob Marshall Wilderness Area. A framework for future methods was developed using these fire sequences. The results of this initial research verified that previous fires affect the behavior and effects of subsequent fires, including the spread, severity, size, timing, and location. The perimeter data were useful for investigating fire spread, and chapter three is devoted to analyses involving only perimeter data. The classified data enabled an understanding of fire effects, such as the severity trends that have occurred on the landscape, which facilitated the formulation of good research questions. Additionally the methods for the next stages of research were developed and tested. While only the classified severity was reported in this chapter of the research, the continuous NBR (pre- and post-fire) data were used in the analysis that is presented in chapter four. Given the lack of literature regarding the interactions of new fires with old fires, this stage of research has provided the ability to define and refine future questions based on the work to date. In the next two chapters, focused research questions will be explored using the methodological framework developed in this chapter.

In summary, the temporal, spatial, and severity characteristics of a previously burned area interact with and affect subsequent fires in those places common to them. Places that have burned multiple times are different from places that have burned only once; previous fires affect subsequent fires in several ways; unburned patches appear to be persistent; and the temporal and spatial scales of fires are intertwined.

- In fire sequences within the Greater Bob Marshall Wilderness Area, previous fires do affect subsequent fires. Previously burned areas affect the spread of subsequent fires in three ways: Re-burns completely within a previous fire, shared edges, and re-burning onto or out of a previously burned area. As a whole, previously burned areas act either as complete barriers to spread, or as barriers limiting the spread of fire. Additionally, unburned islands within fire intersections persist.
- The severity of a previous fire affects the severity of a subsequent fire in those places where the fires intersect. If a burned area is initially classified as High Severity, the likelihood of it re-burning and being classified as High Severity again is reduced, perhaps due to both the reduced amount of biomass available to burn as well as how the severity is characterized from the dNBR (Figure 4).
- There appears to be a pattern of existing patches that are reinforced on the landscape. Unburned patches, as a rule, remain largely intact. These distinct areas may serve as a means to sustain vegetation patches – including species and age class diversity – on the landscape, thereby influencing the potential behavior of a subsequent fire (*i.e.*, its ability to spread) and effects (*i.e.*, its size and severity), and providing an opportunity for historical patterns of burning to reoccur.
- Timing between fires appears to be influential in the total area that is available to re-burn, as well as the severity at which that area re-burns. The longer the time between fires, the greater potential for a larger area to burn and perhaps at a higher severity. That is, the first fire transitions from being a complete barrier in a shared-perimeter situation to a limiting barrier in an overlap situation. The size of the intersection is largely dependent on the time between fires, with smaller intersections occurring when

the amount of time between fires is low and larger intersections occurring when it is high.

- Places that re-burn are different from once-burned locations. These differences, combined with both the timing between fires and the demonstrated persistence of unburned areas, likely exemplify the range of vegetative conditions that exist across a burned landscape as well as the ability of vegetation to persist in spite of disturbances.
- Landscapes are self-regulating, which means vegetation composition (*i.e.,* species) and structure (*i.e*., arrangement) are affected by disturbances (*i.e.,* wildfires) and consequently act as feedback mechanisms – both positive and negative. Thus, fire behavior and effects are regulated by the vegetation as it creates landscape structures that subsequent fires burn onto and around.

Next Steps

While chapter two focused on a sub-regional approach to investigating fire-on-fire interactions, the next two chapters address the interactions of large wildfires at a broad regional level. The MTBS data are used to analyze wildfire interactions between 1984 and 2007 in three large wilderness areas – the Greater Bob Marshall, the Selway-Bitterroot, and the Frank Church.

In chapter three, the objectives were to address whether re-burning was occurring in the wilderness areas, and if what is occurring is different from if fires were randomly located across the areas. Additionally, the influence of previous fires on subsequent fire spread was determined; the contemporary rates of burning and re-burning were derived and compared to historical estimates; and differences in fire-on-fire interactions among the three wildernesses are discussed.

In chapter four, the objective was to determine whether burned and unburned areas, as well as once-burned and re-burned areas, could be differentiated and described using texture metrics. The complexity of each wilderness is characterized in terms of pre- and post-fire indices and metrics; similarities and differences among the three areas are discussed.

Chapter 3 – Vector Analysis

Characterizing Fire-on-Fire Interactions Using Fire Perimeters

OVERVIEW

As described in chapter one, wildfire is a key process on many landscapes in much of the western United States. The Greater Bob Marshall, Selway-Bitterroot, and Frank Church wilderness study areas can each be considered individual landscapes that have been shaped by fire over the centuries. The overall fire regime of each landscape differs, and existing fire research suggests that the shortest fire intervals occur in the Frank Church and the longest fire intervals occur in the Selway-Bitterroot. Using methods developed and described in chapter two, and additional methods described in this chapter, this stage of research explores the propagation of large wildfires in the three wilderness areas to determine if and how large wildfire occurrence and behavior differ from what is expected due to chance and from that which has been reported previously by researchers. This chapter also examines how fire edges interact when subsequent fires encounter previously burned areas, and how time-since-previous-fire influences re-burn size characteristics.

BACKGROUND

Reasearchers and fire managers need to understand the occurrence and effects of wildfires on the landscape. Researchers want to improve fire behavior and effects models and fire managers rely on the information derived from fire history studies for fire management plans. Until recently, much of the evidence for the fire history and ecology of an area relied on the analysis of point data. Fire-scarred trees confirm that fires occurred and recurred at a location, and are often used in fire history studies to determine how much fire a location has experienced. Much of the information on fire regimes is assembled from fire history studies created exclusively from point sources such as fire reports, tree rings and dendrochronology, fire-scar and age-class sampling, and charcoal sedimentation in water bodies (Morgan *et al.*, 2001; McKenzie *et al.*, 2004; Lentile *et al.*, 2006). However, relatively few studies have looked at area-based fire perimeters in conjunction with point data (Rollins *et al*., 2001; but see Collins and Stephens, 2007). Additionally, point-source data do not include spatially explicit information, and have been shown to both underestimate the actual frequency and extent of wildfires (*i.e.,* Collins and Stephens, 2007) as well as overestimate them (*i.e.*, Baker and Ehle, 2001).

The Natural Fire Rotation (NFR), also referred to as the fire cycle, describes the amount of time needed to burn a specified proportion of a study area and is a characteristic of fire regimes (Agee, 1993; Baker, 2009). This value is expressed in years and is often used when describing the rate of burning in a given location. Because NFR is not spatially explicit, it includes areas that burned more than once in the period of interest. The terms 'natural fire rotation' and 'fire regime' are often confused. The NFR may be derived for large areas that contain different fire regimes (Agee, 1993); area-based measures, such as the NFR, are necessary to reconstruct the fire regime (Baker, 2009) for a given location. The NFR for a landscape should equal the mean fire interval (Baker, 2009).

Information about the history of fire on the three selected wilderness landscapes – much of it from point sources – has been assembled for multiple studies (Arno, 1980; Barrett *et al.*, 1991; Brown *et al.*, 1994; Rollins *et al.*, 2001; Kipfmueller, 2003). A remotely sensed analysis of fire regime characteristics has not been published for any of the three wilderness areas. The use of the MTBS dataset to derive area-based information and analyze spatial characteristics of large wildfires on these landscapes is therefore timely.

<u>Objectives</u>

This study explores the occurrence of fire-on-fire interactions in three large wilderness areas located in Idaho and Montana, USA, using vector-format data derived from the remotely sensed MTBS dataset. Fire perimeters from the MTBS dataset are analyzed to address the following questions:

1) What is the extent of burning and re-burning in the three wilderness areas?
2) Are contemporary rates of burning similar to historical rates?
3) Do re-burns occur more frequently than would be expected due to chance?
4) Do fires that occur earlier in the record affect the propagation of subsequent fires?
5) What are the differences in fire-on-fire interactions among the three wilderness areas?

These questions are addressed by comparing the current rates of burning to contemporary estimates of historical burning, by simulating fires on a neutral landscape, and by determining how often new fires breach existing fire edges. Similarities and differences among the wilderness areas are discussed.

Wilderness areas are used in this study because they are relatively unaffected by human influences and thereby provide the best available baselines for what is natural in terms of wildfire frequency and extent. As noted in chapter one, these three wilderness areas encompass a substantial area in the Northern Rocky Mountains. Additional selection factors for these areas include the availability of MTBS data for the areas, availability of documented fire history studies, and the differences in physiographic characteristics of the areas. The use of data derived from remotely sensed imagery for systematic fire history analyses with this level of detail and at this scale has not previously been published, and few fire studies have focused specifically on the re-burn and edge characteristics of fire interactions. A better understanding of the implications of fire-on-fire interactions is important to land managers and scientists alike.

METHODS

Vector Processing Methods

Fire perimeters derived by the MTBS project are used in this stage of research; no raster-based data are used. The minimum size for individual large fires included in the MTBS dataset is 405-ha. Re-burned areas are located as described in chapter two: Intersecting areas greater than 40-ha (*i.e.,* 10% of the size of the smallest fires) are retained and attributed as re-burns. Fire perimeters that touched, as well as intersecting areas less than 40-ha and/or less than 60-m wide, are considered shared perimeters, or shared edges, between fires.

Analytical Procedures

Random vs. Observed Fire Interactions

To determine whether the observed fire intersections occur more frequently than what would be expected due to chance, a series of randomized fire occurrences was simulated using a GIS toolbox known as *BIOSCI Tools* (Nielsen, 2010). The *BIOSCI* tool enables the position of a polygon feature to be translated or shifted without rotation or scaling, based on the location of centroid point coordinates. For each study area, fire perimeters were centered on randomly located centroid points. They were not rotated because the tool does not facilitate rotation, and because it was desirable to retain the prevailing direction of fire spread. In this way, existing fire perimeters were randomly moved within each wilderness, maintaining constant burned area for each scenario as well as the same number, size, direction, and shape of fires. The process was repeated fifty times for each study area to simulate many possible outcomes (*i.e.*, expected observations) of fire occurrence and intersection, thereby enabling a comparison of 'observed' versus 'expected' fire occurrence on the landscapes (*i.e.,* if fires on a landscape are random). Changing the orientation of fires may provide different results given the strong directional trends in the data. However, retaining the characteristic direction of fires is logical because that is how fires move in these landscapes, irrespective of the controls of fuels, weather, and topography. An alternative model that allows orientation to change would simulate a fire characteristic that is not typical on these landscapes and result in perpendicular intersections not seen in nature.

The *Topology* tool in ArcGIS (ESRI, 2009) was used to locate fire intersections which were attributed as '> 40-ha', and fire edges which were attributed as '< 40-ha' (*i.e.,* shared perimeters) as described previously in chapter two. Intersections and edges between fires that occurred in the same year were ignored since it was impossible to differentiate the final perimeter of fires by exact date. The average area of the intersections for each of the fifty simulations in each wilderness series was determined, and that number was then compared to the actual area of fire intersections using the Mann-Whitney U test and illustrated with box-and-whisker plots.

Fire Edge Interactions

The GIS tools *Update, Topology,* and *Erase* (ESRI, 2009), and the *calc.sharedborders* command in the Geospatial Modeling Environment (Beyer, 2010), were used to determine the influences of the edges from previous fires on subsequent fire spread. Annual fire perimeters were compiled, for each study area, but interior boundaries of overlapping areas were removed. This resulted in annual outer perimeter boundaries of previously burned areas, which essentially served as 'Available Edge' – the edge that was available for a future fire to encounter. The earliest annual fire perimeters marked the starting condition in each study area. Subsequent annual perimeters were updated using the GIS tool, *Update,* on an annual basis. For example, a starting year (*e.g.,* 1985) and the next year with burned area (*e.g.,* 1988) were updated, such that the 'new' perimeter became the cumulative outer extent of the two inputs (Figure 6).

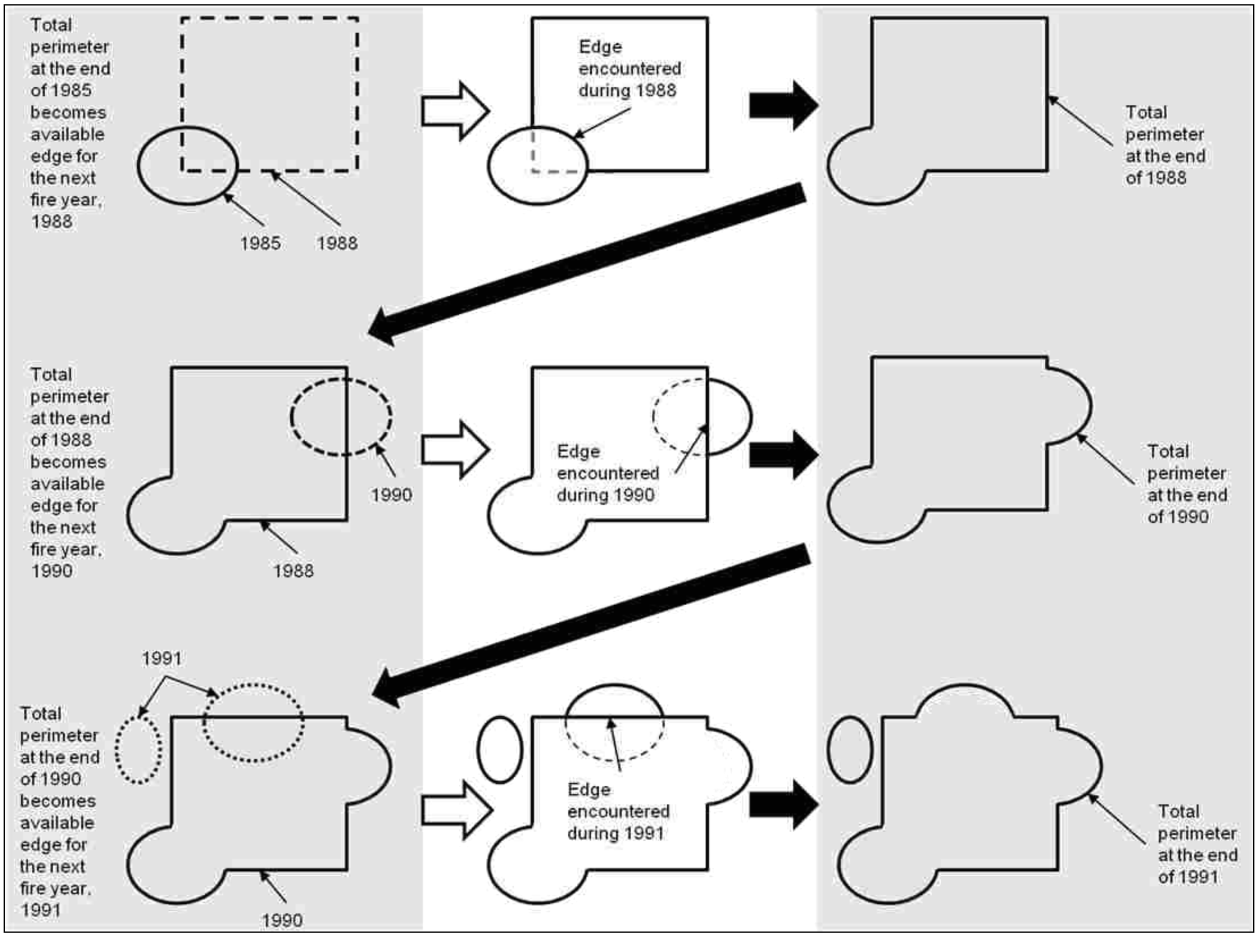


Figure 6: This figure illustrates how fire edges and boundaries were developed using ArcGIS and GME. Final products included Total Outside Perimeter , Total Edge Encountered, Total Edge that Stopped Fire, and Total Edge Breached by Fire (*i.e.,* led to a re-burn).

The *calc.sharedborders* command was then used to identify the common border between adjacent polygons. In this case, the locations and amounts of 'existing outer extent (Available perimeter?)' that were encountered by subsequent fires were identified. The result was 'total edge encountered' on an annual basis. In short, *Update* resulted in a cumulative end-of-year 'available edge' for subsequent annual perimeters to encounter, while *calc.sharedborders* identified common boundaries between previous and subsequent fires using the updated perimeters. The resultant polylines were attributed as 'Edge Encountered.' These common boundaries were then analyzed to determine how much of the previous fire edges 'stopped' subsequent fires (*e.g.,* leading to shared-perimeters) versus how much was re-burned by subsequent fires (*e.g.,* leading to intersections).

Finally, the GIS *Topology* tool was used to identify those areas where the 'Edge Encountered' polylines were covered by 'Intersections' – the re-burned area polygons greater than 40-ha. Shapefiles of these locations were created and attributed as 'Edges Breached by Fire.' The locations where the 'Edge Encountered' polylines were not covered by 'Intersections' became polyline shapefiles representing 'Edges that Stopped Fire.' Total length of 'Edge Encountered', 'Edge Stopped', and 'Edge Breached' were summarized for each study area by year and overall.

Natural Fire Rotations

In this study, the contemporary NFR was calculated for the period 1984 to 2007 for each of the study areas (as a whole) using the following equation:

$$\boldsymbol{NFR = T / P} \qquad \textit{Equation 4}$$

where *T* is the period of interest (e.g., 1984-2007) and *P* is the proportion of the study area burned. Additionally, for each study area, the NFR was calculated according to the following: 1) for large fire years, to determine how long would it take to burn the entire study area if only the area burned in large fire years was considered; 2) for re-burns, to determine how long it would take to burn the entire study area more than one time; and, 3) for once-burned scenarios, to determine how long it would take to burn the entire study area if locations only burned once. These results were compared to the proportion of the study area that burned, and to documented fire regime characteristics derived by other means, such as tree ring reconstructions and fire atlases, to determine if the NFRs derived from large wildfires in the recent past are complementary. Insights from this comparison will help researchers to understand whether present day large wildfires differ from wildfires in these areas historically – as derived from studies that span pre-European to modern suppression periods – in terms of fire frequency.

RESULTS

<u>Summarizing Fire in the Wilderness Areas</u>

The number of large wildfires within each wilderness area differs, as does the proportion of the study area burned and the number of years with large wildfires recorded (Table 4). In the 24-year record, the Frank Church experienced at least one large fire in twenty-three of those years and has the highest number of large wildfires (187). The Bob Marshall has the lowest number of years with large wildfires (13), as well as the fewest large fires (59). In total, more than half of the Frank Church, one quarter of the Bob Marshall, and fifteen percent of the Selway-Bitterroot burned; this number includes re-burned areas.

Despite the large areas burned, only a small fraction of each wilderness area burned more than once (*i.e.,* 0.9%, 1.0%, and 7.3% in the Bob Marshall, Selway-Bitterroot, and Frank Church, respectively; Table 4C). This equates to 4-ha re-burning for every 100-ha that burned in the Bob Marshall; in the Selway-Bitterroot, the re-burn rate is 7-ha per 100, and 13-ha per 100 in the Frank Church for the 24-year period. Most fire occurred in a few *large fire years.* These are defined as years where greater than 40,500-ha burned – or, ten times the minimum fire size. The largest fire years for each study area are different, and the Selway-Bitterroot did not have any year where more than 40,500-ha were burned. In fact, the last time 40,500-ha burned in a single year in the Selway-Bitterroot was in 1934 (Gibson, 2005). However, the largest fire years for the Selway-Bitterroot are the same as those for the Bob Marshall, although the years were ranked differently (Table 4G). The year 2007 stands out as ranking highly for all three wildernesses, while 2003 ranked as a large fire year in the Bob Marshall and the Selway-Bitterroot but not the Frank Church.

<u>Natural Fire Rotations</u>

The Natural Fire Rotations were derived for a variety of scenarios, which are shown in Table 4. The occurrence of large wildfires in the three wilderness areas was evaluated in terms of the Natural Fire Rotation (NFR; Table 4A) to determine whether the amount of burning that occurred in each of the wilderness areas during the 24-year period was similar to what has been documented in other studies historically (Table 5). The NFR differs for each study area; the Selway-Bitterroot has the longest overall NFR (157 years) and the Frank Church has the shortest NFR (44 years), despite sharing administrative boundaries. The individual area NFRs remain nearly the same as the overall NFRs when only the areas that burned once (Table 4B) are used to calculate the NFR because such a small fraction of the landscapes burned multiple times. When only the large fire years (Table 4D) are used to calculate the NFR, the resultant NFRs are slightly longer in all instances; however, if large fire years are removed (Table 4E), NFRs become much longer in all instances. This indicates that large fire years are primary drivers of NFR in each of the study areas. Nevertheless, the NFRs derived from the MTBS data for the 24-year period of record are within the ranges published for the different fire regimes of each of the study areas, as described earlier (Table 5).

Random vs. Observed Fire Interactions

The locations of re-burns within each of the study areas are shown in Figure 7. There are 228 instances of re-burn during the 23 different years that had a fire in the Frank Church, versus 26 re-burns in 15 different years in the Selway-Bitterroot, and 28 re-burns in 13 different years in the Bob Marshall (Tables 4 and 6). Re-burns are roughly ten times more prevalent in the Frank Church than the Bob Marshall or the Selway-Bitterroot, partly because of more years having fires and larger areas being burned in the Frank Church than the other two areas (Table 4). The largest re-burns in the Frank Church are much larger than those in either the Selway-Bitterroot or the Bob Marshall (Table 6). For all three study areas, at least 20% of the re-burns are larger than 405-ha. The Selway-Bitterroot has the highest proportion of re-burns occurring in the 121- to 405-ha range. The re-burns for the Bob Marshall and Frank Church are distributed nearly equally across the three size ranges.

Table 4: Fire occurrence information and Natural Fire Rotations (NFR) for each of the study areas for the period 1984-2007. The Frank Church has the shortest NFR in every instance.

		Bob Marshall	Selway-Bitterroot	Frank Church
	Number of Years with Large Fires Recorded	13	15	23
	Total Number of Fires	59	81	187
	Amount of Burnable Area within Study Area (ha)	1,630,026	876,118	2,365,449
(A)	**Total Area Burned (ha)**	398,441	134,262	1,276,542
	Proportion of Study Area (%)	*24.4*	*15.3*	*53.9*
	NFR (yrs)	*98*	*157*	*44*
(B)	**Total Area Burned Only Once (ha)**	382,307	125,325	1,104,865
	Proportion of Study Area (%)	*23.5*	*14.3*	*46.7*
	NFR (yrs)	*102*	*168*	*51*
(C)	**Total Area Burned More Than Once (ha)**	16,144	8,937	171,674
	Proportion of Study Area (%)	*0.9*	*1*	*7.3*
	NFR (yrs)	*2,429*	*2,353*	*331*
(D)	**Total Area Burned in Large Fire Years (ha)**	291,967	79,838*	1,004,121
	Proportion of Study Area (%)	*17.9*	*9.1*	*42.4*
	NFR (yrs)	*134*	*263*	*57*
(E)	**Total Area Burned in Non-Large Fire Years (ha)**	106,444	54,757*	272,422
	Proportion of Study Area (%)	*6.5*	*6.2*	*11.5*
	NFR (yrs)	*368*	*386*	*208*
(F)	**Total Area Re-burned During Large Fire Years (ha)**	10,617	6,699	152,985
	Proportion of Study Area (%)	*0.7*	*0.8*	*6.5*
	NFR (yrs)	*3,685*	*3,139*	*371*
(G)	***Large Fire Years (Ranked in Order of Most Acreage Burned)***			
	Year #1	*2003*	*2007**	*2007*
	Year #2	*1988*	*1988**	*2000*
	Year #3	*2007*	*2003**	*1994*
	Year #4	-	-	*1988*
	Year #5	-	-	*2006*

**Note: In the SBWA, the three years with the highest annual area burned were used since more than 41,000-ha were not burned in any single year.*

Table 5: Fire history study findings for each of the three study areas.

Source	Location *Bob Marshall (BM)* *Selway-Bitterroot (SB)* *Frank Church (FC)*	Fire Rotations (yrs)	Fire Regime Description
Arno, 1980	**BM**	40-yrs to 150-yrs	Mixed Severity/High to Low Frequency
Barrett *et al.*, 1991	**BM**	25- to 75-yrs	Mixed Severity/High Frequency
	BM	120- to 350-yrs	Stand Replacing/Low Frequency
THIS STUDY	***BM***	****98-yrs***	***Includes All Fire Regimes***
Brown *et al.*, 1994	**SB**	54-yrs to 197-yrs	Stand Replacing/Low Frequency
	SB	22-yrs to 56-yrs	Low- to Mixed-Severity/High Frequency
Kipfmueller, 2003	**SB**	139- to 341-yrs	Stand Replacing/Low Frequency
Rollins *et al.*, 2001	**SB**	*194-yrs	Includes All Fire Regimes
THIS STUDY	***SB***	****157-yrs***	***Includes All Fire Regimes***
Barrett and Arno,	**FC**	4-yrs to 41-yrs	Low Severity/High Frequency
1988	**FC**	40-yrs to 200-yrs	Stand Replacing/Low Frequency
USDA, 2002	**FC**	15- to *84-yrs	Low Severity/High Frequency
	FC	35- to *105-yrs	Mixed Severity/High Frequency
	FC	75- to *100-yrs	Mixed Severity/Low Frequency
	FC	150- to *198-yrs	Stand Replacing/Low Frequency
THIS STUDY	***FC***	****44-yrs***	***Includes All Fire Regimes***

NOTE: Estimates of present-day fire frequency are indicated with an asterisk (*). Other estimates of fire frequency, derived from contemporary fire history studies, are considered 'historical' frequencies here.

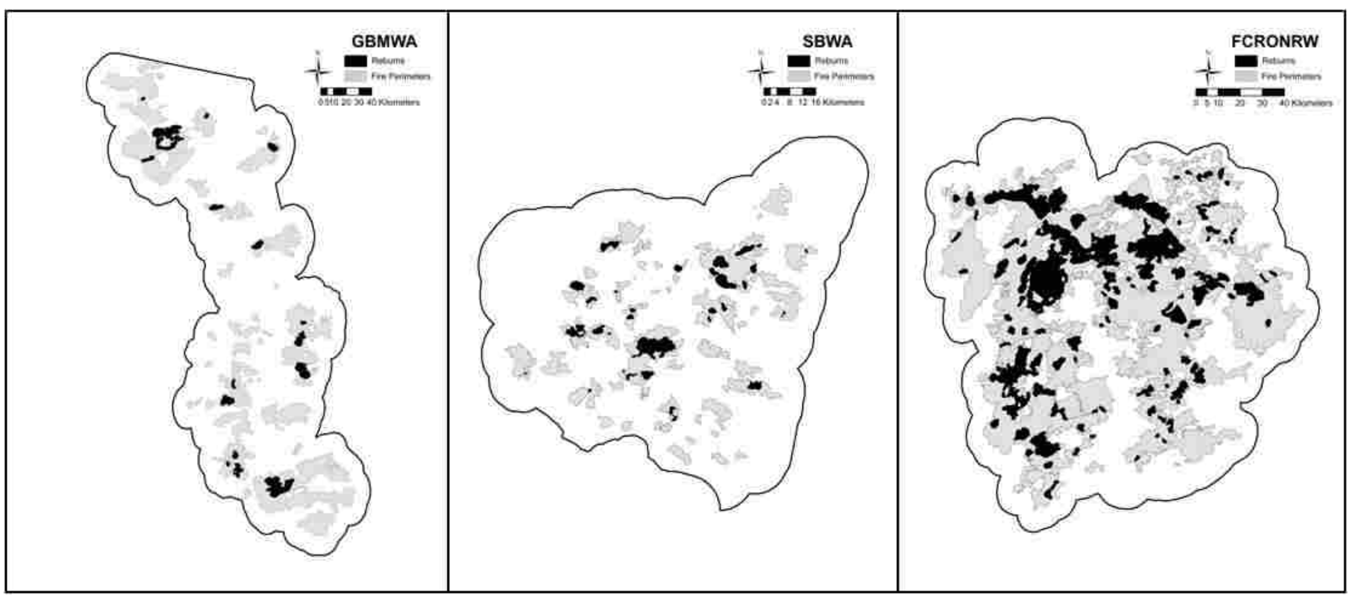


Figure 7: Locations of fires (grey) and re-burn areas (black) within each wilderness area.

The results of the fifty randomized fire occurrence simulations, as well as the actual observations from the MTBS data, are presented in Table 6. Analysis of simulated fire occurrences indicates that the total area of re-burn observed for the Selway-Bitterroot is nearly identical to the range of values exhibited by the simulated fires occurring across that landscape (Figure 8). The area of re-burn observed in the Frank Church is lower than what would be expected if fires were randomly occurring on the landscape, and the amount of re-burn observed in the Bob Marshall also occurs at the low end of the simulated amount. In addition, the numbers of re-burn patches are fewer than expected by chance in the Bob Marshall and Frank Church but identical to chance in the Selway-Bitterroot (Figure 8, Table 6).

In all the wilderness areas, the number of small re-burn patches (40- to 121-ha) is greater than was predicted, while the number of medium (121- to 405-ha) and large patches (>405-ha) is less. These differences are within one standard deviation of the simulated means. Looking at the distributions of re-burned patch sizes, only the Frank Church presents a statistically significant difference between the observed versus the random (Table 7; Mann-Whitney U = 1,118,051, n = 12,412, P = 0.000). In both the Bob Marshall and the Selway-Bitterroot, there is no significant difference between the observed and the random re-burn patch size distributions (for the Bob and the Selway, respectively: Mann-Whitney U = 20,948, n = 1,847, P = 0.057; Mann-Whitney U = 13,628, n = 1,337, P = 0.080). In short, re-burn appears to be occurring less frequently than chance in the Frank Church, perhaps less frequently in the Bob Marshall, and the same as chance in the Selway-Bitterroot. To clarify, *chance* here refers to the fifty simulations of random fire occurrence described earlier.

Table 6: Characteristics of re-burns by size class for each study area. Size class thresholds reflect the common fire size classes as recognized by the NWCG (2006). The numbers for the 'simulated' values reflect the average of the fifty simulations. A large number of re-burns are in the smallest size class.

		OBSERVED			SIMULATED		
Study Area	**Size of Re-burn**	**Frequency (Proportion of total occurrence)**	**Total Area Re-burned (ha)**	**Average Size of Re-burn (ha)**	**Average Frequency (Proportion of total occurrence)**	**Average Total Area Re-burned (ha)**	**Average Size of Re-burn (ha)**
Bob Marshall	**40-121 ha**	11 (38%)	698	63	8 (22%)	606	73
	121-405 ha	6 (21%)	1,593	266	10 (28%)	2,413	237
	>405 ha	12 (41%)	13,853	1,154	18 (50%)	36,078	2,025
Bob Marshall, Total		***29***	***16,144***	***557***	***36***	***39,098***	***1,075***
Selway-Bitterroot	**40-121 ha**	13 (50%)	925	71	8 (31%)	572	73
	121-405 ha	8 (31%)	2,070	259	11 (42%)	2,702	240
	>405 ha	5 (19%)	5,942	1,188	7 (27%)	6,317	880
Selway-Bitterroot, Total		***26***	***8,937***	***344***	***26***	***9,591***	***366***
Frank Church	**40-121 ha**	85 (37%)	6,040	71	54 (22%)	3,968	74
	121-405 ha	63 (28%)	15,535	247	72 (30%)	17,775	247
	>405 ha	80 (35%)	150,099	1,876	118 (48%)	251,656	2,134
Frank Church, Total		***228***	***171,674***	***753***	***244***	***273,399***	***1,122***
All Study Areas	**40-121 ha**	*109 (39%)*	*7,662*	*70*	*70 (23%)*	*5,146*	*74*
	121-405 ha	*77 (27%)*	*19,198*	*249*	*93 (30%)*	*22,890*	*246*
	>405 ha	*97 (34%)*	*169,894*	*1,751*	*143 (47%)*	*294,051*	*2,056*
All Study Areas, Grand Total		***283***	***196,755***	***695***	***306***	***322,088***	***1,052***

Table 7: The results of comparisons between observed and randomized re-burn size distributions for each of the three study areas. The distributions of all observed and randomized re-burn patches greater than 40-ha in size were tested using the Mann-Whitney *U* test statistic (α=0.05). Only the Frank Church showed a difference between the observed and randomized re-burn size distributions (indicated by ***bold*** significance values).

	Bob Marshall	**Selway-Bitterroot**	**Frank Church**
Number of Cases (n)	1,847	1,337	12,412
Mean Size (ha)	1,067.2	365.4	1,115.2
Median Size (ha)	388.4	224.9	382.4
Maximum Size (ha)	20,259	5,091	50,602
Standard Deviation	1,805.6	453.0	2,437.6
Mann-Whitney *U*	20,948	13,628	1,118,051
Significance (*P*)	0.057	0.080	***0.000***

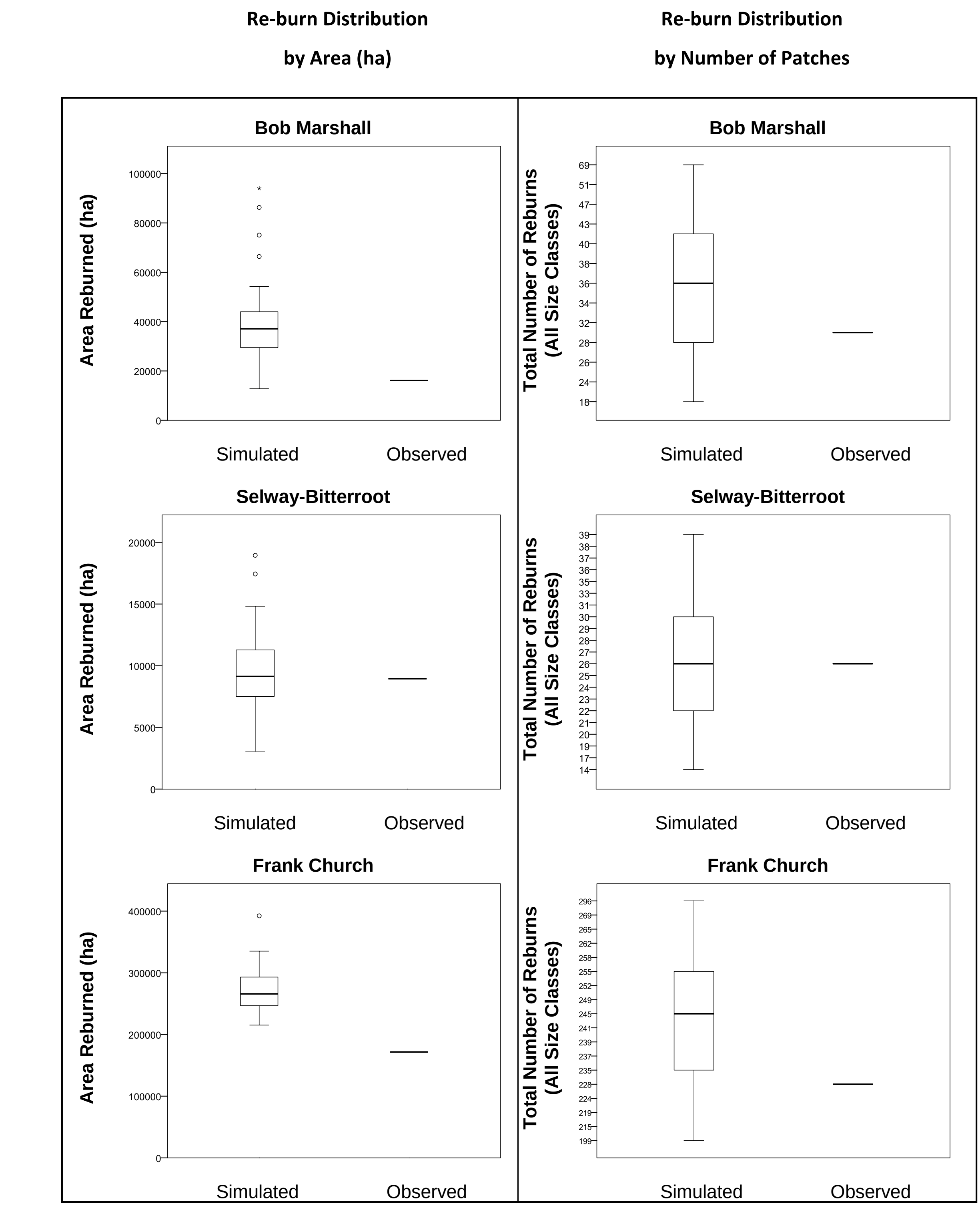


Figure 8: Box-and-Whisker plots showing simulated and observed re-burn distributions by area in hectares (*left)* and by number of patches *(right)* for each wilderness area. In the Frank Church, the amount of re-burn observed is lower and outside of the simulated distribution. The number of re-burn patches observed is within the simulated number distribution for all three study areas. Only in the Selway-Bitterroot are the number of re-burns observed generally the same as those simulated.
Note: The Y-axis scales differ for each of the study areas.

Fire Propagation in Recently Burned Landscapes

When a new fire reaches the edge of a previously burned area, one of two things can occur: The new fire is stopped either at or near the edge of the previous burn, or the new fire re-burns onto the previously burned landscape. In each of the three study areas, the total amount of edge where a fire meets another fire is less than three percent of the total available perimeter (1.4% for both the Bob Marshall and Selway-Bitterroot, and 2.9% for the Frank Church; Table 8). However, in each study area, nearly 80% of the total edge encountered was breached, allowing fire to spread into the previously burned landscape (based on criteria identified in methods; Table 8).

Year-to-year variability in re-burn occurrence is high. For example, the Frank Church has three years in which all of the edge encountered was completely burned over (1987, 1988, and 2001). In the two largest fire years, 2007 and 2000, the most edge was encountered, and 80% of the edge was breached. In the Bob Marshall, 82% of the edge encountered in the largest fire year (2003) led to re-burn. Only 2001 had a higher percentage of edge leading to re-burned areas (96%), and largely as a result of one of the largest fires in the study area (the Moose Fire) re-burning across a large portion of the perimeter of one earlier fire (the Anaconda Fire) and engulfing nearly the entire perimeter created by two other fires (the Anaconda Fire and the Adair 2 Fire). In the Selway-Bitterroot, 2007 was the largest fire year and the year when the most edge was encountered and the most edge was breached.

Large fires that occur completely within previously burned areas are rare. This is observed only once in the Bob Marshall and twice in the Frank Church. There are also three instances in the Frank Church where more than 95% of a subsequent fire occurred within a previously burned area, although the data do not indicate whether these fires started outside of the previous fire and spread into it, or whether they started within the previous fire and spread out of it.

Table 8: Edge characteristics of fire-on-fire interactions for each study area. Nearly 80% of the previously created fire edges encountered by a subsequent fire were breached, leading to a re-burn of greater than 40-ha.

	Bob Marshall	Selway-Bitterroot	Frank Church
Total Available Outside Perimeter (km)	21,248	12,716	66,104
Total Edge Encountered (km)	306	174	1,916
Proportion of Available Perimeter (%)	*1.4*	*1.4*	*2.9*
Total Edge that Stopped Fire (km)	63	32	323
Proportion of Total Edge Encountered (%)	*20.6*	*18.4*	*16.9*
Total Edge Breached by Fire (km)	242	142	1,594
Proportion of Total Edge Encountered (%)	*79.1*	*81.6*	*83.2*

Time Since Previous Fire and Re-burn Characteristics

Chapter two noted that the time between successive fires seems to influence re-burn sizes. Recognizing that the 24-year period encompassed by this dataset is relatively short, the numbers and sizes of re-burns can be explored with respect to time-since-previous-fire (TSPF). Time-since-previous-fire is the difference expressed in years between the year of an initial fire and the year of a subsequent fire. Figure 9 shows a general decrease in the frequency of small (*i.e.,* 40- to 121-ha) and medium (*i.e.,* 121- to 405-ha) re-burns as TSPF increases in all three wilderness areas. Large re-burns generally occurred six or more years after the initial fires burned, although there is no apparent trend for the Selway-Bitterroot or the Bob Marshall wilderness areas for this size range of re-burns as TSPF increases. In the Frank Church, however, as TSPF increases, the frequency of large re-burns increases, while both small and medium re-burn frequency decrease.

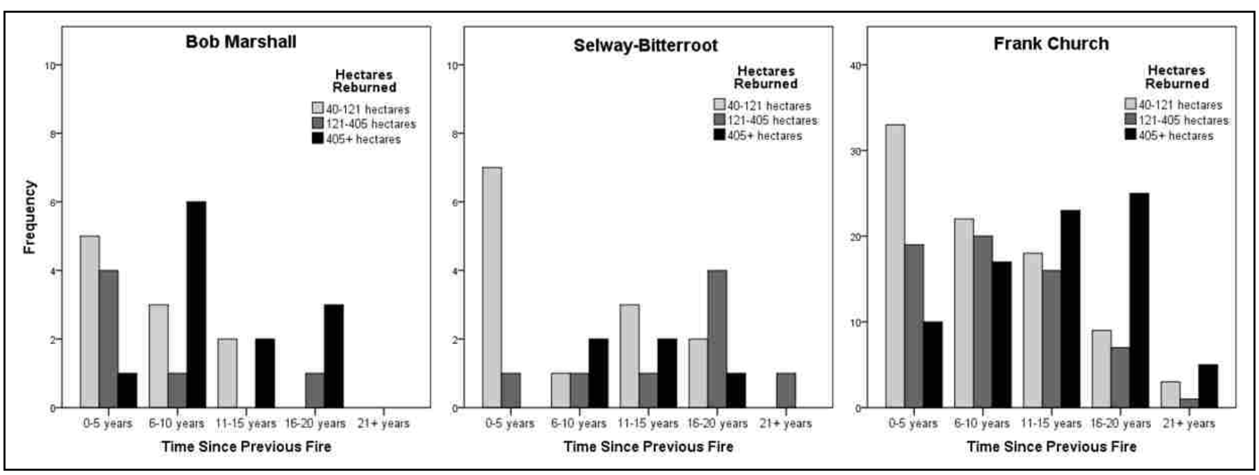


Figure 9: Frequency of re-burn patch size occurrence by time-since-previous-fire for each wilderness area. Note that the frequency for the Frank Church is four times that of either of the other two study areas.

DISCUSSION

Natural Fire Rotations

Conventional wisdom that wildfires are much larger and occurring more frequently than in the recent past appear well-founded, given that many of the largest fire years in this study have occurred since the year 2000. However, the occurrence and sizes of these large fires and re-burns in recent years are not unprecedented. In the early part of the 1900s, a number of large fires during a few large fire years were responsible for burning and re-burning much of the three wilderness areas (Rollins *et al*., 2001; Gibson, 2005; Baker, 2009), and remnant burn scars are still prevalent on much of the landscape. In fact, the area burned within each of the study areas since 1984 yields NFRs consistent with results derived from long-term fire atlases and tree-ring research studies for these areas (e.g., Arno, 1980; Brown *et al.*, 1994; Rollins *et al.*, 2001; see Table 5). That is, these results imply that the last 25 years have not been atypical for what is considered 'natural' in terms of frequency or area burned for these wilderness areas. Further, the results suggest that large fire years drive the fire rotation, which highlights the importance of large fire years to the fire regimes of the study areas. Large fire years create much of the burned area and most of the fire edge on any given landscape. The amount of existing fire edge breached during large fire years is generally higher than in less active fire years, and the largest amount of re-burn generally occurs during large fire years; these results are discussed later in this chapter. Evidence of the impact of large fire years is seen in the resultant NFRs derived when large fire years are excluded.

Random vs. Observed Fire Interactions

The size of re-burns in the Frank Church are slightly smaller than expected based on random simulations, suggesting that older fires constrain the spread of newer fires by acting as barriers, or that the size and/or shape of the study area and its fires predisposes the landscape to produce more re-burn than expected by chance. Certainly the abundance of small (40- to 121-ha) re-burn patches versus simulated can be explained by the propensity of shared edges to naturally intertwine in ways that cannot be duplicated in simulated redistributions of large fire polygons. Similar to the Frank Church, the Bob Marshall exhibited smaller and less frequent re-burns overall, although differences between simulated and observed results are not as pronounced as in the Frank Church.

Conversely, the results for the Selway-Bitterroot show that the observed numbers and sizes of re-burn patches are nearly identical to what would be expected if fires were randomly distributed across the landscape. In a landscape that is described by fire managers as 'fire constrained,' this is not the expected result. There should be fewer re-burns than modeled if the landscape is fire constrained, as observed in the Frank Church and the Bob Marshall. Indeed, there are more small (40- to 121-ha) re-burn patches observed than simulated in the Selway-Bitterroot, suggesting that in reality, once a fire does encroach into a previously burned area, it stops spreading. Perhaps current fires in the Selway-Bitterroot are constrained by smaller and/or older burn scars that are outside of either the size range or the time period of this study (or both) and whose influence cannot be determined, or the size and shape of the study area and the fires within the area influences the outcome of interactions.

Many re-burns are actually as big as the smallest fires in the MTBS dataset. That is to say, many of the re-burned patches in the three wilderness areas are as large as what are currently considered 'large fires' by fire management standards (see NWCG, 2006). This may be of interest from an ecological standpoint, since these patches contribute to the landscape in a number of ways. For example, the diversity of both animal and plant species in an area may be enhanced if there is a variety of vegetation types and age classes, as well as variations in patch size, shape, and distribution across the landscape.

Fire Propagation in Recently Burned Landscapes

Complex factors determine whether an area re-burns, related to the interactions of fuels, weather, and topography. However, the causal mechanisms are difficult to substantiate and beyond the scope of this investigation. This research finds that in the majority of cases, when a fire meets an edge created by a previous fire, it results in a re-burn. While this may seem counterintuitive, many of the re-burned areas are small (40- to 121-hectares), indicating that previous fires probably do keep subsequent fires in check much of the time. Perhaps if the size thresholds for re-burns were larger, the net effect would be that the majority of edges inhibit the growth and spread of new fires.

Further, fires generally breach existing edges more frequently during large fire years than in other years, and more area re-burns during large fire years than in other years. From these results, it can be inferred that the conditions that allow fires to burn onto previously burned areas are more favorable in large fire years; that the ability of an old fire to limit the spread of a new fire is not the same all the time; and that there is a wide spectrum of possible outcomes for fire-on-fire interactions. The broad range of descriptions provided by fire managers about fire spread onto previously burned landscapes should not be surprising; that is, any or all of the anecdotes about the influence of old fires on new fires may be reliable. From an ecological perspective, these results suggest that fire propagation is a consequence of the complex interactions of the environmental conditions at the time of the incident.

Only a few large fires occur completely, or nearly completely, within previously burned areas. This supports the idea that old fires constrain the spread of new fires and create more edge – in this case, edges within edges. Perhaps numerous ignitions actually do occur within previously burned areas, but remain small. It would be interesting to characterize how and when fires burn onto previous burn scars from unburned locations versus spreading from previously burned locations onto unburned locations. However, although these ideas may be worth considering in future research, they cannot be explored using only the MTBS dataset.

Confounding Factors and Additional Considerations

A number of considerations may offer insight into the results. For example, MTBS perimeter data alone may not be sufficient to fully enumerate fire-on-fire interactions. The inclusive dates of the MTBS dataset span only a portion of the fire rotation and thus provide a short period of record and an incomplete picture of fire-on-fire interactions, especially for areas that typically have long fire rotations. Secondly, the MTBS project maps only wildfires greater than 405-ha in size. While a few large fires contribute to the majority of the total area burned, perhaps the smaller fires are as important to include and analyze in the context of fire-on-fire interactions. A different data source, such as a fire atlas that spans a longer period and includes more small fires, may help to explain and/or corroborate the findings of this research.

A second consideration is that the amount of re-burn and the subsequent NFR calculations for this study may be affected by the fact that interior unburned islands are not explicitly mapped in the fire perimeters supplied by the MTBS project. Large unburned islands could in effect lengthen NFRs, as these locations are not technically burned. However, unless these unburned islands are common or encompass sufficiently large areas, they are within a predominantly fire-affected area. As such, the exclusion of these unburned areas should not significantly affect the total area burned, or the length of the calculated NFRs, especially considering that only large wildfires were analyzed in this study.

Finally, MTBS data may not perform efficiently for some land cover types, such as grasslands, because of how the products are derived for individual fires. The 'actual' amount of burned area may be reduced when MTBS data are created for fires that burn in vegetation that regenerates quickly following fire, such as grasses, because the MTBS products for individual fires in predominantly forested regions are derived using the 'Extended' method – which utilizes imagery acquired one-year post-fire – as opposed to the 'Initial' method, which uses imagery acquired nearly immediately post-fire. For example, the MTBS perimeter for the 1988 Canyon Creek Fire in the Bob Marshall is nearly 10,000-ha smaller in size than the actual fire perimeter that was mapped on the ground during the fire; the difference in area is nearly all on the eastern side of the fire, which is predominantly in grasslands. If this happens often, old fires may possibly constrain fire spread in some areas, but perhaps fire is actually burning and re-burning onto previously burned areas more frequently than is captured by current MTBS methods. In such cases, calculated NFRs may be shorter – a real possibility in places like the Salmon River breaks in the Frank Church, where the lower reaches are predominantly grasslands.

CONCLUSIONS

This stage of research performed a systematic assessment of fire-on-fire in large wilderness areas of the Northern Rocky Mountains. The results provide a unique perspective for exploring fire regime characteristics by describing the impacts of older fires on subsequent fires using consistent data, criteria, and definitions, and by explicitly quantifying edge effects, the relationships of edges with re-burns, and re-burn characteristics. The results show a high degree of complexity in fire-on-fire interactions, and provide insights into some of the fire behavior anecdotes widespread in fire management. However, comparisons between wilderness areas are difficult. Additional characterization of fire-on-fire interactions should include examination of factors such as the terrain, fuels, biophysical settings, fire effects, and seasonality. Further, MTBS contains several additional data sets, such as pre- and post-fire NBR, dNBR, and RdNBR rasters, which may provide explanatory power in further explorations of fire-on-fire interactions.

In sum, this research finds the following:

- 54% of Frank Church, 24% of the Bob Marshall, and 15% percent of the Selway-Bitterroot has burned since 1984. The rate of re-burning in the Bob Marshall was 4-ha re-burned for every 100-ha burned; 7-ha per 100 burned in the Selway-Bitterroot, and 13-ha per 100 in the Frank Church.
- The area and frequency of re-burn in the Frank Church is significantly less than chance, suggesting that fire may constrain fire on this landscape. The Bob Marshall exhibits similar characteristics, but less conclusively, and the Selway-Bitterroot is not fire constrained during the period of record.
- The largest re-burns are larger than the minimum size criteria in MTBS (*i.e.*, >405 ha).
- Natural fire rotations derived from MTBS fire perimeters (*i.e.*, 44 years for the Frank Church, 98 years for the Bob Marshall, and 121 years for the Selway-Bitterroot) are within the ranges described by independent studies that use historical data and tree ring analysis.

- When fires encounter previous burns, these areas re-burn 80% of the time on average, but year-to-year variability is high. However, the size of re-burns is generally small, suggesting that older fires constrain new fire spread.
- There is a systematic decrease in the frequency of small to medium sized re-burns (40- to 121-ha) as time since previous fire (TSPF) increases in all three wilderness areas. The frequency of large re-burns increases with TSPF in the Frank Church, but this trend is not apparent in the other wilderness areas.

Additional exploration of re-burn characteristics using the MTBS data, in conjunction with other data sources, may provide results that are more robust. Additionally, standardized observations and documentation about fire-on-fire interactions by field-based fire observers during an active wildfire could enhance these results, and would provide useful information to researchers and managers alike.

Chapter 4 – Raster Analysis

Characterizing Fire-on-Fire Interactions Using Texture Metrics

OVERVIEW

The two previous chapters detail methods that were developed to analyze fire-on-fire interactions. Chapter two focused on method development, and used the fire perimeters and the classified severity data provided by the MTBS project. In chapter three, fire propagation was explored using only fire perimeter data. Results were verified with empirical and statistical evidence, and suggest that earlier fires affect subsequent fires in terms of spread – whether or not the fire stopped or re-burned onto the previously burned area – and effects. However, the continuous (NBR) data products provided with the MTBS dataset, including new data derived from these products, were not used in those analyses. These continuous data are used in this chapter, which explores pre-fire, post-fire, once-burned, and re-burned landscapes. Fire sequences are assumed to make the landscape more simple (within the burned areas) by increasing the uniformity and reducing the contrast between components in the burned areas; re-burning is assumed to reinforce these effects. This chapter focuses on the interactions of large wildfires, in terms of both pattern and process, within the Bob Marshall, Selway-Bitterroot, and Frank Church wilderness study areas. In this chapter, *pattern* refers to the organization of the landscape components as measured by the NBR and metrics based on NBR. *Process* refers to the sequence of burning and re-burning on the landscape (and the components therein), and the growth and regrowth that follows these burn events.

BACKGROUND

The reciprocal interaction of patterns and ecological processes on the landscape is a foundation of landscape ecology (Turner, 1989; McGarigal and Cushman, 2002; Li and Wu, 2004). Patterns on the landscape exist in many forms and arrangements, and across many scales. Variability in fire occurrence, successional time lags, and fire sizes combine to produce a complex and dynamic mosaic that fluctuates and shifts continuously through time and space on many landscapes of the western United States (Wimberly, 2002) and within fire perimeters. Many studies recognize the importance of the remnant patterns caused by disturbances such as wind throw and wildfires, and the influences and interactions of these disturbances on and with future processes (Sprugel, 1991; Baker, 1992; Agee, 1993; Finney, 2001; Morgan *et al.*, 2001; van Wagtendonk, 2004; Malamud *et al.*, 2005; Moritz *et al.*, 2005; Thompson *et al.*, 2007; Falk *et al.*, 2007). The current landscape patterns and structure interact with disturbances into the future in a continuous cycle (Sprugel, 1991; van Wagtendonk, 2004; Falk *et al.*, 2007). To study and understand the pattern-process relationships requires methods that quantify both the patterns (*e.g*., landscape metrics and indices) and the processes (*e.g.,* disturbance indices and return intervals) (Turner, 1989; McGarigal and Marks, 1994). A spatial characterization of wildfires gives a better understanding of the interactions of wildfires on the landscape.

To uncover the relationships between and among landscape complexity and fire occurrence, analyses that quantify and explain fire patterns on the landscape exploit landscape metrics such as those developed by McGarigal and Marks (1994). These metrics have advanced our understanding of pattern-process relationships largely because of the patch-mosaic paradigm, which categorizes or groups the landscape into mosaics of discrete patches (McGarigal *et al.,* 2009; Cushman *et al.*, 2010). Many branches of ecology have benefitted from the metrics used in these categorical representations. For example, much work has focused on the arrangement of burn scars on the landscape and on the remnant patch mosaic with respect to vegetation and other processes (Turner *et al.*, 1994; Turner *et al.*, 1999; Farris *et al.*, 2008). The patch, in these instances, is defined as a homogeneous region for the property or attribute of interest, such as the dominant vegetation type or fire severity.

While these studies and metrics provide insight into the interactions of organisms on the landscape, they often rely on classified (*i.e.*, thematic or categorical) data to quantify the patterns. Landscapes, however, are not comprised of discrete patches and abrupt edges; rather, they are represented by a range of organisms and processes that interact and overlap in space and time at multiple scales (Turner, 1989; Turner, 2005a,b; Falk *et al.*, 2007; McGarigal and Cushman, 2002). Landscapes form a multilevel, hierarchical structure having different levels of distinctive scales with cross-scale interactions (Agee, 1993; Gunderson and Holling, 2002; Folke *et al.*, 2004). They are dynamic and exhibit intricate spatial and temporal patterns due to the variety of species and process interactions that occur (Agee, 1993; Bolliger *et al.*, 2003; Carpenter *et al.*, 2001). Before the patterns on the landscape can be identified or quantified, the landscape must be appropriately defined (McGarigal and Marks, 1994; Turner, 1989).

Wildfires, and the scars left by them, are part of a disturbance cycle that creates different levels of heterogeneity across the landscape as well as within wildfire perimeters (van Wagtendonk, 2004). Wildfire behavior and effects are impacted in part by the arrangement and variety of components present on the landscape at the time of the fire, such as pre-existing burn scars from previous wildfire events. In fire ecology, the role wildfire plays in an area is often assessed by examining the landscape complexity contributing to and resulting from fires. In many instances, the pattern-process relationships are represented categorically, even though they are typically more continuous in nature and boundaries between different landscape components are not often distinct (Agee, 1993;Turner, 2005b). For example, depictions of wildfire severity indicate discrete boundaries between different severity categories, and between burned and unburned areas. However, the edges of burned areas are often indistinct in reality; in few instances do wildfires burn in a constant way that would result in precise edges. Nonetheless, numerous metrics – including shape, size, percent edge, fragmentation, continuity, juxtaposition, interspersion, and heterogeneity – are regularly used to quantify patch categories across the landscape of interest (O'Neill *et al.*, 1988; Fortin *et al.*, 2003; Li and Wu, 2004; Turner, 2005a,b).

While a few studies have utilized continuous data to investigate patterns following a disturbance (*e.g.,* Nellis and Briggs, 1989; Briggs and Nellis, 1991), this research arena has not been comprehensively described with respect to wildfire and its effects. The effects of wildfire and other disturbances and their controls have been studied extensively (Falk *et al.*, 2007; Collins *et al.*, 2007), especially using *patch metrics* techniques that quantify categorical data (Rollins *et al.*, 2001; McGarigal and Cushman, 2002), although little research has been done on re-burns as noted in chapter one. The use of patch metrics is appropriate to enhance our understanding of the interactions of disturbance and landscape complexity. However, in the case of wildfires, which do not burn in a constant or homogeneous fashion across the landscape, measures of texture may be better able to detect subtle variations in post-fire effects than classic patch metrics. The edges of burned areas are fuzzy in the real world, but these edges are discrete as implied by the burned area delineations in the MTBS data. To mitigate the shortcomings associated with categorical data, this research analyzes the continuous NBR data derived from the MTBS dataset in order to remain near to reality. Texture metrics that are not reliant on categories are used to quantify these data, and the metrics are related back to the burning and re-burning within each of the three wilderness areas.

Texture is the spatial variation in neighboring pixel values of an image (Baraldi and Parmiggiani, 1995; Wulder, 1998), and may be useful to investigate continuous patterns in space and as an ancillary information source. Texture is an innate property of all surfaces, and contains important information about the structural arrangement of surfaces (Haralick, 1979; Jensen, 2005; Culbert *et al.*, 2009). Texture metrics are statistically derived to characterize the local variability of tone (*i.e.,* pixel value or intensity) and structure (*i.e.,* spatial relationships) in imagery. Thus, spatial heterogeneity can be quantified using texture measures (Haralick, 1979; Culbert *et al.*, 2009).

First-order texture measures are first-order statistics (*e.g*., minimum, mean, variance, skewness) derived from image spectral values in a defined *n* x *n* neighborhood, but they provide no insight into the spatial arrangement of the spectral values within the neighborhood (Culbert *et al.*, 2009). Second-order texture measures consider the spatial distribution of spectral values, and are commonly derived using the Grey Level Co-Occurrence Matrix (GLCM). The GLCM, an *n x n* matrix where *n* is the number of possible grey tones in an image, provides an approximation of the joint probabilistic density function of pixel pairs at specified distances and directions within the study area actually under investigation (Baraldi and Parmiggiani, 1995; Jensen, 2005; Herold *et al.*, 2003; Culbert *et al.*, 2009). A GLCM can be calculated using eight possible directions, and an infinite number of window sizes and distances between neighbor and reference pixels. Limitations to using the GLCM occur as *n* becomes large, which results in a sparsely populated matrix and little ability to describe probabilities of co-occurrence (Baraldi and Parmiggiani, 1995). Increases in any of the number of window size/direction/distance combinations, and an increase in *n,* will all increase computing requirements but not necessarily measurement performance.

Both first-order and second-order texture measures can add explanatory power to the characterization of things such as identifying different types of sea ice (Clausi, 2002; Clausi and Yue, 2004), differentiating between vegetation structures (Kayitakire *et al.*, 2006; Nellis and Briggs, 1989), discriminating among types of sandstone (Haralick *et al.*, 1973), and land cover classifications (Maillard, 2003). In fact, many multi-spectral classifications have incorporated texture measures as additional features or 'layers' in the classification process (Jensen, 2005). The texture values derived from GLCMs reflect the amount of diversity within a region of interest (Briggs and Nellis, 1991). However, as with many metrics, a single texture metric (or group of metrics) is not appropriate for all landscapes or applications (Nellis and Briggs, 1989; Clausi, 2002; Jensen, 2005). Second-order texture measures are grouped to describe an image in terms of contrast and orderliness, but many measures are highly correlated (Haralick, 1979; Culbert *et al.*, 2009; Baraldi and Parmiggiani, 1995).

As mentioned in chapter one, remotely sensed data products provide a systematic, objective, and replicable way to investigate disturbances at extensive landscape scales. The ratio data forms derived from remotely sensed images have the potential to provide more information about wildfires and other disturbances than thematic data. The use of the GLCM to derive second-order texture metrics, which are measures of diversity, is particularly useful with remotely sensed datasets. Second-order texture metrics provide insight into the spatial arrangement of pixels in remotely sensed imagery, suggesting that these metrics may be useful to investigate and quantify where and how landscape diversity changes as a result of disturbances such as wildfires. This chapter links pre-fire, post-fire, once-burned, and re-burned landscapes patterns to the process of burning and re-burning within fire perimeters in each of the three wilderness study areas.

Objectives

The phenomena of interest here are the interactions of large wildfires with each other on the landscapes. The objective of this chapter is to detect texture differences within fire perimeters in order to determine whether burned areas are becoming more simple or more complex. Pre-fire, post-fire, once-burned, and re-burned areas within the fire perimeters delineated by the MTBS project were compared using texture metrics. Second-order texture metrics were computed to help explain how landscapes change as a function of the sequence of burning and re-burning.

Specifically, these objectives are addressed through the following questions: 1) Are post-fire NBR texture measures different from pre-fire NBR texture measures regardless of whether an area burned more than one time? And, 2) Are post-fire NBR texture measures in re-burned areas different from respective measures in once-burned areas, within fire perimeters?

Assuming that pre-fire landscape conditions reinforce post-fire landscape conditions, it is assumed that the overall pattern in post-fire landscapes are the same as in pre-fire landscapes, but that the contrast on post-fire landscapes should be different. Furthermore, if an area burns more than once, the landscape elements in that location should have a more systematic arrangement (be more uniform) and have more similarities than those of a once-burned landscape. These assumptions are tested using four texture metrics to describe the landscape: *GLCM Mean*, *GLCM Variance, Contrast*, and *Entropy.* These metrics are further discussed in the Methods section.

METHODS

Raster Processing Methods

The MTBS pre-fire and post-fire reflectance images were used to create pre- and post-fire NBR images, and differenced NBR (dNBR) images for every fire in each of the study areas using Equation 2 (see chapter two). These images were then combined into a layer stack that contained pre- and post-fire NBR and differenced NBR images for each fire. The layer stacks were stratified by year and by study area, such that all fires that occurred during a given year in a given study area were mosaicked into a single layer; this yearly layer is referred to as a 'disturbance landscape.' In all, there were 51 disturbance landscapes: 23 for the Frank Church, 13 for the Bob Marshall, and 15 for the Selway-Bitterroot. Each disturbance landscape was resampled to a 90-m spatial resolution using bilinear interpolation to reduce data dimensionality, and to optimize computer processing and mitigate storage limitations. Additional layers depicting the numeric codes for the study area, the year, the number of times each pixel burned, and the number of years between successive fires were created and added to the stack. The Geospatial Modeling Environment (GME; Beyer, 2010) was used to mask the non-fire areas from the fire areas, with annual fire perimeters from the MTBS dataset serving as the mask boundaries. Pixels having more than half of their area within the perimeter were retained, and all others were masked.

Texture Metrics

The Grey Level Co-Occurrence Matrix (GLCM) tool in the ENVI software package (ITT Visual Information Solutions, Boulder, CO) was used to derive texture metrics for each of the masked disturbance landscape layers. Four second-order co-occurrence metrics were calculated for each of the pre-NBR and post-NBR layers of the disturbance landscape layer stacks: 1) *GLCM Mean*, 2) *GLCM Variance*, 3) *Contrast*, and 4) *Entropy*. These metrics are italicized when they appear in the text. Table 9 shows equations and descriptions of these metrics.

Table 9: Equations, definitions, and descriptions of the second-order texture metrics that were calculated for each landscape.

GLCM MEAN: $$\mu_i = \sum_{i,j=0}^{N-1} i(P_{i,j})$$ $$\mu_j = \sum_{i,j=0}^{N-1} j(P_{i,j})$$ *P(i,j) is the (i,j)th entry in the normalized GLCM. μ_i calculates mean based on reference pixels, μ_j calculates mean based on neighbor pixels; $\mu_i = \mu_j$ for symmetrical GLCM.*
GLCM VARIANCE: $$\sigma_{i,j}^2 = \sum_i \sum_j (i-\mu)^2 P(i,j)$$ *Increases as grey level values differ from their mean. A measure of non-uniformity.*
CONTRAST: $$\sum_{n=0}^{N-1} n^2 \left\{ \sum_{i=1}^{N} \sum_{j=1}^{N} P(i,j) \right\}$$ where *n* = $\lvert i-j \rvert$. *Measures the difference between the lowest and highest values of a contiguous set of pixels; high contrast images have high spatial frequencies (e.g., high contrast texture)*
ENTROPY: $$-\sum_i \sum_j P(i,j) \log(P(i,j))$$ *Measures the disorder of an image. The values are low when an image is texturally uniform.*

GLCM Mean and *GLCM Variance*

The *GLCM Mean* is the mean derived from the GLCM, thus the pixel values are weighted by the frequency in which they occur in combination with a neighboring pixel value. The *GLCM Mean* is thereby different from the ‘regular’ mean that can be derived from the original image, where pixel value frequencies are determined individually. *GLCM Variance* also is derived from the GLCM and deals with the dispersion around the mean of reference-neighbor pixel combinations. It answers the question “What is the dispersion of the difference between the neighbor and reference pixels?” for a specific window of interest. This value increases as grey levels differ from the mean, indicating more heterogeneity as the values become large.

Contrast and *Entropy*

Contrast characterizes the degree of distinction between pixel pairs. *Contrast* indicates a measure of similarity between GLCM value combinations. The further away from the diagonal on the GLCM (where values of the reference and neighbor pixels are the same), the higher the value of the *Contrast* measure. *Entropy* describes the regularity of pixel pair combination. *Entropy* measures the disorder or chaos in an image; low values indicate low entropy, or more uniformity.

As noted previously, while the MTBS dataset is considered a census of large wildfires, each disturbance landscape must be sampled to derive the texture metrics. Only one window size, one pixel-pair orientation, and one distance were used to derive these metrics. Each of the texture metrics was calculated using a 3x3 window on a connected northeast-southwest diagonal pixel-pair on 6-bit data. The co-occurrence directionality was generalized based on the orientation of the major axis of all of the fires, the majority of which aligned azimuthally between 10° and 80°, or along a northeast-southwest (NE-SW) orientation. These pairs are hereafter termed *diagonal pairs.* The texture measure outputs were saved as individual layers and added to the disturbance landscape layer stack. As a result, each disturbance landscape consisted of fourteen layers (Figure 10). The pixel values for the disturbance landscapes were converted to ASCII text files for use with statistical software packages.

Statistics

Statistical analyses of the texture measures were performed using the SPSS statistical software package (PASW Statistics Release 18.0.0). Because the MTBS dataset is a census of large fires, only descriptive statistics were generated. For each study area, the calculated texture measures for associated pre- and post-fire NBR bands were compared to see if there was a difference in each of the five texture measures. The calculated texture measures for once-burned and re-burned areas were also compared to see how fire frequency affects post-fire landscape texture.

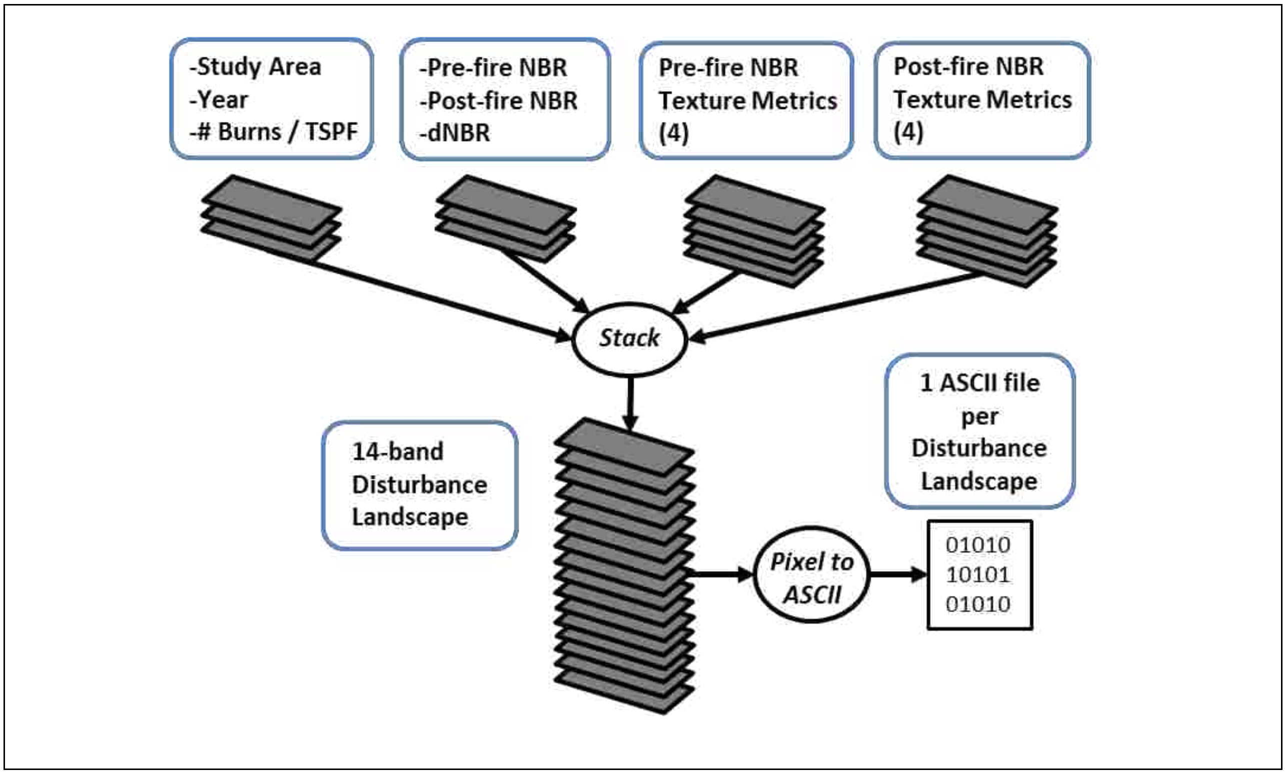


Figure 10: A 14-band disturbance landscape layer stack was created for each year in which a fire occurred within each wilderness area. All records for each band were output to a single ASCII text file for statistical analyses.

RESULTS and DISCUSSION

Pre- vs. Post-fire Landscapes

Wildfires cause shifts in landscape components and structure, as evidenced by the pre- and post-fire NBR. Overall, the pre-fire NBR and post-fire NBR are different. In the Bob Marshall (BM), Selway-Bitterroot (SB) and Frank Church (FC) study areas, the mean post-fire NBR values are lower (BM=34.30; SB=166.18; FC=92.49) than the mean pre-fire NBR values (BM=533.72; SB=475.84; FC=378.15; Table 10). This is expected, since pre-fire vegetation should reflect more in the near-infrared (LANDSAT TM and ETM+ band 4; NIR) and less in the shortwave infrared (LANDSAT TM and ETM+ band 7; SWIR) portions of the electromagnetic spectrum, while post-fire vegetation should reflect less in the NIR and more in the SWIR. Because plants exhibit higher spectral reflectance in the NIR relative to the SWIR, the signature of the NBR should shift to the left (*i.e.,* to a lower value) if vegetation is removed due to a fire. This relationship is true for each of the three study areas, although the shift behaves differently in each study area (Figure 11). The line centered on zero in each of the histograms is a visual reference to help show how the response shifts as a result of fires (Figure 11).

The use of the GLCM to derive texture metrics adds efficacy to these results; the *GLCM Mean* and *GLCM Variance* describe how the data behave within fire perimeters and between landscapes, while *Entropy* and *Contrast* describe how uniformly landscape elements are arranged and the similarities between neighbors. Given the performance of the NBR, and applying the GLCM, the question of whether the landscape becomes more complex as a result of wildfires can be addressed.

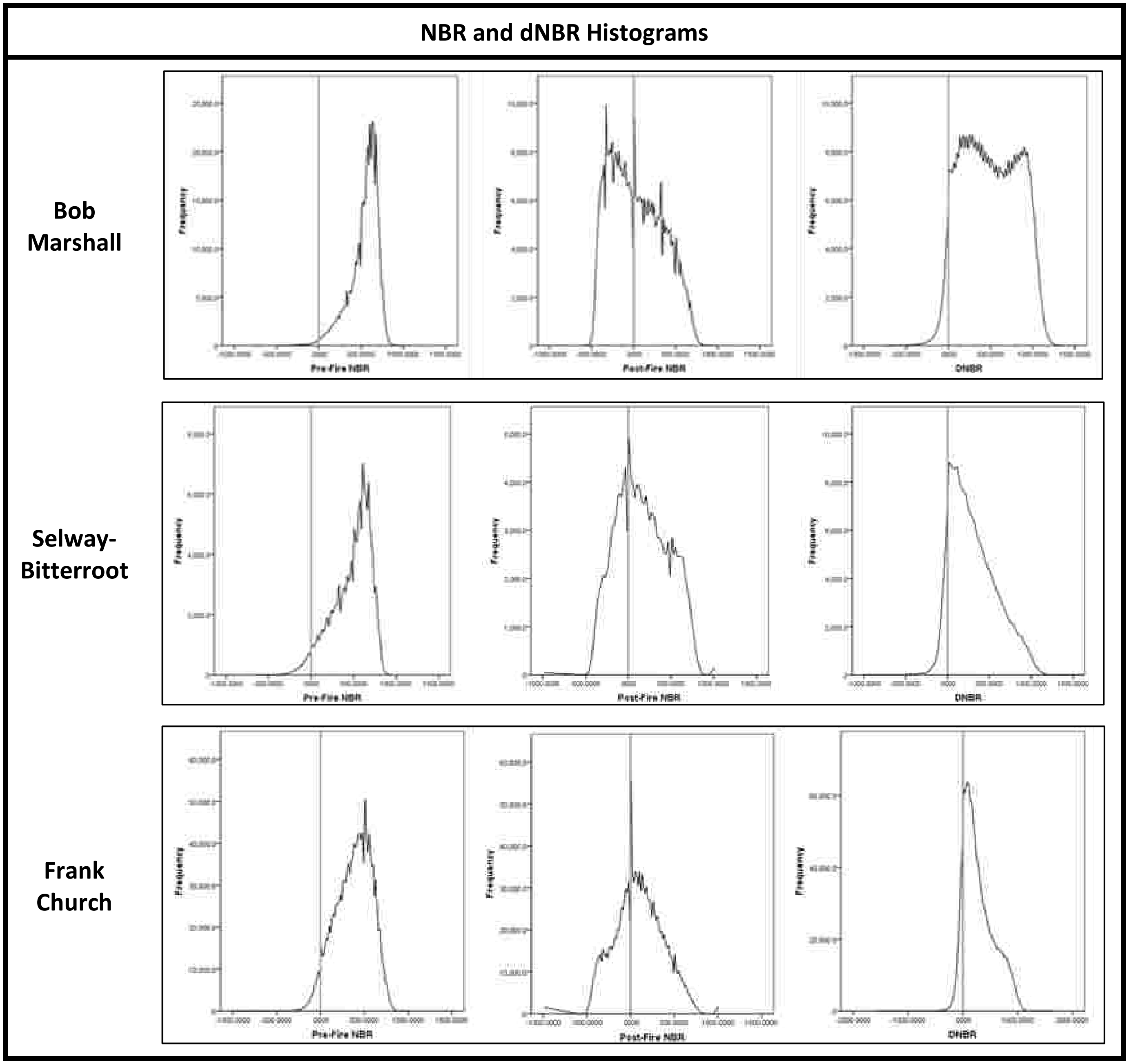


Figure 11: Overall pre-fire *(left),* post-fire *(center)*, and dNBR histograms (*right)* for fires in the Bob Marshall (*top*), Selway-Bitterroot (*center*), and Frank Church (*bottom*). Grey lines are centered at zero on the histograms to help illustrate how the response shifts to the left following the wildfires, due to the change in spectral reflectance in the NIR and SWIR bands.

The mean post-fire values for each variable have the most power to explain what is occurring on the landscape. Thus, to discuss these results, the mean value of each texture measure is referred to when comparing pre-fire to post-fire values in each landscape. The texture metrics for pre- and post-fire disturbance landscapes confirm that there are changes between pre- and post-fire landscapes (Table 10) in the Bob Marshall (BM), Selway-Bitterroot (SB) and Frank

Church (FC) wilderness areas. In the tables, measures that indicate greater dissimiliarities or variations are indicated in bold italics. For example, higher *Entropy* values represent less uniformity in an image; therefore, the mean post-fire *Entropy* value for the Bob Marshall is highlighted with italicized bold letters (Table 10). Additionally, for each wilderness, the direction of change between pre- and post-fire for the NBR and four texture metrics is illustrated in the graphs in Figure 12.

In all study areas, the mean *GLCM Mean* is higher in the pre-fire landscape than the post-fire landscape (as a percentage, the mean *GLCM Mean* dropped 25-35%). This suggests that a wildfire changes the landscape, which causes the values in the GLCM to change. The probability of the diagonally oriented pixel pairs having a specific combination of values is reduced following a fire (Table 10; Figure 12). If the *GLCM Mean* is viewed in map form, spatial patterns are apparent that indicate where other metrics may show pre- and post-fire differences (Figure 13).

Table 10: Mean pre-fire and post-fire NBR and texture metric values for the three wilderness areas. For each metric, values that indicate greater heterogeneity in the diagonal pixel pairs appear in ***bold italics***. All texture metrics, excluding *Entropy* in the Frank Church, suggest that greater differences exist post-fire than pre-fire between diagonal pairs of pixels.

Study Area	Statistic	Image	NBR	GLCM Mean	GLCM Variance	Contrast	Entropy
Bob Marshall (BM)	Mean	Pre-Fire	533.72	44.16	39.21	91.34	2.09
		Post-Fire	34.30	***29.70***	***59.36***	***136.50***	***2.13***
	Std. Error of Mean	Pre-Fire	0.25	0.01	0.14	0.35	0.00
		Post-Fire	0.45	0.01	0.13	0.28	0.00
Selway-Bitterroot (SB)	Mean	Pre-Fire	475.84	42.41	75.13	158.54	2.09
		Post-Fire	166.18	***31.83***	***90.48***	***205.76***	***2.11***
	Std. Error of Mean	Pre-Fire	0.57	0.03	0.36	0.73	0.00
		Post-Fire	0.77	0.03	0.32	0.73	0.00
Frank Church (FC)	Mean	Pre-Fire	378.15	39.08	40.04	83.80	***2.13***
		Post-Fire	92.49	***28.74***	***66.30***	***159.72***	2.12
	Std. Error of Mean	Pre-Fire	0.17	0.01	0.07	0.16	0.00
		Post-Fire	0.23	0.01	0.08	0.20	0.00

Pre- and Post-Fire NBR and Texture Metrics

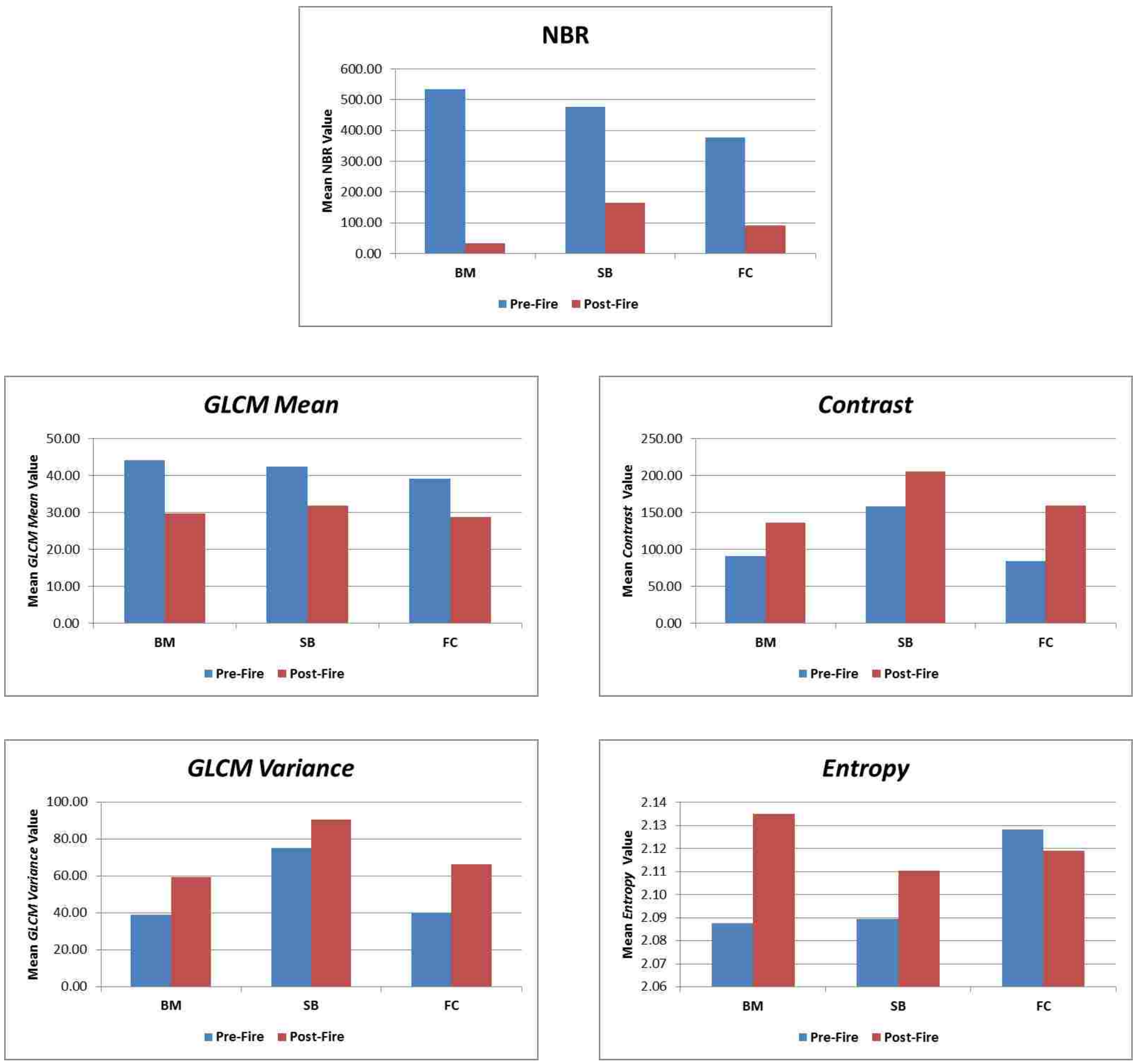


Figure 12: Mean Pre-Fire (blue) and Post-Fire (red) NBR and texture metric values for the Bob Marshall (BM), Selway-Bitterroot (SB), and the Frank Church (FC) study areas. Except for *Entropy* in the Frank Church, all other indices and metrics indicate similar differences in the direction of the change between pre- and post-fire values.

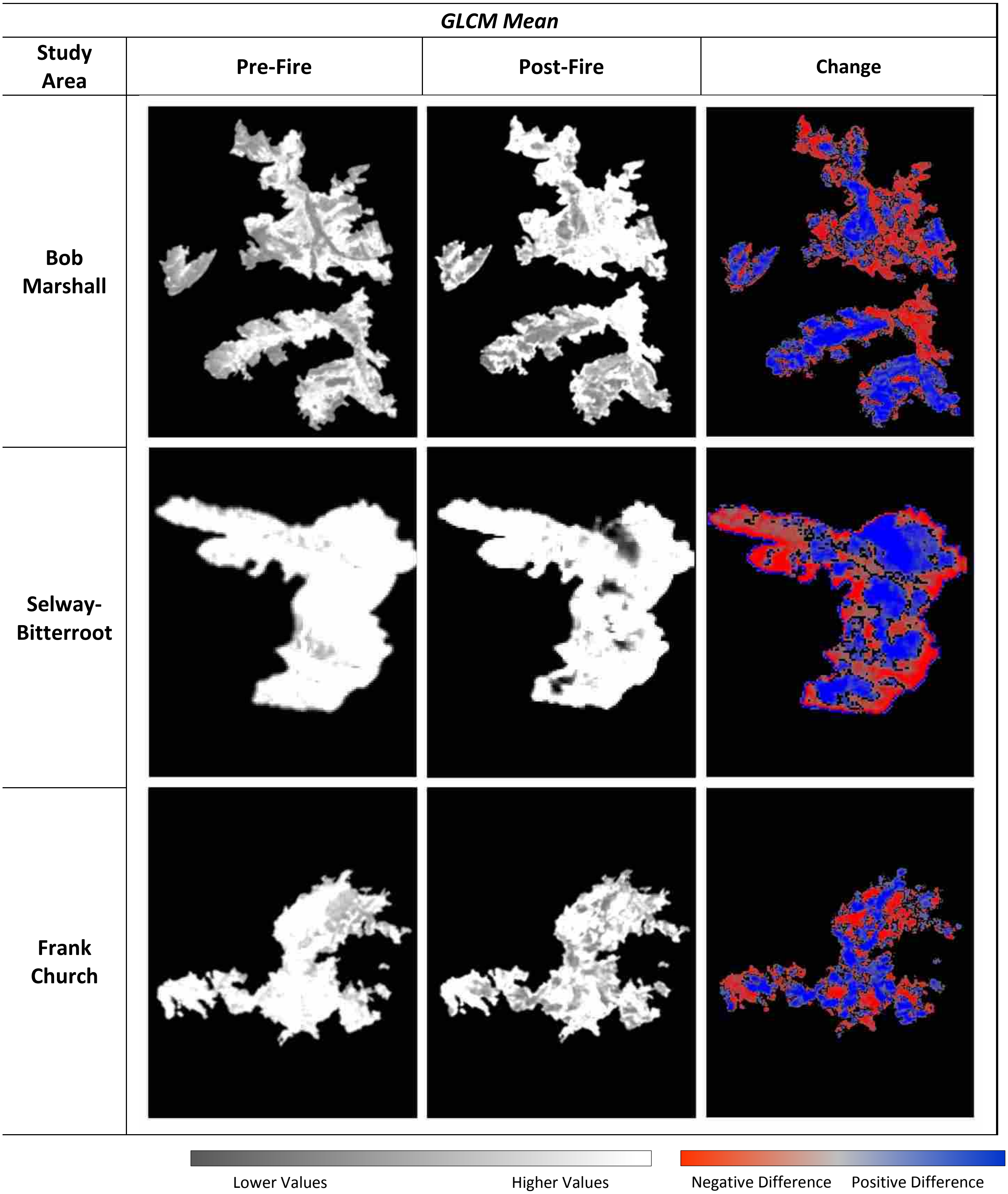


Figure 13: Examples of pre-, post-fire, and change maps for some *GLCM Mean* images in the Bob Marshall (*top*), Selway-Bitterroot (*center*), and Frank Church (*bottom*) wilderness areas. Lower *GLCM Mean* values indicate greater differences between diagonal pixel-pair values (dark grey areas in pre- and post-fire maps); locations where a positive difference between pre-fire and post-fire *GLCM Mean* exist are shown in blue in the change maps.

The mean *GLCM Variance* is a measure of non-uniformity; results in Table 10 suggest that post-fire landscapes exhibit more differences in neighboring pixels than pre-fire landscapes. The mean *GLCM Variance* values are 20-30% lower prior to fires than following fires in all study areas, an indication of more variability on post-fire landscapes. The increases in post-fire heterogeneity (from pre-fire) are illustrated by the larger mean *GLCM Variance* values on the post-fire landscapes in Figure 12. Both the pre- and post-fire mean *GLCM Variance* values are higher in the Selway-Bitterroot than the other two study areas, suggesting that the co-occurring NBR values in the pixel combinations on both pre- and post-fire lands in the Selway-Bitterroot are more highly variable than in the other two areas.

Post-fire landscapes in each of the three study areas exhibit a high degree of distinction between diagonal pairs, as inferred from the *Contrast* texture metrics. All three study areas have 20-50% lower mean pre-fire *Contrast* values than on the post-fire landscape, suggesting that there is a greater difference between neighboring pixel values on the landscapes after fires than before fires (Table 10; Figure12).

The Frank Church exhibits more uniformity post-fire than pre-fire as shown by the *Entropy* measure (Table 10; Figure 12). The pre- and post-fire numbers are significantly different (t-test; P=0.000, α=0.05). In the Bob Marshall and the Selway-Bitterroot, the uniformity of the pre-fire landscapes are nearly identical. In each of these areas, the mean pre-fire *Entropy* value is lower than the mean post-fire *Entropy* value, which indicates that the pre-fire landscape is more uniform than the post-fire landscape.

To summarize, the differences between pre- and post-fire landscapes are shown by the changes in NBR as well as the changes in each of the texture measures. In each wilderness area, the pre-fire NBR is higher than the post-fire NBR, which is the expected result of a wildfire in a forested ecosystem. *GLCM Mean* decreases, indicating the probability of the diagonally oriented pixel pairs having a specific combination of values is lower post-fire than pre-fire. *GLCM Variance* and *Contrast* both increase, suggesting greater variability on post-fire landscapes than pre-fire landscapes. In the Selway-Bitterroot and Bob Marshall, post-fire *Entropy* is higher than pre-fire, but the reverse is true in the Frank Church suggesting that the post-fire landscapes in the Frank Church are more uniform than pre-fire. The texture metrics are consistent and generally behave as anticipated. When combined with the post-fire response of the NBR, these measures endorse the assumption that the post-fire landscape is different from the pre-fire landscape in terms of contrast in all three wilderness areas. However, the uniformity as a result of wildfires is not what is expected in the Bob Marshall or Selway-Bitterroot, suggesting that post-fire landscapes are less uniform than pre-fire landscapes and do not reinforce pre-fire landscape arrangement.

Once-burned vs. Re-burned Landscapes

The previous section described how pre- and post-fire landscapes change using texture metrics and the NBR. Another dimension is added to the previous analysis and described in this section. Within the burned area delineations, once-burned and re-burned areas are quantified and compared to each other for each wilderness area. The changes in the NBR and each metric are discussed and compared in four ways: 1) pre-fire and post-fire once-burned, 2) pre- and post-fire re-burned, 3) post-fire once-burned and pre-fire re-burned, and 4) post-fire once-burned and re-burned.

In all instances, mean pre-fire NBR values for both once-burned and re-burned areas are greater than mean post-fire values (Table 11; Figure 14). The mean post-fire NBR values are also lower in once-burned areas than in re-burned areas, except for in the Selway-Bitterroot. The trajectory of mean NBR signatures from once-burned pre- and post-fire values to re-burned pre- and post-fire values roughly illustrates this concept (Figure 14). Once-burned pre-fire NBR values are the highest in all instances, and are lower following the initial fire. Prior to the re-burn, NBR values rebound back up to a higher value than following the first fire, and then dip again following the subsequent fire. Post-fire NBR values should be low since plants have lower spectral reflectance in the NIR compared to the SWIR following fires. Lower post-fire NBR values in the once-burned areas compared to the re-burned areas suggest that landscape elements (such as vegetation) in the once-burned areas experience more of a change from pre-fire to post-fire than do re-burned areas.

In each of the three study areas, the mean post-fire *GLCM Mean* values were lower in once-burned areas than in re-burned areas (Table 11, Figure 15). This means that the probability of re-burned areas having a specific combination of values occurring in the diagonal pairs is higher than in once-burned areas; that is, there are a greater amount of similar neighboring pixels in re-burned landscapes than once-burned landscapes. The mean post-fire *GLCM Variance* of re-burned landscapes is higher than once-burned landscapes in the Frank Church, but is lower in both the Bob Marshall and in the Selway-Bitterroot (Figure 15). That is, re-burned areas in the Frank Church exhibit more variety (instead of less) in the diagonal pair values. Conversely, there is more similarity in the northeast/southwest oriented pixels on re-burned areas than once-burned areas in the Bob Marshall and the Selway-Bitterroot. Taken together, these two texture measures indicate that there is a high probability of the diagonal pixel pairs having a specific combination of similar values in re-burned areas in both the Bob Marshall and the Selway-Bitterroot study areas, although subsequent metrics show that *GLCM Mean* and *GLCM Variance* alone are insufficient to show actual changes that do occur on the landscape.

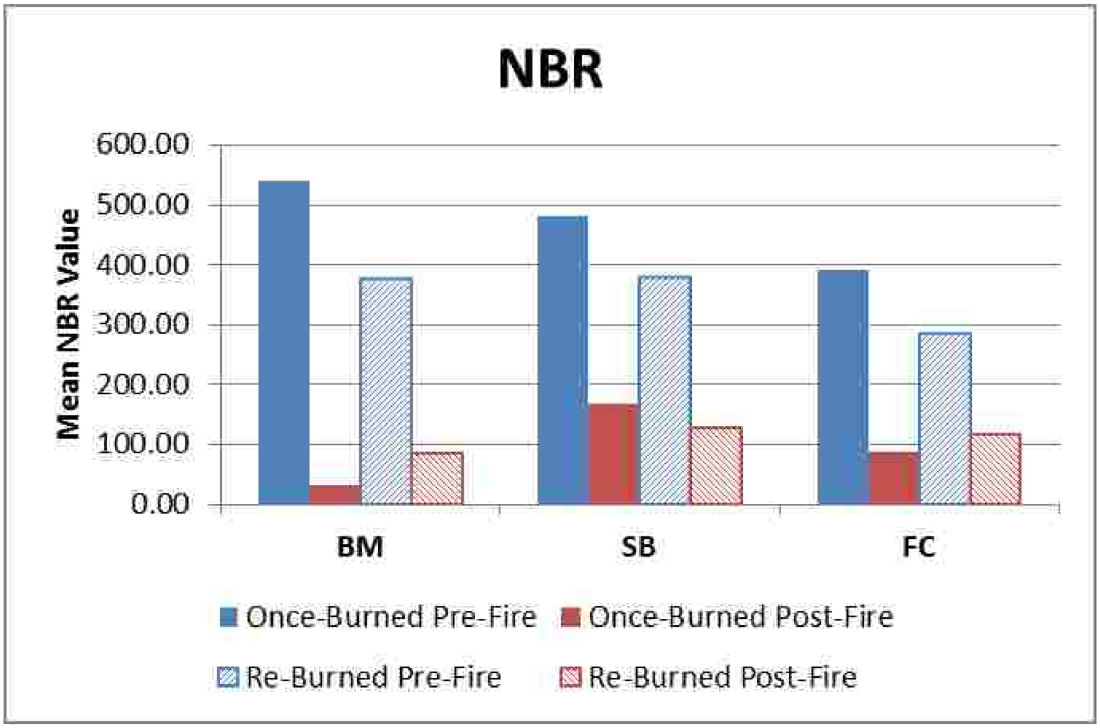


Figure 14: Mean Pre-Fire and Post-Fire NBR values for the once-burned and re-burned areas of the Bob Marshall (BM), Selway-Bitterroot (SB), and the Frank Church (FC). NBR values are on the y-axis. Notice that all study areas exhibit similar trends through time in the mean NBR values.

Mean post-fire *Contrast* values indicate that re-burned landscapes in the Frank Church are more highly contrasted than once-burned landscapes (Table 11). Conversely, the post-fire once-burned landscapes of the Selway-Bitterroot and the Bob Marshall display more contrast than re-burned landscapes. Additionally, the *Contrast* measures illuminate how these landscapes change through time because of burning and re-burning.

As *Contrast* values increase, the dissimilarity between neighboring diagonal pixel-pairs increases. Figure 15 illustrates the general trends of each landscape in terms of *Contrast*, beginning with the landscape before the first fire and ending with the landscape following the subsequent fires. For example, in the Bob Marshall, the post-fire landscapes of once-burned and re-burned areas both show more dissimilarity than the respective pre-fire landscapes, as indicated by the higher *Contrast* values. In the first fire, the mean pre-fire *Contrast* value is 90.92, while the mean post-fire value is 137.06 (post-fire is more dissimilar than pre-fire). The mean *Contrast* value for the pre-fire re-burned landscape is 100.86, and the post-fire value is

124.01 (again, post-fire is more dissimilar than pre-fire). Thus, the landscape is less similar after the first fire than prior to the re-burn, and there is a slight decrease between the post-fire once-burned and post-fire re-burned mean *Contrast* values. All these results suggest that neighboring areas in re-burned landscapes are more similar than once-burned landscapes in the Bob Marshall. The changes in C*ontrast* in the Selway-Bitterroot and Frank Church follow the same trends as shown in the Bob Marshall, although the magnitude of change in each area is different. However, the re-burned post-fire landscape of the Frank Church becomes increasingly more dissimilar as it re-burns although both the once-burned an re-burned pre-fire landscapes are quite similar.

Table 11: Mean values of the pre- and post-fire NBR and texture metrics in once-burned and re-burned areas of each wilderness. Values that indicate greater heterogeneity or variation appear in ***bold italics***.

Study Area	Image	Burn Descriptor	NBR	GLCM Mean	GLCM Variance	Contrast	Entropy
Bob Marshall	Pre-Fire	**Once-Burned (Std. Error of Mean)**	540.68 (0.25)	44.38 (0.01)	38.98 (0.15)	90.92 (0.36)	2.09 (0.00)
		Re-Burned (Std. Error of Mean)	376.59 (1.40)	***39.31*** (0.06)	***44.58*** (0.71)	***100.86*** (1.46)	***2.11*** (0.00)
	Post-Fire	**Once-Burned (Std. Error of Mean)**	31.98 (0.46)	***29.69*** (0.01)	***59.53*** (0.13)	***137.06*** (0.29)	2.13 (0.00)
		Re-Burned (Std. Error of Mean)	86.87 (1.91)	29.98 (0.07)	55.48 (0.56)	124.01 (1.20)	***2.14*** (0.00)
Selway-Bitterroot	Pre-Fire	**Once-Burned (Std. Error of Mean)**	482.76 (0.58)	42.55 (0.03)	***76.52*** (0.38)	***161.18*** (0.76)	2.09 (0.00)
		Re-Burned (Std. Error of Mean)	379.17 (2.14)	***40.45*** (0.09)	55.61 (1.09)	121.67 (2.27)	***2.11*** (0.00)
	Post-Fire	**Once-Burned (Std. Error of Mean)**	168.91 (0.80)	***31.73*** (0.03)	***91.80*** (0.33)	***208.41*** (0.77)	2.11 (0.00)
		Re-Burned (Std. Error of Mean)	128.06 (2.54)	33.23 (0.08)	71.94 (1.07)	168.69 (2.44)	***2.12*** (0.00)
Frank Church	Pre-Fire	**Once-Burned (Std. Error of Mean)**	391.07 (0.18)	39.30 (0.01)	***40.46*** (0.08)	***84.90*** (0.17)	***2.13*** (0.00)
		Re-Burned (Std. Error of Mean)	286.62 (0.49)	***37.57*** (0.02)	37.11 (0.19)	75.99 (0.36)	2.12 (0.00)
	Post-Fire	**Once-Burned (Std. Error of Mean)**	88.85 (0.25)	***28.43*** (0.01)	65.09 (0.08)	154.26 (0.20)	***2.12*** (0.00)
		Re-Burned (Std. Error of Mean)	118.28 (0.54)	30.93 (0.02)	***74.88*** (0.27)	***198.40*** (0.68)	2.09 (0.00)

Mean post-fire *Entropy* values in the Frank Church decrease as areas re-burn, and the re-burned post-fire landscapes in the Frank Church are the most uniform (Table 11). The opposite is true for the Selway-Bitterroot and Bob Marshall areas: Mean post-fire *Entropy* values are higher in re-burned landscapes than in once-burned landscapes.

Figure 15 also illustrates the changes in *Entropy* values through multiple fires for each study area; higher *Entropy* values indicate less uniformity between diagonal pixel pairs. For example, the first pre-fire landscape for the Frank Church shows the least uniformity (2.13); the uniformity increases as a result of the first fire (2.12). Prior to the next fire, the uniformity remains the same (2.12); but following a subsequent fire, the landscape again becomes more uniform (2.09). The Bob Marshall begins with a uniform landscape, which becomes less uniform after one fire. The landscape becomes more uniform ahead of the next fire, and then becomes less uniform once again after re-burning; the Selway-Bitterroot becomes less uniform as fires burn and re-burn the landscape. The areas each behave differently as they re-burn. The Frank Church becomes more uniform as it re-burns, the Selway-Bitterroot becomes less uniform as it re-burns, and the Bob Marshall becomes more uniform between initial fires and subsequent fires.

Once-Burned and Re-Burned Pre- and Post-Fire Texture Metrics

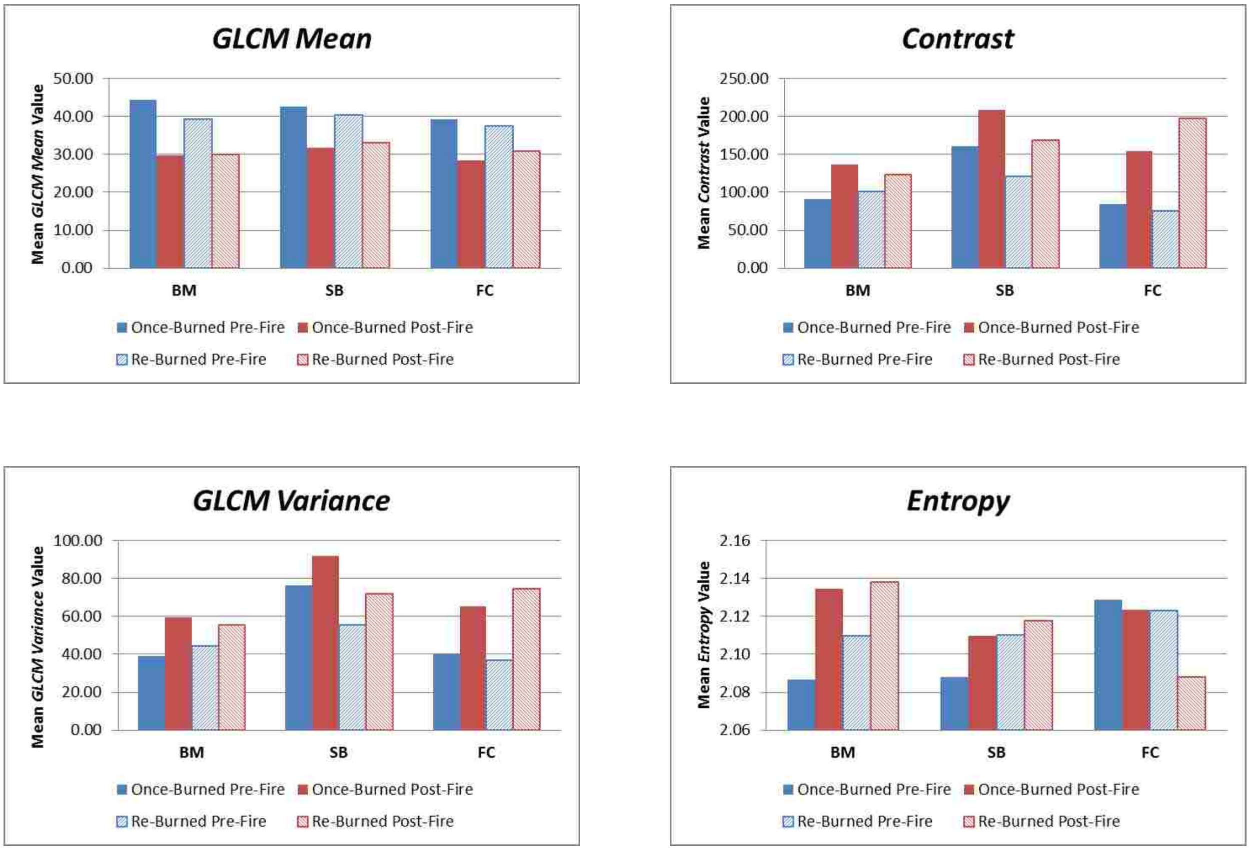


Figure 15: Mean Pre-Fire (blue) and Post-Fire (red) once-burned and re-burned (blue or red striped) texture metric values for the Bob Marshall (BM), Selway-Bitterroot (SB), and the Frank Church (FC) study areas. Except for *Entropy* in the Frank Church, all other indices and metrics indicate similar differences in the direction of the change between pre- and post-fire values.

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Interpretation of Findings

The results show that pre-fire, post-fire, once-burned, and re-burned landscapes are different (with respect to texture) within a study area. Additionally, there are differences among the wilderness areas, although these differences can be explained in an ecological context. Wildfires maintain ecological resilience by restructuring the landscape through space and time. Assuming they have an ecological context, post-fire patches – whether burned once or more than once – add diversity to the landscape, provide additional mechanisms for successional pathways to exist, and promote tree recruitment and plant establishment. The various textures of these patches add dimensionality to the landscape, and influence things like wildlife habitat and future disturbance pathways. Analyzing remotely-sensed datasets using texture metrics can inform us about the post-fire landscape patterns and give us insight into first order fire effects.

In each study area, the differences in the pre-fire and post-fire landscapes are detectable and measurable, both on the ground and through the imagery. However, between landscapes, these differences are not necessarily of the same magnitude, nor are they in the same direction. Wildfires cause changes in the plant canopy, which yields changes in the spectral response detected at the satellite sensor, which in turn results in variations in the values of the texture measures derived through image processing. When cumulative disturbances such as re-burns occur on the landscape, additional changes to the plant canopy occur which alter spectral responses and textural variations.

The values for the *Entropy* and *Contrast* measures of post-fire landscapes are different from the respective values of pre-fire landscapes. *Contrast* measures indicate that post-fire landscapes display more dissimilarities than pre-fire landscapes, which supports the assumption that post-fire landscapes exhibit more variation than pre-fire landscapes. The *Entropy* measures also suggest that post-fire landscapes and pre-fire landscapes are different in terms of uniformity, with post-fire landscapes being less uniform than pre-fire landscapes (except for in the Frank Church). This finding does not support the assumption that pre-fire landscape conditions reinforce post-fire landscape patterns, although in some instances this uniformity is maintained between subsequent fires (see Figure 15). Similar to the findings of chapter two, the results from the texture metrics in all cases suggest that time influences the uniformity and similarities of the post-fire landscape elements, which can be attributed to successional characteristics of the vegetation in each of the study areas.

Pre-fire and post-fire landscapes are different in terms of both normalized burn ratio (NBR) values and texture measures (Figures 14 and 15). This is true for each of the three study areas, although not all changes are equal in magnitude or direction. This is shown by the post-fire NBRs for each of the areas, which are lower following fires proving that wildfires cause changes in vegetation resulting in spectral response shifts and decreased NBR values. The *GLCM Mean* values decrease and *GLCM Variance* values increase following fires, which means that burning causes landscapes to exhibit more variations within burned areas, although with more similar neighbors at the pixel scale. As different landscapes exhibit variations, it follows that wildfire behavior should also vary, and that within-perimeter variations of wildfire effects might be expected. For example, within the perimeters of wildfires, not all areas will burn and a combination of factors will influence the resultant fire effects on the landscape in those areas that do burn. However, *GLCM Mean* and *GLCM Variance* alone are not sufficient to describe what is happening on the landscape, and other texture measures (such as *Entropy* or *Contrast*) can add explanatory power.

The assumption that pre- and post-fire landscapes exhibit similar uniformity was examined using the *Entropy* texture measure. The expectation that the organization of patterns on the landscape would not change, in spite of wildfires altering the vegetative elements comprising these patterns, is not true. In fact, *Entropy* measures showed that the post-fire landscapes were less uniform than pre-fire landscapes in the Bob Marshall and Selway-Bitterroot, but more uniform in the Frank Church. This suggests that wildfires do alter landscape elements in these areas, and that the ways in which wildfires affect the areas (*i.e.,* fire effects) is what determines the outcome of the texture metrics, especially as these areas re-burn.

For each of the texture measures, the pre- and post-fire trends of re-burns showed the same directionality as the pre- and post-fire trends of once-burned areas. However, the ways in which re-burns changed the landscape was different for each study area. Re-burned areas in the Frank Church tended to become more uniform but with higher contrast than once-burned areas, while re-burned areas in the Selway-Bitterroot became less uniform but with somewhat similar contrast as once-burned areas. The Bob Marshall became less uniform and had slightly more contrast as it re-burned. These differences are likely attributed to successional traits and stages of each wilderness landscape, and do not entirely support the assumption that re-burns make landscapes more similar and more uniform.

For example, wildfires can affect an area that 1) is larger than the pre-fire patch (and re-burns across an entire fire); 2) is just a portion of the pre-fire patch (and re-burns entirely within a previous fire); or, 3) crosses patch boundaries, thereby altering portions of more than one patch. The first case would create post-fire landscapes that are potentially more uniform than the pre-fire landscapes, and wildfires, in the Frank Church appear to behave in this way. The latter two cases would create post-fire landscapes that are less uniform than pre-fire landscapes. Wildfires in the Bob Marshall and Selway-Bitterroot appear to behave in the last manner.

CONCLUSIONS

This stage of research utilized data from the MTBS project to perform an objective and systematic assessment of the texture of large wildfires on three wilderness landscapes The MTBS project provides a rich dataset that can be used to investigate fire in an ecological context across large land areas and through time. Because the MTBS data are in essence a census of large wildfires, the findings presented here describe what occurred on each of the wilderness landscapes, using consistent definitions and analytical procedures. These findings are summarized for the landscapes, not for individual fires.

This research aimed to understand whether pre-fire and post-fire landscapes are similar, and also if the areas that re-burn on the landscape are different than those areas that only burn one time. NBR values and texture metrics were used to quantify change, and the changes were described in terms of pre-fire to post-fire differences in once-burned and re-burned areas, and between occurrences. By using texture metrics, this study utilizes the continuous data from the MTBS project to understand fire and fire-on-fire interactions, and is one of a very few that has used continuous data (as opposed to categorical data) at the landscape scale for wildfire research. Although the thematic and categorical generalizations are often necessary for discussing patterns and processes, the full spectrum of the impacts of wildfire on the landscape cannot be wholly represented by classes or categories alone. The use of texture metrics provides another way to characterize and explain the structural variability and arrangement of post-fire and re-burned landscape elements.

Texture metrics can help explain post-fire landscapes, but this analysis is not common, especially over large land areas with a range of forest types. Ostensibly, these metrics can help to explain ecological conditions following fires, especially if used in conjunction with another dataset – for example, high quality imagery, or categorical data. The texture measures add value in that they provide another quantifiable way to characterize and explain fire effects. However, limitations of this methodology include the difficulty of programming these functions into another cross-platform program (*e.g.*, python or IDL), the complexity of interpreting what the texture metrics mean, and picking the most appropriate metric for the research question. A case study of a fire (or fires) that has plentiful data (*i.e.,* photo and video, weather observations, daily perimeters, monitoring plots, etc.) would be a useful way to choose the appropriate metrics to use, as well as tease out explicit meanings of the metrics.

The findings of this research corroborate previous studies that suggest that wildfires influence, and are influenced by, the complexities of landscape components. The convergence of evidence from the second-order texture measures in this chapter of research yields high confidence in these results. Disturbances have ecological value in that they influence future processes and pathways, and are an essential part of landscape formation. The wildfire events that have occurred during the last quarter century in the three study areas are no exception. Each landscape responded differently to wildfire events, partially because of the arrangement and composition of pre-fire landscape components. In general, wildfires result in less uniformity and more contrast between landscape components, and repeated wildfire occurrences at a location result in less uniform and more contrasted landscape, especially when wildfire events occur within a short time period as in this study. However, the uniformity and contrast of pre- and post-fire landscape components depends on whether or not they burned more than once, and differs for each wilderness landscape. As was suggested in chapter three, the results indicate that there is a high degree of complexity in wildfire effects not only within each study area, but also among them.

In sum, the research showed assumptions of pre-fire and post-fire landscapes displaying similar uniformity are not true, whether or not they burn more than one time. The Frank Church landscape behaves in a way that is opposite from the Selway-Bitterroot and the Bob Marshall, with fires tending to increase uniformity and also increase dissimilarities. While re-burns in the Selway-Bitterroot and Bob Marshall behave as expected in terms of *Contrast,* they do not behave as expected in terms of *Entropy*. Re-burns create more dissimilarity and less uniform landscapes in these areas. The time-since-previous-fire is too low for vegetation to recover in these two landscapes, but these results suggest that repeated burning creates more complexity in terms of vegetation diversity and arrangement. In the Frank Church, texture metrics suggest that TSPF is sufficient for vegetation recovery to occur in a way that may be conducive to more frequent burning cycles.

Chapter 5 – Research Summary

The purpose of this research was to examine fire-on-fire interactions in three large wilderness areas using products from the MTBS dataset. This dissertation utilized the MTBS dataset and contemporary GIS and remote sensing software and tools to 1) create three contemporary large wildfire histories, and 2) to explore fire-on-fire interactions in three wilderness areas between 1984 and 2007. The MTBS dataset allows wildfires to be assessed using a consistent and replicable method and includes an area-based component (Eidenshink *et al.*, 2007). The result is a robust approach for analyzing fire interactions with vector- and raster-based data that can be applied in many different fire-affected landscapes, especially large landscapes where field-based sampling is not cost-effective or practical. Burned, unburned, and re-burned areas within fire perimeters, as well as fire edges and perimeters, can be characterized and analyzed using the vector-based fire perimeters and raster-based fire effects data included in the MTBS dataset.

Although the software and tools exist to analyze spatial fire history datasets such as the MTBS, descriptions of appropriate and relevant methods to analyze and describe the interactions of multiple large wildfires are scarce (but see Collins *et al.*, 2007; Collins *et al.,* 2009). The first stage of the study formulated tractable research questions, and explored methods to facilitate analysis of the data. These questions were addressed in two stages using vector- and raster-based data from the MTBS dataset. The overall results from this research support the supposition that previous fires affect subsequent fires in terms of behavior and effects, and that once-burned and re-burned areas differ from each other and from unburned areas.

As shown by this dissertation, the use of the long-term remotely sensed MTBS dataset in conjunction with contemporary software and tools, yields methods and analyses that apply to burns and re-burns alike. Accomplishments of the research include:

1) A contemporary large fire atlas for each wilderness area developed solely from the MTBS dataset including only large wildfires that occurred between 1984 and 2007. This has not previously been documented for any of these wilderness areas.
2) Calculations of the natural fire rotations (NFRs) for each wilderness area. NFRs derived from the fire atlases indicate that wildfires in these areas are not different from what has been estimated by other methods.
3) Characterizations of fire edges and re-burned areas for each wilderness area in terms of fire propagation. The analysis of the interactions of multiple large wildfires with each other at their common boundaries gives researchers and land managers a perspective on fire regimes that is largely missing from current literature.
4) An analysis of the textural characteristics of pre- and post-fire landscapes. Textural analysis provides insight into the effects of wildfires on the arrangement and similarities of landscape components, and has not previously been described for large wilderness landscapes.

Knowing how and when large wildfires occur, and how and when re-burns occur, is important for thoroughly understanding fire regimes. Although large wildfires occur as frequently as has been estimated in the past on these wilderness landscapes, only a small portion of each landscape re-burns. Re-burns play an ecological role on the landscape through time and affect the fire regimes of each area, as evidenced by the longer natural fire rotations calculated using only once-burned areas. When burned and re-burned areas are analyzed using continuous data, as opposed to thematic data, the character of fire effects can be seen. The textural variability displayed within fire perimeters because of burning and re-burning are worth investigating further in a strictly ecological context. The information derived from these results can be applied to fire behavior and effects models and land management plans across the range of landscapes in the western United States. Case studies and additional datasets used in conjunction with the MTBS dataset would provide supplementary information and characteristics with which to explore fire-on-fire interactions further.

Five types of fire-on-fire interactions discovered and explored in this dissertation are:

1. Edges that stop and/or re-direct the new fire (*i.e.,* Conger on Cabin);
2. Re-burns in which the old fire acts as a buffer and redirects the new fire (*i.e.,* Moose on Anaconda);
3. Re-burns in which the old fire is partially re-burned by a new fire (*i.e.,* Biggs on Gates);
4. Re-burns in which the old burn is (nearly) completely re-burned by a new fire (*i.e.,* Moose on Howling); and,
5. Re-burns which occur completely within the old fire (*i.e.*, Cabin on Canyon).

Additionally, unburned islands that remain unburned in subsequent fires can be characterized, as well as whether large wildfires burn onto or out of old burn scars. However, the latter characterizations were not done in this dissertation as they are not possible to do using the MTBS data alone. As suggested in chapter three, it would be possible to achieve a deeper understanding of fire-on-fire interactions if research were to be done using the MTBS data in conjunction with other datasets, such as daily fire progression maps and weather data.

All three stages of research indicate that burn scars from previous wildfires can be (and are) re-burned by subsequent large wildfires; this is true in all three wilderness areas. The time between successive fires, as well as the severity of the first fire in places that re-burn, influence the spread and effects of future fires. Much edge is created by large wildfires. However, in most cases, where edges of previous burns are encountered by subsequent fires, the subsequent fire re-burns across the edge onto the old burn scar. Previously burned areas can and do check the spread and regulate the growth of new fires, however, as shown by the small size of many re-burned areas. This process yields diversity on the landscape, and a unique and dynamic mosaic as a result of a number of factors, including the effects of the previous fire and the timing and behavior of past and current wildfires in an area.

Descriptions of landscape texture offer a unique perspective on wildfires and patchiness, that is not commonly found in the literature. The similarity and arrangement of neighboring landscape components within burned and re-burned areas were analyzed using the MTBS data. The similarity of the landscape within burned areas is regulated by the sequence of burning and re-burning, although the degree to which this occurs differs in each wilderness area. Additionally, the similarity and uniformity of pre- and post-fire landscapes are different from each other and for each wilderness area. Post-fire landscapes exhibit more variation in neighboring areas than pre-fire landscapes in terms of normalized burn ratios. In the Frank Church, the post-fire landscape (which includes both once-burned and re-burned areas) is more uniform than the pre-fire landscape, while the opposite is true in the other two wilderness areas. When comparing re-burned to once-burned areas, the Frank Church exhibits increasingly more uniform as it re-burns, while the other study areas overall become less uniform as they re-burn. The diversity of these characteristics adds to the complexities of understanding wildfire effects on the landscape. How textural diversity plays into the propagation of large wildfires remains to be seen. However, the textural characteristics exhibited by burn scars in the NBR images are likely an expression of the predominant vegetation (or regeneration) at each stage in the successional pathways of an area following a fire. As such, they should correspond to the resultant behavior and effects of a subsequent fire when it encounters that location.

As noted by many fire history studies, large wildfires did occur on the three wilderness landscapes in the past. The wildfires of the past interacted with each other in the same way as the contemporary large wildfires of this research. Besides influencing future fires, the interactions of previous large wildfires on subsequent large wildfires at their common locations serve an ecological purpose. These landscapes and their components developed and aged with intermittent wildfires (and other disturbances), leading to changes in the type and arrangement of components; pattern and process are intertwined infinitely on the landscape. When these landscapes burn and re-burn, the fire effects within fire perimeters are displayed as a mosaic of many patch types, sizes, and textures across the area. For example, unburned islands within fire perimeters can contribute to the regeneration of vegetation species and provide refuge and habitat for animals and birds, while areas that burn multiple times may serve to maintain a single species for an indefinite period. Because the interactions of patterns and process are continuous through time, the net effect is a self-regulating landscape, whose components are created and influenced by disturbances, and have an effect on future disturbances (see Falk *et al.*, 2007; McKenzie *et al.,* 2011). As a result of these interactions, landscapes with assorted patterns of juxtaposed and interspersed vegetation species, age classes, and structures exist. These components lead to various fire behavior and fire effects into the future as the landscape ages. Thus, the role of large wildfires in these wilderness areas – including the episodes of multiple large wildfires and the interludes with few large wildfires – creates and maintains an assortment of patches and edges across the landscape in order to preserve ecological diversity and function.

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