Post-fire Vegetative Regrowth Associated with Mature Tree Stands and Topography on Sofa Mountain

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ABSTRACT

Plant compositions are constantly changing in response to biotic and abiotic factors. Adaptability of these vegetative assemblages to change is a concern for land managers and ecologists in fire-prone montane regions of North America. In 1998, a holdover fire event burned 1521 ha of primarily coniferous forest on Sofa Mountain, located in Waterton Lakes National Park, southwestern Alberta, Canada. This was the first significant burn within the park in 130 years and offers a unique opportunity to study possible effects of topographic influences on the spatial relationship of residual mature tree stands within the burn and associated reestablished vegetation with these stands. A mixed-methods approach utilizing GIS, remote sensing, and statistical regressions determined that clustering of vegetation was influenced by topographic features slope and aspect. New growth was more likely to be a product of fallen trees and debris rather than associations with mature trees.

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TABLE OF CONTENTS

PAGE

1. INTRODUCTION

2. LITERATURE REVIEW

3. METHODOLOGY

4. RESULTS AND DISCUSSION

5. CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

TABLE PAGE

INTRODUCTION

1.0 Overview of Project

It has long been understood that the joint effects of climate and topography have created a unique and diverse ecosystem assemblage ranging from montane regions of the Rocky Mountains to the prairie grasslands of the Great Plains. However, the importance of disturbance events in establishing and generating patterns of the landscape is relatively understudied. Fire is an important disturbance agent that is structured by spatial patterns of fuels, climate, weather, and topography and plays an important role in vegetative succession (Haire et al. 2013) and landscape structure (Buckler 2012). Fire disturbance events offer unique opportunities to study large, infrequent disturbances and address basic ecological questions surrounding ecosystem structure and dynamics. For much of the twentieth century, though, fire had been suppressed throughout North America, including Waterton Lakes National Park (WLNP) in Alberta, Canada (Parks Canada 2013a), affecting the nature of its ecosystem structure, function, and dynamics.

The study of pre- and post-fire vegetative composition is useful in understanding ecosystem behavior in response to fire and, on a more broad scale, disturbance. With projections suggesting that a warming climate will only increase the frequency and severity of fire, effective management of natural landscapes is more of a necessity than in previous years (Baker 2009; Mustaphi and Pisaric 2013). Fire management requires the understanding of vegetative response over time to burns of varying severities and intensities as well as the frequency at which they occur (Turner et al. 2001; Baker 2009). This research is of particular importance to ecologists, land managers, and park management in making decisions regarding management practices and conservation efforts of natural, complex landscapes in order to maintain ecosystem health, integrity of the area, and make informed decisions with changing conditions.

The most recent major burn in WLNP occurred on the north-facing slope of Sofa Mountain, where an intense fire was ignited by a lightning strike on September 2, 1998. This event was the first significant fire within the park in 130 years. A smoldering lightning strike coupled with dry conditions and high winds common to the area combined to create an intense crown fire that burned 1521 hectares (Schwanke 1998). The area was littered with dead vegetation and composed of stands of flammable conifers such as the lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), and Engelmann spruce (*Picea engelmannii*), allowing the fire to move rapidly (Schwanke 1998). The fire was difficult to contain until winds from an adjacent valley created an eddy effect, causing the fire to turn back on itself, slowing its advance (Parks Canada 2013a). The burned area is characterized by complex topography, which influenced fire behavior and, possibly, vegetative reestablishment. This thesis will investigate topographical conditions and spatial vegetation associations across the landscape that influences post-fire vegetative growth and succession on Sofa Mountain in WLNP where a 1998 holdover fire occurred.

1.1 Thesis Objectives and Summary

This thesis investigates spatial relationships of the reestablished vegetation associated with mature tree stands after a fire event on Sofa Mountain, Waterton Lakes National Park. This thesis will answer the following questions:

1. Where are mature, unburned tree stands located within the burn area in relation to topography?
2. How is reestablishment of trees spatially associated with these mature stands?
    a. Is seedling maturation greatest adjacent to these mature tree stands?

This thesis discusses two interrelated objectives. Firstly, it spatially delineates mature tree stands, or islands of unburned vegetation, deriving topographic influences on survival. Secondly, it determines the post-fire composition influenced by topography and external seed sources. Mature tree stands are expected to have survived the fire event due to topographic influences, such as slope, aspect, and elevation. The post-fire reestablishment of trees is anticipated to be associated with these mature stands, where seedling maturation is greatest in close proximity to these stands, as well as topography.

This thesis is divided into five chapters. Chapter Two provides context and background information about the study area and species composition of WLNP as well as previous analyses of Sofa Mountain used for this project. Chapter Three discusses the methods used throughout this study and Chapter Four incorporates the results and discussion sections into a comprehensive analysis. Finally, Chapter Five consists of the conclusions and recommendations for future study.

LITERATURE REVIEW

2.0 Introduction

The composition of plant communities, particularly those in forest ecosystems, is constantly changing as a result of abiotic and biotic factors, disturbances, and other natural processes (Brown and Smith 2000). The adaptability of certain vegetation assemblages in response to fire events is indicative of a functioning and healthy ecosystem. For example, fire is integral to the montane ecosystem as it influences stand composition and age structure, and affects soil and slope processes (Mustaphi and Pisaric 2013). Low intensity fires can cause thinning and all-age tree stands, while high intensity fires are more likely to decimate tree stands resulting in new even-aged stands (Brown and Smith 2000).

Fire suppression was common practice throughout North America for much of the twentieth century due to the view of fire as a threat to people, wildlife, and important resources (Aplet 2006). However, by the mid-twentieth century, it was recognized that fire played a large and very important role in maintaining the character of ecosystems by enriching soils, reducing the fuel load, stimulating new growth, and creating a heterogeneous landscape with a variety of vegetation types and ages. As a result, fire management policies changed drastically to reflect these findings. However, decades of suppression allowed highly flammable coniferous species such as lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), and Engelmann spruce (*Picea engelmannii*) to become abundant in some areas (Levesque 2005), in addition to the accumulation of dead timber and vegetation that served as fuel for unmanageable and intense fires (Keeley and Fotheringham 2001). Patches, or discrete areas with a distinct function and vegetative assemblage, varying in size and burn severity, produce a mosaic pattern across the landscape as a result of fire. The resulting distribution of these patches affects patterns of reestablishment (Pickett and McDonell 1989; Agee 1993; Turner et al. 1994; Forman 1995; Turner et al. 2001).

Reestablishment of vegetation after a fire event may be determined by proximity to surviving trees as neighbor interactions between plants can potentially play an important role in plant community organization and forest succession (Kikvidze 1996; Ponge et al. 1998). These neighbor interactions, or positive plant interactions (i.e. ‘nursing effect’ in which a plant provides ecological facilitation to seedlings, shade, or support to another plant), can determine spatial and temporal species associations helping to create a suitable environment for growth, particularly in disturbed environments (Kikvidze 1996). Previous research has illustrated spatial correlation of reestablishment based on proximity to mature stands. Agee and Smith (1984) demonstrated that higher rates of succession were directly related to close proximity with surviving trees. Keeton and Franklin (2005) demonstrated that seedling densities decline significantly with distance from remnant conspecific trees. Further, Stueve et al. (2009) discovered that proximity to older, mature trees was important in determining patterns of establishment throughout the landscape.

2.1 Study Area

Waterton Lakes National Park (Figure 2.0; WLNP) is located in southwest Alberta, Canada, adjacent to the U.S./Canada International Boundary and is one component of the Waterton-Glacier International Peace Park. Together, the combined parks are an UNESCO World Heritage Site (Reeves 1975). The park is found on the eastern slopes of the Western Cordillera, an extensive mountain chain in western North America (Reeves 1975).

Figure 2.0 - Map of WLNP and location of Sofa Mountain.

2.1.1 Geology

The Lewis Overthrust fault is responsible for the formation of the Rocky Mountains between 50°53’38” N, 115°11’24” W and 47°17’11” N, 112°33’47” W (Rockwell 2002), which includes WLNP. Sedimentary rocks that were deposited here around 1.6 to 0.8 billion years ago have undergone intense deformation: collision of crustal plates caused the sedimentary rock to push eastward overriding younger, more easily deformed rocks to create the Rocky Mountains (Harrison 1976). More recent modification of the Waterton landscape occurred through forces of erosion and deposition during late Cenozoic periods of glaciation (Harrison 1976). Elevations throughout the park range from 1280 meters at the Waterton townsite, to 2920 meters at the peak of Mount Blakiston (Coen and Holland 1976). This varied landscape creates a complex topography as well as diverse microclimatic conditions across the landscape (Harrison 1976).

2.1.2 Climate

The climate of southwestern Alberta is distinctive as it is influenced by two opposing climatic systems, the Arctic Continental and Pacific Maritime. The Arctic Continental system brings cold, dry air into the area, causing extended cold seasons, while the Pacific Maritime system is dominant year round. Summers are short, dry, and cool, and winters are mild and snowy (Cerney 2006). The Pacific air mass frequently breaks through the Arctic air mass in winter, producing warming Chinook winds, which are common to WLNP (Reeves 1975).

Vegetation patterns are influenced greatly by changing climates (Harrington and Harman 1991; King and Neilson 1992); adaptability is therefore important in this area of the Rocky Mountains. A combination of dendrochronological records, pollen records, and the glacial record has been used to explain climate trends in the Canadian Rocky Mountains (Luckman 2000). Glaciers throughout the Canadian Rocky Mountains reached their Holocene maxima during the Little Ice Age (1300-1870), as this era was marked by a sustained cold period followed by a warming trend (Luckman 2000). The mean annual temperatures at WLNP have risen 0.6-1.4 degrees Celsius throughout the twentieth century, and tree-ring reconstructions suggest that these warming temperatures, particularly during the 1990s, are greater than any period over the last 900 years (Luckman 2000; Levesque 2005). Optimal elevation ranges of plant species have increased with this warming trend resulting in the upslope migration of the coniferous forest (Levesque 2005; Letts et al. 2009).

2.1.3 Topography and Geomorphic Characteristics

The combination of mountain building, erosion, and geomorphic processes create rough surfaces, which are measured in ruggedness, or the sum of the slopes, valleys, peaks, exposures, and elevation of an area (Forman 1995). Rugged characteristics dictate the flow of water across a landscape creating microsite characteristics that influence land-cover conditions (Forman 1995). Topographic features also vary in solar radiation and soil moisture, which alters the distribution of vegetation across a landscape (Ryan 1976; Baker and Kipfmueller 2001).

The resulting topographically influenced variations in solar and moisture conditions produces a heterogeneous landscape of varying environments suited to distinct vegetative assemblages. For instance, the impact of aspect on the ecosystem's vegetation is important: north and east facing slopes are generally moister and more supportive of forests, whereas south and west facing slopes are dryer and favor grasslands (Letts et al. 2009; Schwanke 1998). Wetlands and riparian forests correspond with rivers and floodplains and are generally found at lower elevations, whereas drier habitats are typical of ridge tops (Turner et al. 2001). Swanson and colleagues (1988) categorized the general effects of landforms on an ecosystem and its processes into four classes:

- Class 1 – Landforms (by their elevation, aspect, parent materials, and steepness of slope) influence air and ground temperature and the quantities of moisture, nutrients, and other materials such as pollutants available at sites within a landscape;

- Class 2 – Landforms affect the flow of organisms, propagules, energy, and materials through a landscape;
- Class 3 – Landforms may influence the frequency and spatial characteristics of disturbance;
- Class 4 – Landforms constrain the spatial pattern and rate of frequency of geomorphic processes that alter biotic features and processes.

Patterns of biota across natural landscapes reflect interactions among most, if not all, of the four classes creating complex landscapes (Swanson et al. 1988). In montane environments, for example, wind exposure and canopy mediate slope-aspect-related microclimatic differences that result from seasonal acclimation and variable solar insolation (Letts et al. 2009).

In WLNP, there is little transition zone between the mountains and plains. Glacial deposits near the bottom of the main valley buried the foothills, leaving eskers and moraines (Cerney 2014). Complex ridges also characterize the park creating valleys. The primary valley has a north-south orientation and secondary valleys run east to west in direction. The varied topography of the area contributes to local site conditions influencing the patterning of vegetation across the landscape.

2.1.4 Montane Ecosystem of WLNP

WLNP boasts high biodiversity as a result of four intersecting ecoregions: foothills parkland, montane, subalpine, and alpine (Parks Canada 2013b). The foothills parkland ecoregion has a limited geographic range on the east side of the park between

1280-1500 meters in elevation and is characterized by rough fescue grasslands and aspen (*Populus tremuloides*); (Parks Canada 2013b). The montane ecoregion occurs at elevations between 1280-1600 meters consisting of drier grasslands and some open mixed poplar and conifer forests (Parks Canada 2013b). Douglas fir (*Pseudotsuga menziesii*) and limber pine (*Pinus felxilis*) are significant tree species of this ecoregion (Parks Canada 2013b). The subalpine ecoregion covers the largest geographic area of the ecoregions throughout WLNP. This ecoregion is divided into two sub-regions: the lower subalpine occurs at elevations between 1650-1950 meters and the upper subalpine occurs at elevations between 1950-2250 meters (Parks Canada 2013b). The lower subalpine region is moist and cool, dominated by Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), while the upper subalpine region is more open and characterized by whitebark pine (*Pinus albicaulis*); (Parks Canada 2013b). The alpine ecoregion also covers a large geographic area throughout the park and occurs at elevations of 2250-2650 meters or higher (Parks Canada 2013b). However, this ecoregion is sparsely vegetated and treeless (Parks Canada 2013b).

Coniferous forests dominate land cover, comprising half of the park. Bare rock, aspen groves, prairie grasslands, and bodies of water account for other significant land cover types throughout the park (Barrett 1996; Schwanke 1998). Generally, the eastern slopes of the Rocky Mountains predominantly contain prominent pure and mixed stands of lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), as well as some significant stands of limber pine (*Pinus flexilis*); (Levesque 2005; Axelson et al. 2011).

Natural disturbances are a principal mechanism in shaping the composition and structure of montane forest ecosystems. Affected areas and severity of the disturbance varies, as these events do not act uniformly throughout a landscape; they contribute to creating complex heterogeneous vegetation patterns across that landscape (Turner et al. 2001). Specifically, fire is an important natural disturbance to the montane ecosystem. Pre-twentieth century fires, as well as other disturbances, produced complex vegetation patterns of burned and unburned areas across the northern Rocky Mountains (Turner et al. 2001; Cerney 2006). However, twentieth century fire management within the park consisted mainly of suppression, which has led to a more homogenous landscape and vegetative cover, altering the natural ecological function (Levesque 2005).

The mountain pine beetle (*Dendroctonus ponderosae,* MPB) is a natural agent of disturbance affecting lodgepole pine forests. Outbreaks of MPB have led to more resilient stands of lodgepole pine as well as an increased number of mixed stands resulting in greater species diversity, creating a more heterogeneous landscape (Axelson et al. 2011). MPB outbreaks have shaped the structure and composition of forests by causing high rates of pine mortality and increasing the fuel for fire disturbance events (Kaufman et al. 2008; Axelson et al. 2011). Additionally, these insect infestations create gaps in the canopy allowing for understory growth and an increase in forest species diversity (Dordel et al. 2008).

A non-native invasive fungus, *Cronartium ribicola,* which is a threat to whitebark pine (*Pinus albicaulis*) and limber pine (*Pinus flexilis*) throughout WLNP, results in white pine blister rust (WPBR); (Smith et al. 2013a; Smith et al. 2013b). Trees at any lifestage are susceptible to this lethal fungus (Schoettle and Sniezko 2007). Smith et al.

(2013a; 2013b) studied the changes in infection and mortality of these tree species and found that mortality of whitebark pine trees infected with WPBR increased from 26% in 1996 to 65% in 2009 and, for limber pine trees, mortality increased from 30% in 1996 to 46% in 2009 (Smith et al. 2013a; Smith et al. 2013b). A MPB outbreak during the 1980s, followed by WPBR in the 1990s, led to destruction of the pine stands on Sofa Mountain, increasing the fuel load for the 1998 fire (Schwanke 1998).

2.1.5 Sofa Mountain

Sofa Mountain is located in the southwestern portion of WLNP at 49°01’15” N, 113°47’08” W (Figure 2.0) and reaches a height of about 2450 meters (Baird 1964; Figure 2.1).

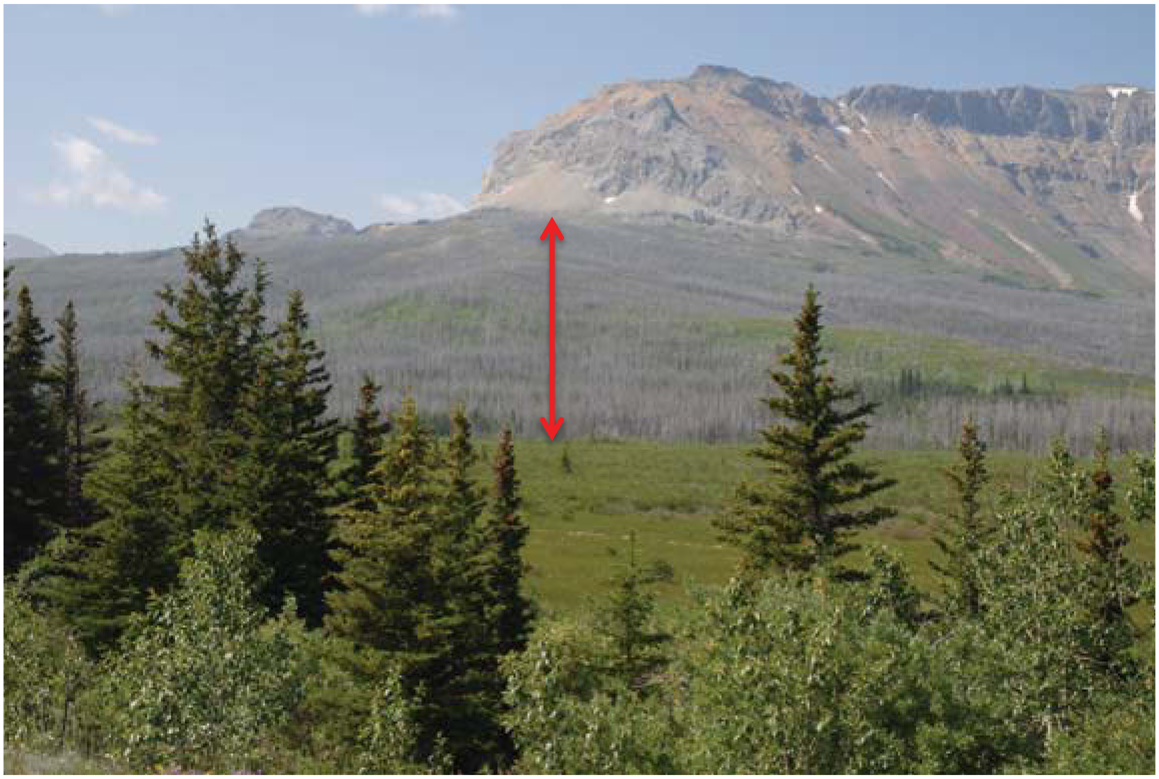

Figure 2.1 – Southern view of Sofa Mountain and a portion of the 1998 burn scar as indicated by the area between the red arrow and grey vegetation. Image provided by Dr. Dawna Cerney.

On September 2, 1998 a lightning strike on the north-facing slope was fanned by strong winds into an intense fire that moved rapidly across the landscape. The fire burned a total area of 1521 hectares (Figure 2.2), mostly within the park (Schwanke 1998; Parks Canada 2013a), and in the montane ecozone between 1500 and 2000 meters where the forest composition consisted mainly of lodgepole pine, Douglas-fir, limber pine, Engelmann spruce (*Picea engelmannii*), white spruce (*Picea glauca*), quaking aspen (*Populus tremuloides*), subalpine fir (*Abies lasiocarpa*), and fescue grasslands (Levesque 2005; Cerney 2006; Buckler 2012). It went undetected in its early stages and efforts to suppress the fire were unsuccessful. The fire was declared officially contained within sixteen days of ignition having burned a total of 1521 ha. This was the first significant fire in 130 years within the park (Schwanke 1998).

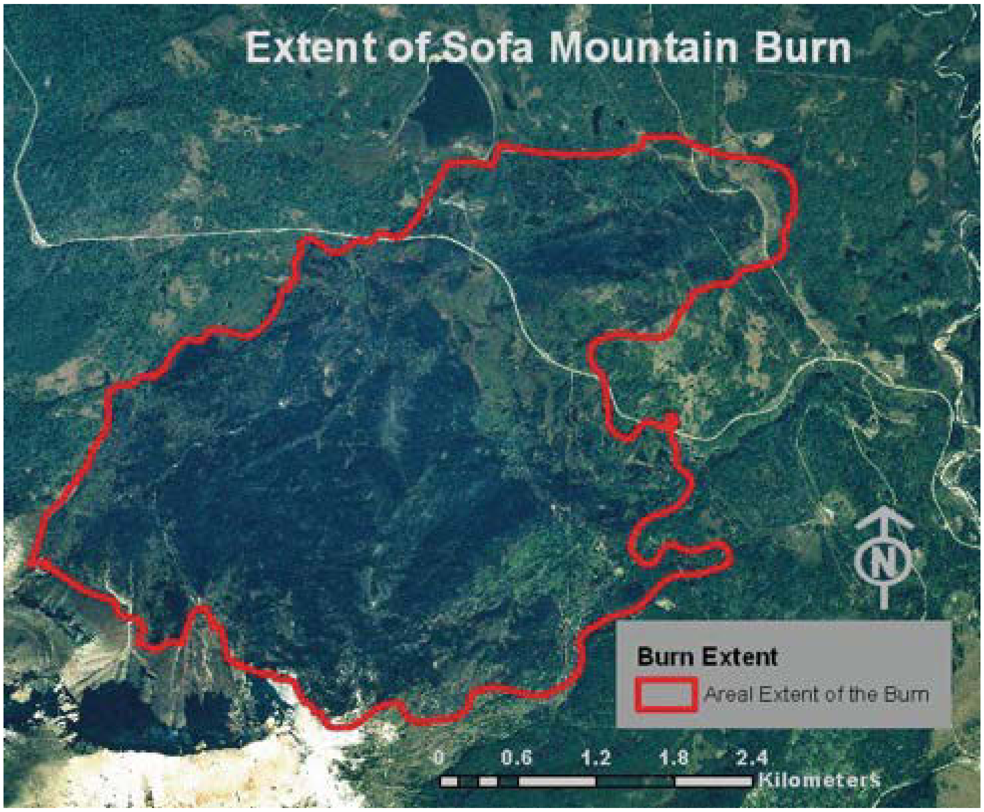

Figure 2.2 - Extent of 1998 Sofa Mountain fire. Derived from 1998 aerial image (Buckler 2012). Note the Chief Mountain Highway bisecting the burn area.

2.1.6 Vegetation

Understanding the biology and disturbance response of tree species common throughout WLNP allows for the assessment of successional pathways and is useful in determining the probable post-fire vegetative composition of the landscape, which is helpful in park ecosystem management.

2.1.6.1 Trees

Lodgepole pine (Pinus contorta)

Lodgepole pine (*Pinus contorta*) is a shade-intolerant, serotinous tree species that reproduces and establishes extremely well after a fire event (Kaufmann et al. 2008). Seed cones are most often found in the crown and can be serotinous, closed or unserotinous, open cones (Lotan and Critchfield 1990). A shift from open to closed cone dominance, or vice versa, may be an adaptation that permits this species to colonize a multitude of locations in the post-fire environment that proves to be advantageous (Lotan and Perry 1983; Schoennagel et al. 2003).

The immense heat of a fire melts the resin of the tree's serotinous cones allowing them to open and release seeds to the forest floor (Turner et al. 1997; Kaufmann et al. 2008). The newly exposed mineral soil of a post-fire area is conducive to lodgepole pine seedling growth as the species germinates best with these soils conditions and full sunlight (Kaufman et al. 2008).

Pre-fire serotiny has shown to be indicative of post-fire lodgepole pine densities (Schoennagel et al. 2003). Previous stand-replacing fires tend to generate high percentages of trees with serotinous cones post-fire (Lotan and Perry 1983; Schoennagel et al. 2003) and crown fires, such as the event on Sofa Mountain, usually cause maximum release of stored seed (Lotan 1976). Thus, if a pre-fire area has high levels of serotiny, it would be expected that the post-fire environment have high stand densities. On average, lodgepole pine tree stands have less than 50 percent serotinous cones, a percentage that varies over time and space as well as elevation, stand age, and geographic location (Wright and Bailey 1982). Variations in serotiny percentage, however, lead to distinct pathways of regeneration for this species allowing for succession under various environmental conditions (Nyland 1998).

If a landscape has been fire suppressed, much like WLNP had been during most of the twentieth century, lodgepole pine stands will display a shift in dominance from serotinous, closed cones to nonserotinous, open cones (Lotan 1976; Wright and Bailey 1982). Therefore, in the absence of fire, stands adapt in order to continue to propagate an area. Consequently, the ability of lodgepole pine to regenerate well following a fire is not due to serotiny alone. Other characteristics including seed viability, rapid growth, and the ability to establish on a wide variety of site conditions allow for lodgepole pine to outcompete other species in the initial post-fire community compositions (Lotan 1976).

Engelmann spruce (Picea engelmanii) and Subalpine fir (Abies lasiocarpa)

Engelmann spruce (*Picea engelmanii*) and subalpine fir (*Abies lasiocarpa*) are commonly associated with one another. Engelmann spruce is a shade-tolerant species found at elevations between 1000 and 3000 meters (Uchytil 1991b) and is typically a dominant species that coexists with subalpine fir in climax communities (Jenkins et al. 1998). This species is characterized as a mesophytic reseeder: it regenerates by seed from an external source and thrives in environments that are not particularly dry or wet, but has adapted over time to thrive in environments that are dry (McKenzie and Tinker 2012). Subalpine fir is found at elevations ranging from 600 to 3600 meters, has a low tolerance to high temperatures (Uchytil 1991a), and is also identified as a mesophytic reseeder: it regenerates by seed from an external source and thrives in environments that are not particularly dry or particularly wet (McKenzie and Tinker 2012). Both Engelmann spruce and subalpine fir typically establish beneath lodgepole pine 20 years following a stand-replacing fire, but are subject to low-intensity surface fires that kill both while not damaging the lodgepole pine overstory (Jenkins et al. 1998). The shade tolerance of these species allows them to persist over time throughout the ecosystem as seral species (Uchytil 1991a; Uchytil 1991b). After a fire event, the timing of reestablishment of these species is determined by the early vegetative successors establishing adequate shade and site conditions conducive to growth (Uchytil 1991a; Uchytil 1991b).

Douglas fir (Pseudotsuga menziesii)

Douglas fir is a large coniferous tree that is moderately shade-tolerant. It thrives in full or part-shade and regenerates best post-disturbance. The thick bark of Douglas fir enables the species to survive moderately intense fires; however, since most of the trees' foliage is concentrated on the upper bole, crown fire can be significantly damaging. Seeds are typically wind dispersed from a nearby mature tree when colonizing a burn area, but seed dispersal may also be augmented by Clark's Nutcracker (*Nucifraga columbiana*) in some areas. Seedlings cannot survive dense shade or competition from other understory vegetation, particularly if the seedbed is also dry (Uchytil 1991d). This species is typically restricted to hot, dry sites on the south- or southwest-facing slopes at lower elevations.

Quaking aspen (Populus tremuloides)

Quaking aspen (*Populus tremuloides*) is a clonal tree species with an extremely wide geographic range and high genetic diversity (Levesque 2005). Aspen are extremely sensitive to fire and even low to moderate intensity fires can kill the overstory, promoting resprouting as there is an absence of apical dominance (Jenkins et al. 1998; Wen et al. 2014). Local reestablishment is predominantly achieved vegetatively, but may also occur through seed production. Vegetative aspen regeneration has been positively related to fire size and severity with suggestions that larger fires and more severe burns will promote vast regrowth (Wan et al. 2014). Seed production is a secondary mechanism of reproduction that allows for long-distance stand dispersal (Turner et al. 2003). Seedling recruitment of aspen occurs during a narrow opportunistic time frame in which moisture conditions are favorable, there is little to no competition from other species, and there is an abundance of exposed soils from burned sites (Turner et al. 2003). Research from the post-fire environment of Yellowstone National Park demonstrated that aspen seedlings were more likely to be found near adult aspens and in more severely burned areas (Turner et al. 2003), demonstrating the importance of existing mature stands of vegetation from the pre-fire environment as well as burn severity in composing the post-fire environment.

Limber pine (Pinus flexilis)

Limber pine (*Pinus flexilis*) is a slow growing, long-lived species. This tree species has the ability to colonize harsh environments where few other trees can survive, such as xeric patches in rocky and wind-swept terrain (Letts et al. 2009). It can also withstand climate variability (Letts et al. 2009). Limber pine reproduces entirely by seed relying on small mammals and birds, particularly Clark's Nutcracker (*Nucifraga columbiana*) for dispersal; wind dispersal is not an effective mechanism for the species (Johnson 2001). Young limber pine trees have relatively thin bark and are typically killed during a fire event, but mature trees can more readily withstand intense heat (Johnson 2001).

Whitebark pine (Pinus albicaulis)

Whitebark pine (*Pinus albicaulis*) is a conifer species with a history of dominance as it was once plentiful in subalpine plant communities. This species is a small to medium-sized tree that is sometimes found in low shrub or krummholtz forms at high elevations (Fryer 2002). Whitebark pine has a significantly lower genetic diversity than many other North American tree species. Wind and the Clark's Nutcracker (*Nucifraga columbiana*) help to facilitate seed dispersal for this species. However, because the Nutcracker tends to plant seeds from parent sources within the same cache, trees in the same clusters tend to cross- or self-pollinate (Tomback 1978). Cross- or self-pollination is typically favored under conditions where pollinators or mates are rare, but can be problematic as there is a lack of genetic variation, reduced health of the species, and an overall lack of adaptability to changing environments (Wright et al. 2013). Whitebark pine seedlings establish best on open sites following stand-replacing fires. However, due to high competition from other conifer species and the species' late-successional dominance, fire events are more likely to disturb and interrupt Whitebark pine maturation (Fryer 2002).

White spruce (Picea glauca)

White spruce (*Picea glauca*) is a coniferous tree with relatively thin bark and branches concentrated near the crown. This species generally produces seeds at about 30 years of age, which are wind-dispersed, and remain viable for only one to two years. Seedlings grow best on mineral soils and in full sunlight. White spruce establishes under aspens or other hardwoods after a stand replacing fire and eventually replaces those species becoming the dominant tree. However, this species is not adapted to colonize after a fire, as most intense fires occur during the summer before seeds are mature, decreasing the available seed for dispersal (Uchytil 1991c).

Black Cottonwood (Populus trichocarpa)

Black cottonwood (*Populus trichocarpa*) is a member of the willow family and the largest hardwood tree in western North America, primarily growing on moist sites. Moist seedbeds are essential for Black cottonwood's initial establishment but the species can also sprout from roots and stumps. This tree species is very susceptible to fire and does not reestablish very well following a fire event. Despite this, fire can improve seedling reestablishment by increasing the amount of sunlight as well exposing mineral soils (Steinberg 2001).

2.1.6.2 Shrubs and Forbs

Shrubs and forbs are common in this environment and are found in abundance in the early post-fire composition. The following native species are specifically associated with WLNP and the trees found throughout the Sofa Mountain burn area. These species can sometimes overtop tree seedlings inhibiting growth in the initial stages of post-fire regrowth (Crotteau et al. 2013), but can also produce favorable nutrient and climate conditions for subsequent tree communities (Boyd and Davies 2010). While the biology and ecosystem dynamics of these species are important to understand, the nature of this project does not allow for the direct modeling of this vegetation.

Fireweed (Chamerion angustifolium)

Fireweed (*Chamerion angustifolium*) is a robust perennial forb with deep roots and rhizomes, which allows this species to establish well following a disturbance. Fireweed can also regenerate through wind-facilitated seed dispersal. This species is an important off-site colonizer as it establishes within the first year following a fire event in areas where it was not present pre-fire (Pavek 1992). This plant tolerates a wide range of site and soil conditions and is particularly abundant in conifer forests. Fireweed does not readily invade established vegetative communities, but it is known to be problematic in areas where conifer seedlings are trying to establish as it can sometimes overtop conifer seedlings, persist for ten years, and may serve as a source of rootrot (*Armillaria ostoyae*) in ponderosa pine. Following a fire event, fireweed reestablishes well through its rhizomes and its plentiful production of wind-dispersed seed (Pavek 1992).

Wood's Rose (Rosa woodsii)

Wood's rose (*Rosa woodsii*) is a perennial shrub that is widely adapted to grow in various habitats, particularly moist forests where it flourishes in the understory. This species occurs in several stages of succession but is frequently observed in early seral stages as it establishes well in disturbed sites. Wood's rose regenerates by seed and vegetatively from roots, which is most common in post-fire areas (Hauser 2006).

Snowbrush Ceanothus (Ceanothus velutinus)

Snowbursh ceanothus (*Ceanothus velutinas*) is a moderately shade-tolerant shrub that is commonly associated with ponderosa pine (*Pinus flexilis*), lodgepole pine (*Pinus contorta*), and Douglas fir (*Pseudotsuga menziesii*); (Anderson 2001). Snowbrush ceanothus propagates by seed and vegetatively by sprouting (Anderson 2001). The seeds can remain dormant and viable for many years and germinate after a fire event (Shaw and On 1979). When the seeds mature, they are ejected from the plant pods where they filter into the soil due to their heavy weight. This species is typically an early successor in post-fire environments and may retard succession of other vegetation. Snowbrush ceanothus seeds promote germination most effectively through exposure to immense heat, which exposes seeds to the mineral soil (Anderson 2001).

Spreading Dogbane (Apocynum androsaemifolium)

Spreading dogbane (*Apocynum androsaemifolium*) is a mostly shade-intolerant perennial that is adapted for growth in various sites. Spreading dogbane is considered a mid-seral species but is typical in areas of sparse vegetation, particularly disturbed areas.

This species is known to colonize burn sites immediately after the fire through rhizomes. Fire top-kills the spreading dogbane, but with rhizomes extending depths greater than 25cm this plant can resprout within the first year following a severe burn (Groen 2005).

Mountain/Wild Hollyhock (Iliamna rivularis)

Mountain/Wild Hollyhock (*Iliamna rivularis*) is a shade-intolerant, perennial forb commonly associated with quaking aspen stands on mesic sites. This forb reproduces strictly by seed, which are stored in the soil, remain viable for long periods of time, and require heat for germination. Mountain hollyhock is an early successional species following a fire event but is quickly replaced by other vegetation that out-competes and overtops the hollyhock. Mountain hollyhock is not commonly found in pre-fire environments but is very abundant the first year post-fire alongside fireweed (*Chamerion angustifolium*); (Matthews 1993a).

Stinging Nettle (Urtica dioica)

Stinging Nettle (*Urtica dioica*) is a perennial, moderately shade-tolerant, rhizomatous forb common in moist sites along mountain slopes and in disturbed areas. This species propagates by seed and vegetatively. Following a fire event the species typically regenerates from rhizomes. Stinging nettle thrives on disturbance and is typically an early successor in post-fire environments. However, it is outcompeted by many grasses and other groundcover species so that its abundance is low (Carey 1995).

Heartleaf Arnica (Arnica cordifolia)

Heartleaf Arnica (*Arnica cordifolia*) is a perennial herb that is typically dominant among groundcover plants and is accustomed to growing in exposed, moderately dry mineral soils (Reed 1993). Heartleaf arnica is abundant in lodgepole pine forests (Shaw and On 1979). This species can regenerate by wind-dispersed seeds or resprout from rhizomes. However, the rhizomes do not extend deep into the soil (approximately 1-2cm), so they will most likely be destroyed in an intense fire event (Reed 1993). Heartleaf arnica is an early successor and is known to be abundant throughout a burned area two years following the disturbance event (Reed 1993).

Narrow-leaf Collomia (Collomia linearis)

Narrow-leaf Collomia (*Collomia linearis*) is an annual forb that typically regenerates by seed (Lesica 2012). This species is commonly found in lower to middle elevation dry sites, particularly recently disturbed areas as the plant flourishes in the newly established open canopy (Shaw and On 1979; Lesica 2012).

Silky Lupine (Lupinus sericeus)

Silky Lupine (*Lupinus sericeus*) is a perennial forb found in a range of habitats, but in particular aspen and conifer forests. Silky lupine can be found growing in shade, but grows best in sunlight and with lower competition from other vegetation. Although it has a deep root system, it is not rhizomatous and, thus, resprouts from the caudex and by seed. It is typically found as part of the initial community post fire (Matthews 1993b).

Greene-Mountain Ash (Sorbus scopulina)

Greene-Mountain Ash (*Sorbus scopulina*) is a moderately shade-tolerant shrub species best adapted to well-drained soils of open conifer forests. It is an early- to mid-successional species that propagates by seed or vegetatively (MacKinnon et al. 2004).

2.2 Landscape Ecology and Disturbance

Landscape ecology attempts to describe the relationships between landscape structure and ecological processes, emphasizing spatial relationships as well as the causes and consequences of spatial heterogeneity (Turner et al. 2001). Resulting form of the ecological landscapes are a product of many factors including climate, topography, past land use, natural disturbance, and succession.

Disturbance is recognized as a driver of landscape heterogeneity and is important to maintaining healthy ecosystems. A disturbance is “any relatively discrete event in time that disrupts an ecosystem, community, or population and changes resource availability or the physical environment” (White and Pickett 1985). While disturbance is a driver of spatial heterogeneity in the landscape, it is also a response to that spatial heterogeneity (Turner et al. 2002). Disturbance events function in a heterogeneous manner where frequency, severity, and type of disturbance are influenced by physical properties, such as geology and climate, and vegetation (Turner 1989).

Landforms vary from flat plains to rolling plains, low mountains to high mountains and are characterized by elevation, aspect, and slope (Turner et al. 2001). Particular landforms affect the frequency and spatial pattern of natural disturbances such as fire (Swanson et al. 1988). Topography can influence the susceptibility of an area to disturbance. For instance, landform features such as major ridges and valley bottoms serve as barriers to the passage of fire in the forested areas around Mount Rainier (Swanson et al. 1988). However, in extreme events, such as the 1988 Yellowstone National Park high-intensity crown fires, topographic characteristics have little influence on the susceptibility of sites to disturbance (Turner et al. 2001).

When a disturbance occurs in a landscape, it does not act uniformly throughout. Disturbances create a heterogeneous pattern across the landscape where some areas are affected while others may not be affected by the event. Further, the severity of the disturbance varies within the affected area (Turner et al. 2001). The spatial pattern imposed by a disturbance event creates a mosaic of patches across the landscape and will structure the vegetation age and species composition of that landscape until the next disturbance (Turner et al. 2001).

2.3 Fire

Fire is an important natural disturbance agent, which plays a significant role in vegetative succession and landscape structure. Fuel, oxygen, and heat are the three requirements for fire if combustion is to be maintained (Schwanke 1998). Together these three factors result in a dynamic process that varies over time and throughout landscapes. Additionally, spatial and temporal variations in weather and climate, lightning, fuel type, and topography further influence regional, landscape-scale, and local variation in fire occurrence and behavior (Baker 2009).

2.3.1 Weather and Climate

Fire behavior is most influenced by climate and weather conditions including drought, high temperatures, strong winds, unstable air, low precipitation, high humidity, and fuel moisture. During dry seasons, such as a drought, a higher percentage of the forest canopy is expected to burn or be consumed, whereas, during wet seasons, less of the canopy and fewer belowground plant parts are consumed (Brown and Smith 2000). As periods of drought lengthen, moisture in fuels decrease and they become more combustible. Fuel continuity, or the connectedness of fuels, also increases with longer drought seasons allowing for more intense and larger fires (Turner et al. 1994). Fuel and soil moisture influence heat flow of a fire as seasonal fluctuations in temperature and precipitation can cause considerable variations in fire behavior and effects (DiBiase 2014). Increases in severity and length of drought conditions may be conducive for fires with higher fuel consumption and greater intensity and severity (Agee 1993).

Wind is a strong agent to spread fire. It forces oxygen into fuel beds and changes flame angles to preheat downwind fuels (Rothermel 1991). In simulation studies of wind and intense fire propagation, Linn et al. (2013) demonstrated that most fuel loads are not sufficient to carry fire throughout the landscape in the absence of wind and, thus, fire must move from tree to tree in order to spread. Under high wind conditions, much like those common to WLNP, the spread of fire is enhanced. The potential for large fires increases as the frequency of high winds increase as well (Rothermel 1991; Linn et al. 2013). Further, in decreased moisture conditions, the amount of energy needed to ignite a fire is greatly reduced and fire spread is increased (Linn et al. 2013).

Lightning and Ignition

Lightning strikes are common in montane environments and vary geographically in the Rocky Mountains. Flash density (the number of flashes per square kilometer and per year) in North America is, on average, less than three flashes per square kilometer, but increases with elevation (Reap 1986; Huffines and Orville 1999). A spatial analysis of lightning strikes in Alberta has shown the importance of topography, where a high frequency of strikes occurs in western Alberta, particularly near the Edson-Rocky Mountains corridor and the northern Continental Divide (Kozak 1998). Within WLNP, however, lightning ignitions are more rare. According to the fire atlas period (post-1900), lightning ignitions averaged one every 6-7 years (Barrett 1996). The changing global climate will have an effect on thunderstorm patterns, the frequency and length of droughts, and the length of fire seasons, which is expected to cause an increase in the frequency of lightning-caused fires (Price and Rind 1994).

As the topography and landscape changes, particularly in a montane environment where there are drastic elevation changes, the conditions, including slope and aspect, of the area change as well. Different elevations have varying moisture conditions that support some vegetation types over others. This difference in moisture results in dry areas that favor xeric vegetation prone to ignition. Particularly in subalpine forests, fuel loadings are high and the majority of ignitions are in snags, duff, and down wood (Latham and Schlieter 1989). The combined effects of topography, vegetation, and elevation impact the average spatial distribution of lightning (Kozak 1998).

2.3.2 Fuels

Topographic features influence the spatial arrangement of fuels on the landscape and can also influence initial ignition and resultant burn patterns (Turner and Romme 1994). In the Rocky Mountains, fuels are characterized by spatial heterogeneity and variability, not uniform buildup. Fuels are both live and dead vegetation that contribute to combustion (Brown and Smith 2000). The physical properties (e.g. heat content, loadings, packing ratio, time-lag fuel moisture classes) of fuels affect the intensity and rate of fire spread (Burgan and Rothermel 1984; Whelan 1995; Baker 2009).

Fuel load, or loadings, is the mass of a particular fuel per unit area and denotes the potential energy available per unit area from combustion (Baker 2009). This increases over time with tree mortality and the accumulation of biomass as plant communities age through their pathways of succession. Stand development, succession, both natural and human disturbance, disease, parasitism, and decomposition are processes that can change fuels and contribute to flammability in landscapes (Brown and See 1981; Romme 1982; Lundquist 1995). These processes may interact and vary with the environment in which they occur, contributing to the spatial and temporal heterogeneity in fuels and to the overall mosaic landscape (Forman 1995; Turner et al. 2001).

A lightning strike creates a shock wave that disturbs and splinters fuels and volatizes flammable extractives, such as terpenes, which allows for rapid ignition (Taylor 1974). This can then produce a fireball, or “flare-up”, at the base of trees. Forests, particularly the rotten wood found throughout, are among the most easily ignitable fuels (Keane 2008).

Not all fuels build up after disturbances in a predictable fashion. Disturbances can produce dead fuels, consume fuels, break up fuels, and change the properties and locations of fuels (Brown and See 1981; Keane 2008). In Rocky Mountain forests, large fuels do not build up consistently due to legacies from the pre-fire environment as well as other processes, such as low-severity fire or self-thinning, that reduce and change fuels regardless of stand-age (Romme 1982). Mature down wood can be a prominent legacy in young post-fire forests (Brown et al. 1998). However, if young stands burn or the fire consumes much of the wood, then down wood is a small legacy with little influence on the post-fire plant composition (Brown et al. 1998). Fine dead fuels from needles, leaves, and twigs build up following fire events until tree canopies close wherein fuels decline and decompose as stands age (Brown and See 1981). Fuel buildup depends on the amount of time between successive burns. If time between burns is relatively short, there may be less fuel accumulation (Brown and See 1981; Brown and Smith 2000).

2.3.3 Topography

Although climate and weather are the primary drivers of fire behavior, topography also plays a role by aiding or hindering fire progression (Keane et al. 1996). Topographic factors such as aspect, slope, elevation, shape of the area, and barriers are important elements affecting the start and direction of fire spread. Slope is the degree of incline of a mountainside. The steeper the slope, the faster fire travels up slope. Steeper slopes result in a generally drier environment compared to shallower slopes due to high runoff (Ryan 1976). Steeper slopes may also have more rapid fire spread and larger fires because of increased direct flame contact and enhanced forward heat transfer, where fuel further up the mountainside is preheated by the smoke and rising heat (Barrows 1951; Ryan 1976; Schneider and Breedlove n.d.).

Fires are also heavily influenced by ambient winds, which travel up the mountainside. Terrain features can channel and increase wind speeds as well as fire spread or create eddies; up-canyon winds can increase fire intensity and narrow passages can increase wind speed and fire spread (Goens 1990; Thomas 1991; Prevedel 2007; Linn et al. 2013).

Aspect refers to the exposure of the slope to the sun. The amount of solar heat a slope receives results in differences in soil moisture and vegetation conditions. South- and southwest-facing slopes in the Northern Hemisphere receive more sunlight, whereas northern-facing slopes receive the least amount of sunlight (Schneider and Breedlove n.d.). Thus, fire tends to be more prevalent on south- and south-west facing slopes due to differing microclimate conditions related to incident solar heat. However, it has been shown that aspect-related affects on fire behavior are sometimes existent and sometimes not. Baker and Kipfmueller (2001) demonstrated that fire rotation did not vary between aspects in the southern Rocky Mountains, while Howe and Baker (2003) showed that there is a stronger relation of fire behavior to aspect at lower elevations.

Elevation is the height above sea level of an area and affects both the amount of fuel available and the condition of the fuel. As elevations increase, air temperature declines, precipitation and humidity increase, and fuel loadings increase (Ryan 1976). However, steep slopes at high elevations may be well drained and more susceptible to drier conditions, which contributes to rapid fire spread (Barrows 1951; Berg et al. 2007).

Canyons, ridges, saddles, and bowls influence wind and weather throughout the area and can determine the direction and rate of fire spread (Schneider and Breedlove n.d.). Natural and man-made barriers, called firebreaks, may obstruct fire movement. These barriers can include lakes, rock formations, roads, reservoirs, and sometimes even fuel with high moisture content that prevent burning (Schneider and Breedlove n.d.; Baker 2009). Fire breaks can limit fire spread as well as decrease the size of large fires that lead to homogeneity across the landscape (Baker 2003).

2.3.4 Fire Behavior

Fire intensity, severity, and frequency are most useful in assessing ecological impacts on a disturbed area (Turner et al. 2001). Fire intensity refers to the rate of energy release, or the rate at which the fire produces heat (Keeley et al. 2009). Fire severity relates to the immediate effects of the fire resulting from the intensity of the burn and the heat released during fuel consumption (Key and Benson 2006). Fire severity is classified as nonlethal or low, mixed, or stand-replacement or high (Barrett 2004). Fire frequency refers to the number of occurrences of fire with a particular time period. Intensity, severity, and frequency are interrelated: for instance, less severe and less intense fires occur in areas that experience burns more frequently (Keeley et al. 2009). These variables are also used to categorize fire regimes as understory, mixed, or stand-replacing regimes (Barrett and Arno 1991; Morgan et al. 1996; Smith 1998).

As a fire moves across a landscape its behavior and effects can change based on variable stand structure, fuels, topography, as well as changing weather (Brown and Smith 2000). The ecological effects of fire are influenced strongly by physical aspects of fire behavior such as fire spread, fireline intensity, crown fire initiation and spread, spotting, and glowing combustion (Baker 2009).

2.3.4.1 Crown Fire

Crown fires, much like the 1998 Sofa Mountain fire, result from interactions between weather, fuel source, vegetation, and topography. A crown fire advances from treetop to treetop and acts independently of the ground fire, creating a patch mosaic of vegetation succession (Turner and Romme 1994). It is atypical for a large crown fire to consume entire forests. The resulting pattern throughout the landscape consists of heterogeneous age stands from successive burn patterns and islands of unburned vegetation within the most recent burn area (Turner and Romme 1994). Areas of unburned vegetation and tree stands that remain after a fire event provide a seed source for new growth (Turner and Romme 1994).

2.4 Fire Regimes

Fire history and fire regimes are useful in establishing a baseline reference for natural ecosystem functions, monitoring, management, and fire planning activities. Fire regime refers to the pattern, frequency, intensity, and prominent immediate effects of fire occurring over long periods of time (Baker 1992; Schoennagel et al. 2003). Fire in the Rocky Mountains is understood as a landscape phenomenon predominantly shaped by vegetation that varies spatially and temporally across a landscape as conditions, which include elevation, moisture, species composition, and landforms, change (Keane et al. 2003).

The concept of fire regimes was developed to classify the historical impacts of fire on an ecosystem (Schoennagel et al. 2003). Historically, fire regimes have been classified by mean fire interval and fire severity. However, the classification of fire regimes varies, much like the fire regimes themselves, as subjectivity is expected. A common list of classifications used to describe fire regimes was compiled by Kilgore (1987): fire frequency, fire periodicity, fire intensity, size of fire, pattern of fire on the landscape, season of burn, and depth of burn. Baker (2009) simplified the classification of fire regimes in the Rocky Mountains to include fire rotation (short, medium, or long), rate of recovery (the percentage needed to recover prefire composition and structure), and pattern of topkill (e.g. complete death of aboveground biomass). Baker found only eight combinations of fire rotations throughout the Rocky Mountains and determined that a short-rotation (50-200 years), variable severity, slow-recovery (40 percent or more needed to recover) regime occurs in mixed conifer and lodgepole pine forests like those on Sofa Mountain (2009). Overall, though, the classification and description of fire regimes is typically very general because of the variability of fire as it is shaped by interactions among vegetation, topography, and climate (Keane et al. 2003; Baker 2009).

2.4.1 Fire History of WLNP

Limited research has been conducted on the fire history and fire regimes throughout the northern Rocky Mountain Front (southwestern Alberta and north-central Montana). Stephen W. Barrett (1996) completed one of the first and most extensive, multi-year fire history and management studies for WLNP that was important in establishing a reference baseline for ecosystem function and also provides information for future monitoring and management. A total of 119 fire scar samples were recorded throughout this study.

A fire scar forms on a tree when a fire raises the temperature of the cambium (a layer of meristematic tissue between the inner bark and the outer wood) to a lethal level (>60 °C) or consumes the bark, cambium, or inner bark (McBride 1983). Most young trees (<10 years) typically do not survive fire and, thus, have an absence of fire scarring. However, mature trees, especially those beyond 80 years have sufficient bark to insulate the cambium (McBride 1983). As the tree heals, a callus is formed that is eventually covered with new cambium and bark and can then be identified when taking a tree-core sample (McBride 1983). Douglas-fir trees found scattered throughout the park occasionally had as many as three to four fire scars while some lodgepole pine were single-scarred (Barrett 1996). Due to the limited number and locations of these fire-scarred trees, it is most likely that stand-replacement had been the fire severity pattern in recent centuries (Barrett 1996). In support of this interpretation, a stand-origin map shows almost 97 percent of fire-initiated stands as one age (Heinselman 1973). However, it was noted that some valley-bottom benches and upper timberlines contained some multi-age stands and alpine larch, which can exceed ages of 1000 years (Agee 1993; Barrett 1996). This suggests that mixed-severity fires also occurred throughout the area.

Barrett determined that about 46 fires occurred between 1633 and 1940 when the last significant fire, which burned 32 hectares, occurred in WLNP (1996). This yields a mean fire interval (MFI) of about seven years (Barrett 1996). Fire frequency declined during the Little Ice Age (Barrett 1996; Luckman 2000). However, the sustained warming trend following the Little Ice Age, saw fire frequency increase in the mid- to late-1800s and into the 1900s (Barrett 1996). Fire frequency remained high throughout the 1900s with at least 18 fires occurring in the park between 1900 and 1940, resulting in an MFI of 2 years for this time period (Barrett 1996).

Formal efforts to suppress fire throughout WLNP began in 1895 but were unsuccessful (Barrett 1996). By 1940, fire frequency declined drastically throughout much of the Northern Rockies, including WLNP, due to new and widespread federally initiated suppression efforts and made for the longest fire interval in the history of the park successfully interrupting the natural fire cycle of the park (Barrett 1996). During this time, the park experienced several severe single-year droughts (Barrett 1996; Luckman 2000). Barrett's analysis of data from the fire atlas also supports findings that fire suppression programs of this time successfully interrupted the fire cycle of the area. About 65 fires have occurred in WLNP since 1910: 91 percent were extinguished during their initial stages and the rest before any significant amount of terrain could be burned (Barrett 1996).

Barrett determined that stand-replacing fires were the predominant regime throughout the park with occurrences of mixed-severity fires. Some suppressed fires during the mid- to late-1900s would have certainly become major stand-replacing fires and created a more heterogeneous landscape had suppression not been enforced (Barrett 1996). However, given the more uniform stand-age throughout the park, disturbances such as droughts, insect epidemics, and pathogen infections may lead to major stand-replacing fires in the future.

Compared to historic burns, the 1998 Sofa Mountain fire burned a significant area. According to a GIS 'WLNP fire history' map and shapefile provided by Parks

Canada, approximately 177 historic fires overlapped the 1521 ha burn area of the 1998 fire. The fire history of WLNP is not very robust and most records are missing dates or time periods for when the fires may have occurred. This map, however, aids in understanding the historic nature of fire in this area. The seven largest fires throughout the Sofa Mountain area (highlighted in red; Figure 2.3) burned between 30 and 96 ha, a significantly smaller area than the 1998 fire. Three of the seven fires occurred between 1869-1874 and, while the years of the remaining fires are unknown, it is assumed that they are in keeping with the fire cycle of the area.

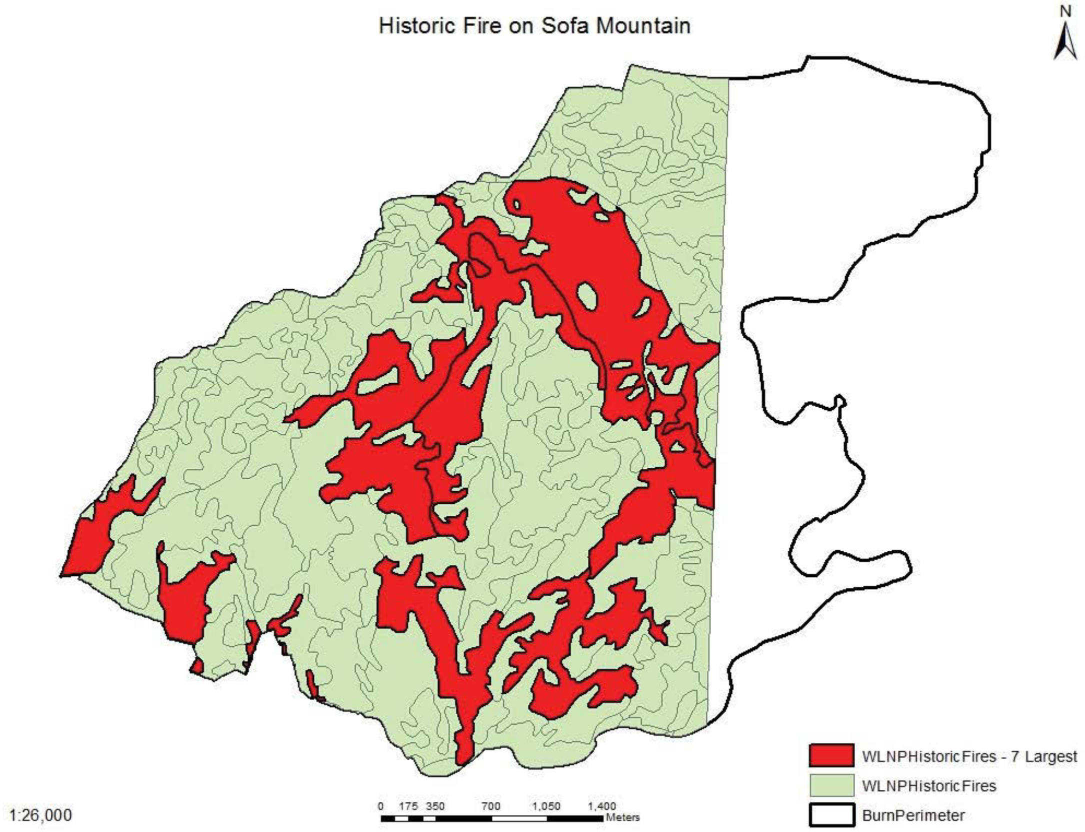

Figure 2.3 - The 177 fires overlapping the Sofa Mountain 1998 burn area. The seven largest fires likely occurring between the years 1869-1874 are highlighted in red. Note: the portion of the shapefile with no data is the Blood Indian Reserve where no data was available. (Parks Canada).

2.5 Autecology and Succession

Fire is an important ecological process in creating a heterogeneous, diverse landscape. Autecology studies the relationship between an individual and its environment while succession is the complex process by which vegetation recovers from disturbance, such as fire, or colonizes newly exposed land (Miller 2000). Both of these concepts are essential to understanding post-fire recovery of an area.

2.5.1 Fire Autecology

Understanding the initial response of a species to fire is essential to the maintenance of a fire-prone landscape, but also necessary in evaluating the adaptability of vegetative assemblages, successional pathways, and ecosystem recovery dynamics. The susceptibility of plants to fire and subsequent recovery vary depending on specific species' characteristics (Miller 2000).

Plant mortality is typical when a fire has injured several parts of the plant (e.g. crown damage and meristematic tissue damage). Tissue damage is attributed primarily to the amount and length of heat that the plant receives, but plants can be protected by structures such as the bark or bud scales (Pausas and Lavorel 2003). Fire resistance is, rather intuitively, highly correlated to bark thickness, where, thick bark insulates and protects tree cambium better than thin bark (Ryan and Reinhardt 1988). Gutsell and Johnson (1996) determined that tissue damage due to fire is a linear function of bark thickness; small increases in bark thickness increase resistance of a species to fire. Branch density is important in predicting likely ignition of a tree species. For example, those species that self-prune lower branches are less likely to experience a crown fire

(Dietrich 1979). Many species require bud survival for plant survival, and bud size as well as needle length are indicative of potential for bud survival and overall susceptibility. Buds are growing points for most tree species and protected by bud scales. Small buds are more susceptible to heat, while large buds tend to be more heat resistant (Miller 2000). Long needles provide initial protection for buds, whereas short needles leave the bud exposed. Table 2.0 displays the survival characteristics of species common in WLNP.

Table 2.0 - Fire survival characteristics of tree species common throughout WLNP. Adapted from Brown and Smith (2000).

Species	Basal Bark Thickness	Branch Density	Bud Size	Needle Length	Size When Fire Resistance Gained	Fire Resistance at Maturity
Lodgepole Pine	Very Thin	Low	Medium	Short	Mature	Medium
Engelmann Spruce	Thin	High	Medium	Medium	None	Low
Subalpine Fir	Very Thin	High	Medium	Medium	None	Very Low
Douglas fir	Thick	High	Medium	Medium	Pole	High
Quaking Aspen	Medium	--	--	--	Mature	Low/Med
Limber Pine	Medium	Medium	Medium	Medium	Mature	Medium
Whitebark Pine	Very Thin	Medium	Medium	Medium	Mature	Medium
White Spruce	Medium	High	Small	Short	Mature	Medium
Black Cottonwood	Medium	--	--	--	Mature	Low/Med

A species' overall resistance to fire increases with age (Miller 2000). However, if fire suppression is practiced, fire resistance characteristics may be developed much more slowly (Miller 2000).

2.5.2 Fire Succession

Classical successional theory proposes that when mature stands are severely disturbed, early successional species will replace late successional species (McKenzie and Tinker 2012). Succession is also known to vary across space, particularly as a function of reproductive sources (Cook et al. 2005). Disturbance creates an ever-changing vegetation pattern on the landscape. Fire disturbance produces patches of varying burn severities that effect the successional patterns of trees and rates of regrowth, which vary, in part, on proximity to seed source and quality of site (Donnegan and Rebertus 1999). Surviving individuals, standing dead trees, seedbanks, and other biotic structures that remain after a disturbance event are referred to as legacies or residuals and their spatial distribution is of particular importance as they influence the composition of the recovering plant community (Turner and Dale 1998; Turner et al. 2001; Figure 2.4). Islands of unburned vegetation, or mature tree stands that remain after a fire has passed through the landscape, provide a seed source post fire. By consuming litter layers and exposing the minerals and organic materials in the soil, fire helps create a suitable environment for seed germination and seedling establishment (Turner et al. 2003). Fire also kills trees and surface plants such as forbs and graminoids minimizing competition immediately following a fire event (Turner et al. 2003).

Post-fire succession is reminiscent of the pre-fire environment as plants that existed at the surface or in the seedbed at the time of the fire event are typically early successors in a post-fire environment (Clark 1991). Vascular plants comprising a post-fire recovering system survived the fire and are growing from basal portions after their aboveground portion was killed or have emerged from seed (Ingersoll and Wilson 1990).

Figure 2.4 – Patchwork composition of succession on Sofa Mountain, composed of mature tree stands, emerging vegetation, and snags of dead trees. Image provided by Dr. Dawna Cerney.

The seedbank refers to all the viable seeds present at a site; seeds in the soil and litter layer as well as those in the canopy (Clark 1991). Resprouters are species that have the ability to resprout from surviving rootstocks as well as seeds, while reseeders are killed by the fire and regenerate from seed in the soil, canopy, or outside the disturbed area (McKenzie and Tinker 2012). Resprouters can have an early recruitment advantage over reseeders because of reserves of rootstocks and deep root systems, which allow for increased water and nutrient uptake (McKenzie and Tinker 2012). A mature conifer forest is comprised of shade-intolerant, early seral species with seeds capable of surviving for long periods of time in the litter layer and soil. Shade-tolerant and large seeded species' seeds tend not reside in these litter and soil layers for long periods of time (Pickett and McDonald 1989; Brown and Smith 2000). Seeds stored in the canopy, such as the seeds of lodgepole pine (*Pinus contorta*), retain their seeds in serotinous cones that remain closed for many years until temperatures of at least 45-50°C (113-122°F) melt the cone's resin, releasing the seed to the newly exposed soil and organic material on the forest floor (Lotan 1976; Fraver 1992; Kaufmann et al. 2008). Amount of serotiny varies within a species. Various studies (Lotan 1976; Tinker et al. 1994; Koch 1996) have noted that the proportion of lodgepole pine trees bearing serotinous cones varies across the Rocky Mountain region and that stand-level proportions of serotiny also vary with stand age. However, a high degree of serotiny is likely to occur where there are stand-replacing fires and higher burn severities (Ellis et al. 1994; Schoennagel et al. 2003).

Seedlings are categorized as either seed dispersed from living plants, seed from off-site plants, and seeds from within the seedbank (Baker 2009). The succession and reestablishment of many montane trees species are reliant on those unburned stands to provide a seed source. The rate of reestablishment of some locations will be influenced by the distance to the nearest unburned forest patch (Turner and Romme 1994). In a study of fire severity and seed source influence of lodegepole pine in Lassen Volcanic National Park, it was observed that trees that survived the fire provided an abundant seed source for new growth and that distance to the nearest cone-bearing lodgepole pine tree was significant (Pierce and Taylor 2011). Fire severity and plants' characteristics determine successional pathways following a burn event and many tree species respond to fire differently. Jenkins et al. (1998) suggests post-fire successional pathways that are species specific. For instance, if present, quaking aspen (*Populus tremuloides*) colonizes after a fire event because of its ability to resprout (Jenkins et al. 2008). As aspen stands mature, Engelmann spruce (*Picea engelmanii*) grows and matures in the shaded understory, eventually towering over the aspen, dominating the stand (Jenkins et al. 1998). Tomback et al. (2001) observed that Whitebark pine (*Pinus albicaulis*) and Engelmann spruce (*Picea engelmanii*) have the potential to be among the first colonizers after a burn event in the absence of aspen and lack of lodgepole pine seed sources (Jenkins et al. 2008). Whitebark pine and Engelmann spruce, however, might be delayed until environmental conditions such as soil moisture needs are met (Tomback et al. 2001). Lodgepole pine tends to dominate early successional stages following a fire (Figure 2.5), but maturation is coupled with competition from other tree species, which thins out the lodgepole pine (Kaufmann et al. 2008). The lodgepole pine pathway quickly colonizes a burned site but once seedling competition produces die off, Engelmann spruce emerges beneath lodgepole pine (Jenkins et al. 2008).

Figure 2.5 – Lodgepole pine seedlings on Sofa Mountain. Image provided by Dr. Dawna Cerney.

Nyland (1998) observed the regrowth following the 1988 fires in Yellowstone National Park and hypothesized four patterns and pathways of lodgepole pine regeneration following a fire that may be applicable in other post-fire environments: 1) a dense, uniformly distributed cohort that develops as a single-storied stand (stands with a single canopy layer), 2) islands that form around isolated seedlings, 3) a moderate or low density cohort that fills with varied age classes, and 4) a cohort of widely scattered single seedlings that form as small tree islands and may eventually converge to a more continuous stand with various age classes. The dense, single cohort pathway is most common where there was an abundance of serotinous cones in the pre-fire environment. In stands destroyed by fire having no or very little serotinous cones, regrowth will follow one or a combination of the three alternative pathways (Nyland 1998).

2.5.3 Microtopography and Islands of Unburned Vegetation

As fire does not move uniformly throughout an area, it's creates non-steady-state mosaics in which large portions of the vegetation across the landscape are in the same successional stage (Chapin et al. 2011). These mosaics are strongly influenced by topographic characteristics, which produce islands of unburned vegetation that act as seed sources and provide protection for new and emerging vegetation (Turner and Dale 1998; Nyland 1998; Turner et al. 2001).

Microtopography site conditions can significantly influence tree establishment patterns as certain features act as seed and nutrient trap, protection, and hold moisture (Shankman and Daly 1988; Stueve et al. 2009; Cerney 2014). The microtopography at the alpine treeline has been discussed and noted in several studies (Butler et al. 2004;

Bekker 2005; Resler et al. 2005). Resler et al. (2005), for instance, establish the importance of features, such boulders and terrace treads, in shaping the spatial nature of alpine treelines. These features allow for site conditions (e.g. moist soils, lower temperatures, protection from the elements) conducive to seedling maturation and plant survival (Resler 2006).

Various studies illustrate the importance of site conditions: Stueve et al. (2009) demonstrated the topographic variability produced sites favorable to upslope migration of trees; Shankman and Daly (1988) exhibited that topographically sheltered sites showed high rates of reestablishment after fire; Agee and Smith (1984) illustrate that high rates of tree establishment is greatest in proximity to surviving tree stands and a lack of deep snow cover.

2.6 Digital Analysis Using GIS and Remote Sensing

Analyzing ecological processes and management practices at broad spatial scales is becoming a necessity in creating adaptive management plans. Until the advent of digital analysis systems, addressing spatial issues, including the pattern and process at these spatial scales, was often clumsy and time-intensive as well as limited to static representations (Gergel and Turner 2002). However, digital analysis techniques more readily allow the assessment of large areas and exploration of long-term consequences of management decisions (Gergel and Turner 2002). Geographic Information Systems (GIS) and remote sensing can be used together to analyze and gather information over various spatial and temporal scales.

2.6.1 GIS

GIS allows for computer-based analysis, manipulation, visualization, and retrieval of location-based data (Jensen 2005; Weng 2012). GIS can, and should, also be used to enhance the functions of remote sensing image processing; remote sensing information is analyzed and interpreted best in conjunction with other supplementary data typically stored in a GIS (Jensen 2005). Landscape ecology, forest policy, and environmental analysis have been altered dramatically with the use of GIS, as access and manipulation of large ecological data sets allows for the exploration of long-term effects of decisions and management plans (Gergel and Turner 2002).

GIS is useful to the field of landscape ecology in varying means and can help in mapping land cover and vegetation of a disturbed area, potential areas for new growth post-disturbance, determine susceptibility to other disturbances, and to develop and decide management practices. In mountain regions prone to forest fires, understanding vegetation response to disturbance on complex topography is important. In a post-fire environment, the burn area and vegetative response to fire can be mapped, investigated, and analyzed. The role topography plays in an ecosystem recovery can be analyzed; slope, aspect, elevation, as well as other topographic factors can be evaluated to help determine why a fire moved through the area as it did as well as determine where new growth may or may not occur as well as help determine fire behavior through an area.

Many studies illustrate the usefulness of GIS analysis in post-fire studies. Examples include: Stueve et al.'s (2009) utilization of GIS to explain landscape-scale patterns of establishment at a disturbed treeline; Lentile et al.'s (2007) assessment of vegetation response to varying burn severities following eight large wildfires; Bebi et al.'s (2003) employment of GIS modeling to assess the susceptibility of young post-fire stands to spruce beetle outbreaks as well as the susceptibility of forests to subsequent fires following beetle outbreaks. GIS is a powerful tool that has effectively allowed for the assessment of post-fire reestablishment and predictive modeling.

2.6.2 Remote Sensing

Remote sensing is the collection of data remotely, typically through the use of sensors onboard aircraft and satellites (Jensen 2005; Weng 2012). The output of a remote sensing system is an image that can be either analog (aerial photographs) or digital (satellite images) depending on the system used. Analog images were not used in this study and, thus, will not be discussed.

Electromagnetic radiation that reaches the Earth interacts with features on the Earth's surface where a portion of the energy is reflected, transmitted, or absorbed and then re-emitted as emittance (Weng 2012). Remote sensing systems detect and record this emittance. Because no two materials have the same reflectance, transmission, or absorption varies, they can be separated by their spectral signatures. This imaging technique is particularly useful in observing vegetation cover conditions and monitoring changes over large landscapes.

Sensors can detect a wider range of wavelengths (from ultraviolet to microwave), which are electronically recorded as a digital value for each pixel associated with a specific location on the Earth's surface (Jensen 2005; Weng 2012). The digital number is the intensity of a given wavelength of radiation reflected from the ground at that specific location (Jensen 2005; Weng 2012). Coarse spatial resolution, atmospheric conditions, limited availability as well as differences in spectral, radiometric, and temporal resolution, often limit the effectiveness of these images.

Aerial images are obtained using cameras mounted to an aircraft and can capture an instantaneous image of the area. Aerial photos normally record the ultraviolet to visible and near-infrared wavelength spectrum (Weng 2012). Aerial images are advantageous in that they provide views of large areas and can be used to extract thematic and metric information. Interpretation of aerial photographs refers to examining these images in order to identify objects and judge their significance (Weng 2012). There are seven commonly used elements when interpreting an aerial image or a photograph: tone/color, which refers to the distinguishable variations on an image and is a record of light reflectance; size, which is a function of scale and is useful when assessing objects relative to on another; shape can be used to separate man-made features from natural features; texture refers to the frequency of change and arrangement in tones, or the smoothness and roughness of an area; pattern, which is the spatial arrangement of objects; shadow relates to the shape and size of an object and be used in determining the heights of objects; and association, which takes into account the relationship between other recognizable features in proximity to the target of interest (Weng 2012).

2.7 Previous Analysis of the Sofa Mountain Fire

This project utilizes and expands upon the work completed by Dan Buckler. His 2011 analysis of species composition on Sofa Mountain (2012) was used in characterizing mature tree stand and new growth polygons and to create a more specific analysis of the vegetation, allowing assessment of the spatial occupation of mature tree polygons throughout the burn area.

The U.S. Geological Survey-National Park Service Vegetation Mapping Program classified vegetation across the entire Waterton-Glacier International Peace Park (WGMAP). The program, however, classified Sofa Mountain as simply “mixed regenerative shrubland”. Buckler (2012) analyzed species composition on Sofa Mountain to accurately reflect the heterogeneity of the successional landscape. Unsupervised classifications were run on Landsat images 1995, 1999, and 2010, representing the periods before, directly following, and a decade after the fire, were used to select field site. Five spectral classes were consistently identified: conifer forests, mixed vegetation (deciduous trees and shrubbery), grasslands/agricultural lands, barren, and water/shadow (Buckler 2012). These reclassified images were combined to produce new pixel combinations that portrayed the vegetation changes over time (Buckler 2012; Buckler and Cerney 2012). Generic polygons and voids in the WGMAP were replaced and vegetation classifications were updated with newly constructed classifications. The new polygons were added to the existing vegetation map of the park and provided updated vegetation classifications and characteristics of the topography used in this study.

Methodology

3.0 Introduction

A mixed methods approach is employed in this study to evaluate and determine the location of mature tree stands throughout the Sofa Mountain burn area and to assess the topography and vegetative regrowth at these sites. Methods employed included fieldwork, GIS and remote sensing analysis, aerial imagery analysis, and statistical analyses.

3.1 Fieldwork

Fieldwork was conducted from June 17, 2014 – June 21, 2014. A flood that occurred on June 22, 2014 restricted access to the field site and evacuation from the park. As a result, little data was retieved. The ground truthing that was completed served as qualitative visual evidence of the volume of vegetation growth and nature of succession. The observations served as a reference for the digital analysis of the area.

Four mature stands were sampled during the shortened field season. The location, perimeter, and specific topography of the mature stands were noted as well as the species and vegetation characteristics of the area (see Appendix A for field notes). The burn area, overall, was difficult to navigate and nearly impassable due to the incredibly dense growth of aspen, lodgepole pine, and douglas fir in addition to downed logs being difficult to detect due to the volume of growth.

3.2 Data Acquisition and Delineation of an AOI

For this research, airborne and spaceborne remotely sensed imagery of WLNP was obtained and utilized. All images were analyzed in ArcGIS and ENVI and projected to the Universal Transverse Mercator North American Datum of 1983 (UTM NAD83) coordinate system where WLNP is located in UTM zone 12N.

Aerial images of the burn area on Sofa Mountain from the years 1998, 1999, and 2009 were obtained. These images have varying spectral resolutions: 3.6 meters for 1998, two images from 1999 with 67 centimeter and 96 centimeter resolutions, and 30 centimeters for 2009. The images were georeferenced, with the exception of the 2009 image that had existing spatial data associated with it, and projected to the UTM NAD83 coordinate system.

Landsat images were obtained from EarthExplorer and the Global Visualization Viewer (GloVis) provided by the USGS. Images selected have limited cloud cover (<10%) and taken during middle to late summer dates when there is full growth of vegetation, permitting for more accurate vegetation distinction. Anniversary date or near-anniversary date images were used to reduce the effect of phenological changes on a temporal scale throughout the area. Data was acquired from the years 1994, 1999, and 2011 from Landsat 5, which carried the Thematic Mapper (TM) sensor and produced images with a 30-meter spatial resolution. These images were selected to represent time periods before the 1998 Sofa Mountain fire, shortly after the fire, and a more recent time period that coincided with previously constructed GIS shapefiles and classifications that will be used in this research.

A SPOT satellite image from 2007 was obtained from GeoBase, a government initiative to provide geospatial data for Canada. The 2007 image obtained for this project has three bands with a 20-meter spatial resolution and a panchromatic band with a 10-meter spatial resolution. This image was orthorectified by merging the lower resolution (20m) multispectral and higher resolution (10m) panchromatic data, creating a single high-resolution image that was projected to the UTM NAD83 coordinate system. While this image is slightly outdated considering the dynamic growth and change of vegetation, it was useful as a reference image.

Elevation data was also obtained from GeoBase. These images were produced using Canadian Digital Elevation Data (CDED) at a scale of 1:250,000. Ground elevations are recorded in meters relative to Mean Sea Level (MSL) and based on the reference datum, NAD83.

As this project utilizes and expands upon work completed by Dan Buckler, his 2011 analysis of species composition on Sofa Mountain (2012) served as the reference layer for this project. Buckler's fieldwork and ground truthing allowed vegetation to be positively identified and his categorized polygons allowed assessment of the vegetation types and characterization of polygon layers of mature tree stands and new growth.

3.2.1 Area of Interest

The selection of an Area of Interest (AOI) reduces the chance of classification errors, such as pixel confusion. Limiting the area of analysis also allows for greater accuracy in locating mature tree stands. Landsat and SPOT images contain an immense amount of data to be analyzed and processed, and were narrowed to include only the burn area and a bordering perimeter. This project did not consider tree stands and vegetation outside the extent of the burn, but because the burn area is small, areas bordering the burn were included to keep the Landsat images from becoming warped once extracted within ENVI and ArcGIS. The burn area consists of 1521 hectares of land mostly within the park and was originally digitized by Buckler (2012) using a physical map and georeferenced aerial image from 1998.

3.3 Remote Sensing

3.3.1 Classification Analysis of Site Characteristics

Satellite images from the time period shortly after the fire were selected to initially analyze where vegetation remained across the landscape following the fire. This analysis would serve to find and delineate mature, unburned stands on aerial images and allow for an analysis of the regrowth on the mountain. A Landsat 5 image from July 1999 was acquired and cropped to an AOI. Both supervised and unsupervised classifications were conducted on this image.

A supervised classification was expected to be the best method for classifying the area as Buckler's 2011 field analysis (2012) together with field observations from the 2014 field season aided in the identification of vegetation. Training sites were created within ENVI and the classification was completed using the minimum distance classification method. This method was selected because of its computational simplicity while remaining comparable to other intensive computational algorithms. Due to the coarse nature of Landsat images, however, the risk of inaccurately classifying the area is increased. Thus, more general classes were used in classifying this initial image (Figure

3.0). The location of vegetation following the fire was more important at this stage, so this was an acceptable method. The classes were limited to seven: forest, grassland, shrubland, water, snow, burnt area, and barren.

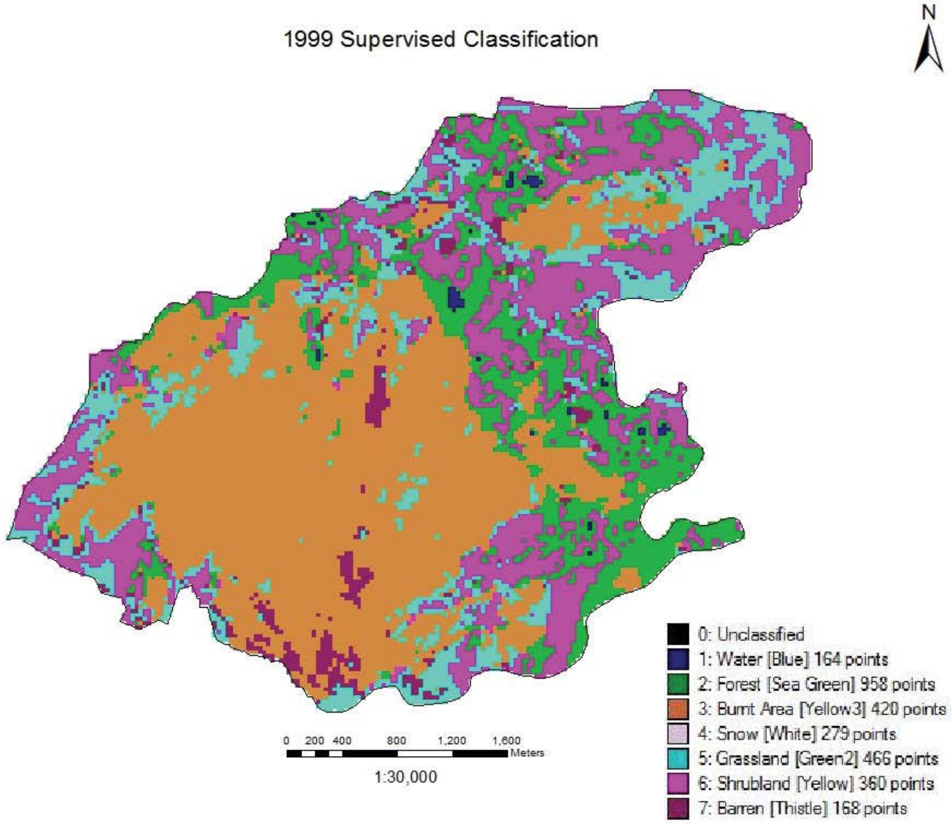

Figure 3.0 - Supervised classification on 1999 image -- one year following the fire.

An unsupervised classification was also executed on the 1999 Landsat image using the ISODATA (Iterative Self-Organizing Data Analysis Technique) method (Figure 3.1). This clustering method uses an algorithm that calculates class means evenly distributed and, then, iteratively groups the remaining pixels by a minimum distance technique; each iteration, or pass through the dataset, recalculates the mean and reclassifies pixels according to the new means (Jensen 2005). Fifteen clusters were produced at ten iterations with a minimum of seventy pixels. The clusters produced were: 1) water/shadow, 2) wet shrubland/herbaceous-conifer forest, 3) conifer forest, 4) conifer forest, 5) mixed forest, 6) shrubland, 7) shrubland/barren-poplar/birch, 8) wet shrubland-wet herbaceous, 9) grassland with shrubs-poplar/birch, 10) grassland herbaceous-poplar/birch, 11) grassland herbaceous, 12) grassland/barren, 13) burnt area, 14) cliff/talus-barren, and 15) snow. This unsupervised classification method proved to be more useful in determining where vegetation remained post-fire.

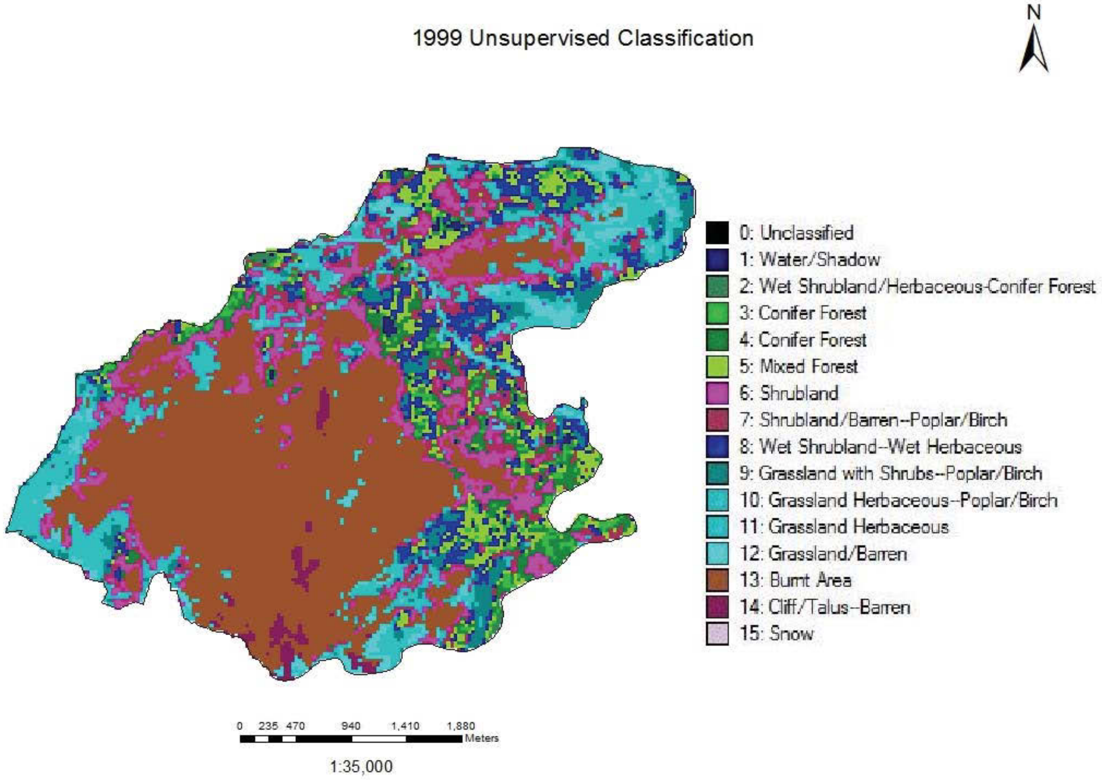

Figure 3.1 - Unsupervised classification on 1999 image -- one year following the fire.

Unsupervised classifications were also completed on Landsat 5 images from 2011 and Landsat 8 images from 2014 that better represented conditions from the field season.

These classifications were completed in the same fashion as the image from 1999 with ten iterations, fifteen clusters, and a minimum of seventy pixels.

3.3.2 Classification Accuracy Assessment

An accuracy assessment was performed to evaluate the accuracy of the classifications conducted. This accuracy assessment compared the results of the unsupervised classification to ground truth information. In ENVI, a confusion matrix was calculated to determine the overall accuracy of the classification, producer and user accuracies (i.e. computer classification vs. human classification), errors of commission and omission (i.e. pixels that are classified incorrectly), and the kappa coefficient (a measure of agreement between model predictions and reality). The accuracy assessment showed that the 1999 unsupervised classification was acceptable with an overall accuracy of 69.1% (Table 3.0).

Table 3.0 – Accuracy assessment of 1999 unsupervised classification.

1999 Accuracy Assessment		
Overall Accuracy = 69.0491%		
Kappa Coefficient = 0.6199		
	Accuracies	
Cover Class	**User (Percent)**	**Producer (Percent)**
Forest	100	74.47
Shrubland	53.47	41.56
Grassland	27.95	60.75
Snow	80.64	67.52
Burnt Area	95.95	99.8
Barren	69.78	83.82
Water	71.92	100

3.3.3 Band Ratio: NDVI

Brightness values from identical surface materials differ due to topographic slope and aspect, shadows, or seasonal changes in sunlight illumination angle and intensity (Jensen 2005). These conditions may hinder the interpreter or classification algorithms from correctly identifying features in a remotely sensed image. Band ratios are a form of spectral enhancement in which the reflectance value of pixels in one band is divided by another, was used to highlight subtle variations in spectral responses of various surface covers (Weng 2012). Normalized Difference Vegetation Index (NDVI) is a measure of healthy, green vegetation or vigor throughout the area and is calculated from the visible and near-infrared light reflected by vegetation. Healthy vegetation absorbs most visible light and reflects highly in the near-infrared wavelengths, whereas, unhealthy vegetation absorbs less visible light and reflects less energy (Jensen 2005). NDVI images were created with Landsat images from 1994, 1999, 2011, and 2014. These images aided in visualizing the regeneration of vegetation throughout the area over time. The band math expression is as follows:

$$\text{NDVI} = (\text{NIR} - \text{red})/(\text{NIR} + \text{red})$$

3.4 Generating New Polygons of Mature Trees and Associated New Growth

3.4.1 Aerial Images and DEM

Aerial images of the Sofa Mountain burn area from 1998, 1999, and 2009 were obtained and used in mapping the extent of the burn area as well as determining the locations of mature tree stands. These images are also useful in comparing the pre- and post-fire vegetative conditions of the site as well as assess the new growth throughout the area.

Georeferencing an image refers to aligning geographic data to a known coordinate system allowing viewing and analysis with other spatial data. This process assigns real-world coordinates associated with a location on the earth’s surface with each pixel in the raster. The images from 1998 and 1999 did not contain spatial reference information and were georeferenced using the 2009 image, which had existing spatial data associated with it. Selecting a minimum of five control points, the images were transformed using a first-order polynomial, which is a linear transformation. Ideally, control points will match the surface coordinates exactly, but this is rarely the case due to discrepancies between the two sets of coordinates. This root mean square error (RMSE) value represents the geometric distortion. The user specifies a threshold of total error acceptable. The United States Geological Survey (USGS) suggests an RMSE of 25 meters or less as the threshold. Due to the nature of this project and the need for accurate polygon digitizing, an average RMSE of less than 15 meters was accepted.

GeoBase elevation data was imported into ArcGIS as a digital elevation model (DEM). The DEM was extracted to include only the Sofa Mountain burn area. Topographic characteristics, slope and aspect, were derived using the Spatial Analyst tool in ArcGIS. Also derived utilizing the Spatial Analyst tool was the flow direction and flow accumulation of the area. This information was useful in visualizing the drainage patterns of the area and assessing the moisture conditions of particular locations throughout the burn site.

3.4.2 Digitizing Polygons

In order to delineate the spatial characteristics of mature tree stands and new vegetation growth on Sofa Mountain, two layers of new polygons were created within ArcGIS. One layer consists of mature, unburned tree stands while the second layer consists of new vegetation growth associated with those mature stands.

Aerial photographs from 1999 were used to determine the location of and digitize eighty stands of unburned vegetation. According to a GIS shapefile of the areas' fire history, this was the first significant burn on Sofa Mountain, allowing mature trees to be easily identifiable in the 1999 photograph. These stands were subjectively located and identified primarily based on color (green vs. burned, brown vegetation), shadow (to determine that the objects are indeed trees), and texture/pattern (full foliage and canopies with openings due to competition); (Weng 2012). It should also be noted that low elevation wetland areas in the northeast portion of the burn are known to have high moisture levels and, thus, high numbers of mature tree stands were expected. As such, few mature stands from this area were included in the analysis (Figure 3.2).

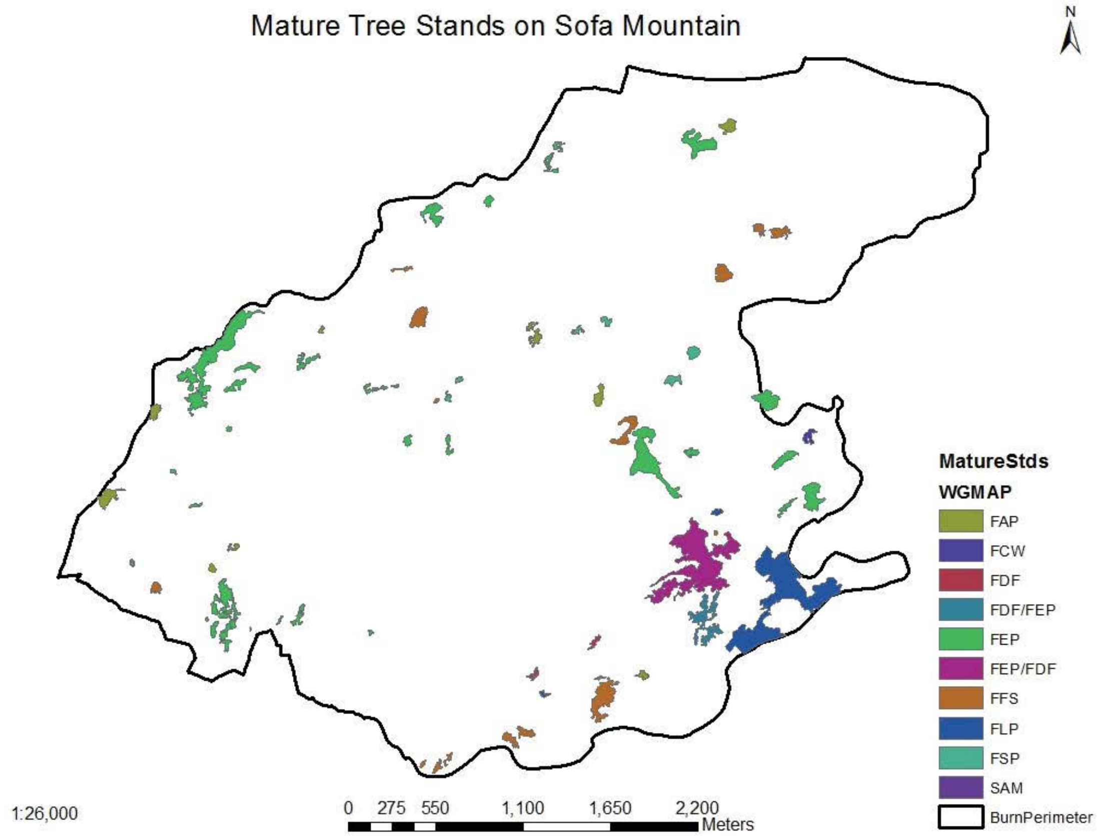

Figure 3.2 - Mature tree stands remaining post-fire color-coded by WGMAP codes. Mature tree WGMAP code listings and descriptions are as follows: FAP – poplar birch forest; FCW – black cottonwood forest; FDF – Douglas fir forest; FEP – mixed conifer-deciduous forest; FDF/FEP – a mix of FDF and FEP (mature stand overlapped two classification polygons in original analysis); FFS – subalpine fir-Engelmann spruce forest; FLP – lodgepole pine forest; FSP – Engelmann spruce forest; SAM – black cottonwood forest. See Appendix A for full code listing.

Since the 2009 aerial image was the most recent and finest resolution image obtained, it was used to delineate the layer of new vegetation associated with the unburned tree stands. Twenty-seven new growth polygons associated with the mature tree stands were digitized from this image, which, was, again, a subjective process (Figure 3.3).

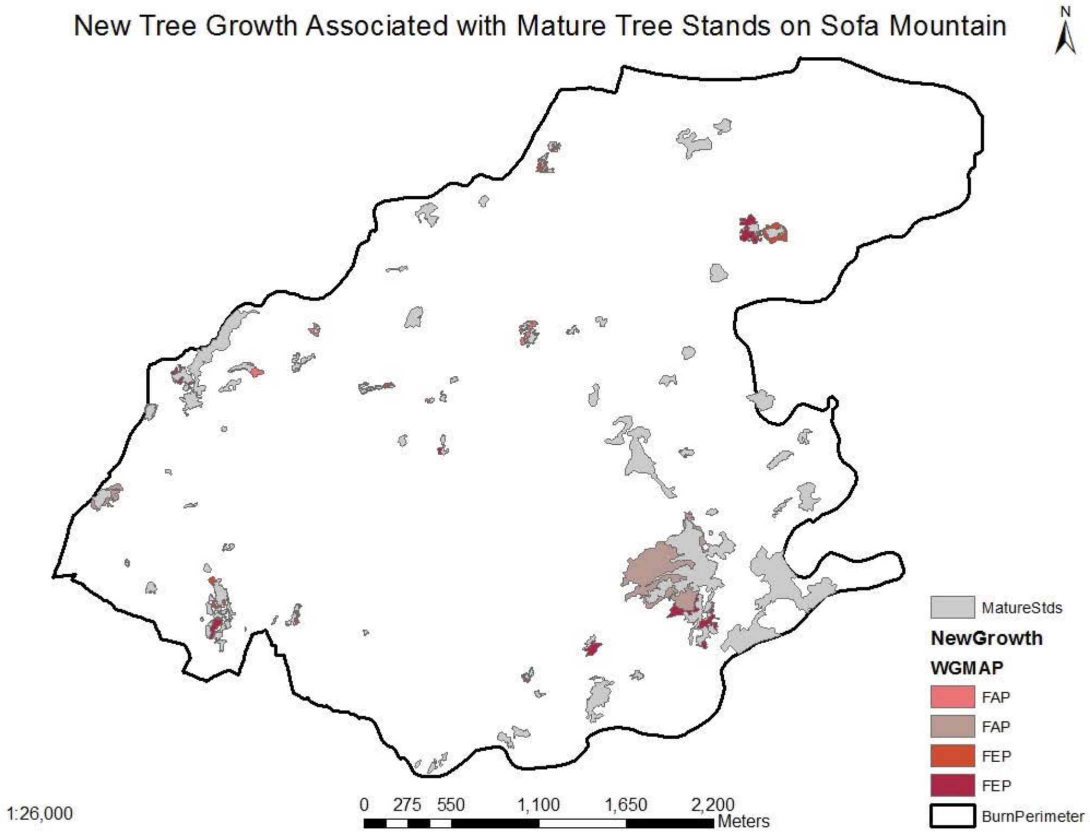

Figure 3.3 – New growth associated with mature tree stands remaining post-fire color-coded by WGMAP codes. Emergent tree WGMAP code listings and descriptions are as follows: FAP – poplar birch forest; FEP – mixed conifer-deciduous forest. See Appendix A for full code listing.

3.4.3 Characterizing Polygons

The digitized layers produced for mature tree stands and new growth were overlaid with Buckler's (2012) analysis and matched with a three-letter WGMAP code (see Appendix B for code listing) as well as a general classification (GENCLASS; see Appendix C for classification listing) and a more specific classification (CLASS; see Appendix C for classification listing) developed by Buckler (2012); (see Appendix D for attribute polygon attribute tables). Slope, elevation, perimeter, and area were obtained for each polygon identified. Area and perimeter were obtained in ArcGIS using the calculate geometry tool, whereas the Spatial Analyst tool Zonal Statistics was used for the percent slope and elevation. These characterized layers were draped over DEMs to determine where the patches fall on the underlying topography.

3.5 GIS Analysis and Statistical Methods

The importance of topography to the survival of mature tree stands was explored throughout the burn area with statistical analyses run in ArcGIS. Using the Spatial Statistics tool Ordinary Least Squares (OLS) in ArcGIS, multiple linear regressions were run in order to model the dependent variable, mature stand survival, and its relationship to other explanatory variables such as elevation, slope, and aspect. This test was used to determine which topographic characteristic was ‘most responsible’ for initiating a positive dependent outcome.

Spatial autocorrelation is a tool to analyze patterns; it is a measure of the degree to which a set of spatial features and their associated data values tend to be clustered together. In a GIS, spatial autocorrelation can be detected by using Global Moran’s I within the Spatial Statistics toolbox. This tool calculated a z-score and p-value indicating if the null hypothesis, that the mature tree stands are random throughout the burn area (complete spatial randomness, CSR), was rejected or not.

RESULTS AND DISCUSSION

4.0 Introduction

The results from the GIS, remote sensing, and statistical analyses are reported in this chapter. Findings include the evaluation of spatial relationships between topography and surviving mature tree stands and the spatial relationships between new growth, mature tree stands, and topography. Analysis and discussion includes specifics regarding location, species, and distinct topographic features believed to contribute to mature tree survival.

4.1 Topography

The topographic characteristics of the Sofa Mountain landscape dictate the flow of water creating micro and mesic moisture characteristics, variations in solar radiation, and soil moisture of a site, which influences survival and the distribution of vegetation throughout the area. Patterns of biota across the landscape reflect the interactions among the four classes of landforms categorized by Swanson et al. (1988), outlined in Table 4.0, which contribute to the creation of complex landscapes. Many of the mature tree stands remaining post-fire are the result of interactions among all classes. Regrowth appears to be regulated by interactions between classes 1 and 2. These classes may be particularly influential and important to reestablishment throughout the burn site. The influence of landforms on temperature, quantity of moisture, nutrients, and materials at sites as well as the influence on movement and flow of organisms, propagules, and materials through a landscape is particularly important.

Table 4.0 – Categories relating to the general effects of landforms on an ecosystem and its processes. Adapted from Swanson et al. 1988.

Class	Description
1	Landforms (by their elevation, aspect, parent materials, and steepness of slope) influence air and ground temperature and the quantities of moisture, nutrients, and other materials such as pollutants available at sites within a landscape
2	Landforms affect the flow of organisms, propagules, energy, and materials through a landscape
3	Landforms may influence the frequency and spatial characteristics of disturbance
4	Landforms constrain the spatial pattern and rate of frequency of geomorphic processes that alter biotic features and processes

The Sofa Mountain area is characterized as having a short rotation, stand-replacing fire regime. The mean fire interval for large infrequent burns throughout the park is approximately 100 years (Barrett 1996; Schwanke 1998). The 1998 fire falls within the mean fire interval. Figure 4.0 shows the extent of the burn: where ignition began, the estimated temporal extent throughout the first day, and the total burnout, or perimeter. The fire occupied the east and west ridges of the mountain on the southeast facing slopes. Spread of the fire appears to be determined by topographic features, site conditions, wind, and vegetation. The fire delineated a clear perimeter with a southern and western extent limited by elevation and wind. The southern portion of the burn was located on steep terrain that culminates in mountains peaks with sparse vegetation and late season snowpack, which was not conducive to fire spread. Wind, in particular, was important in influencing fire behavior. Prevailing westerly winds are common in this region and can be desiccating (Reeves 1975; Schwanke 1998). Blowing from west to east, the winds pushed northeastward. Wind also aided in containing the fire as it turned back on itself (Schwanke 1998).

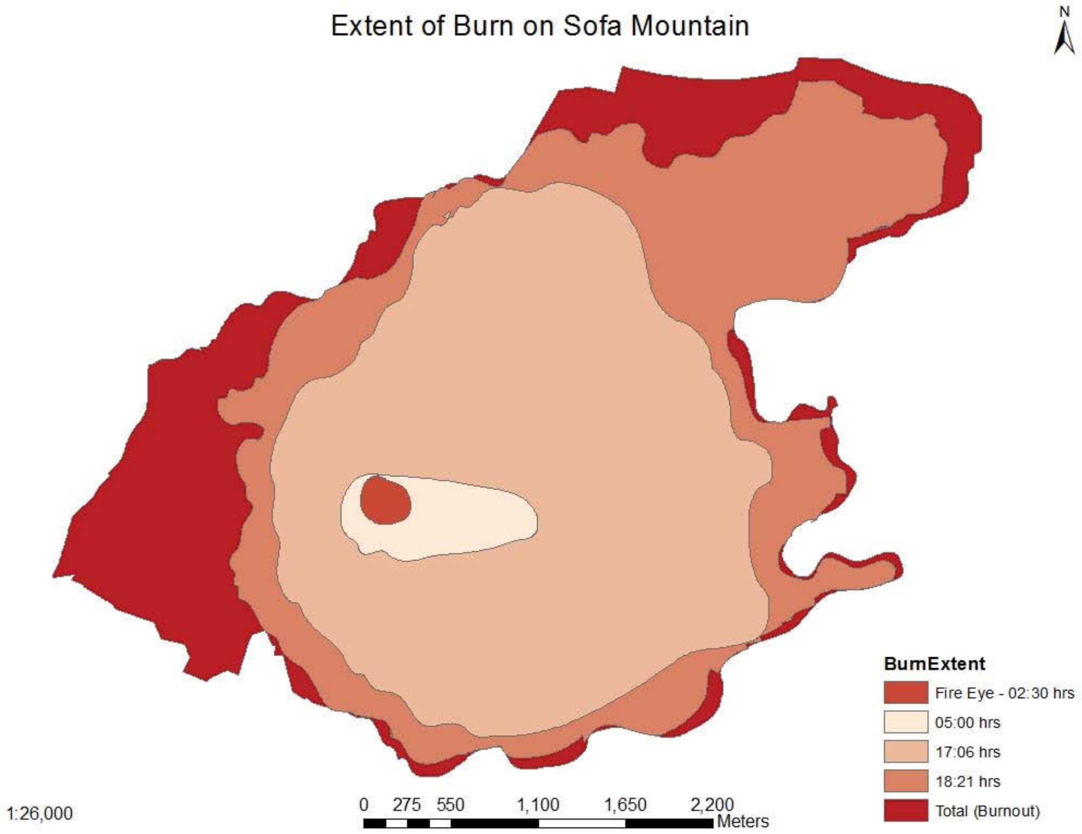

Figure 4.0 - Extent of the burn on Sofa Mountain and estimated temporal periods from Sept. 2, 1998 (day 1) as well as the full extent (total burnout). The fire burned a total of 1521 ha. Adapted from Schwanke 1998 and Buckler 2012.

The northern and eastern extent of the fire was limited by site-specific moisture and vegetation conditions that impeded fire movement. Figure 4.1 shows the hydrologic flow within the burn area on Sofa Mountain, illustrating that the eastern and northern portions of the burn site contain more moist sites that are associated with low elevations and less steep slopes, which allows for localized water accumulation. The difference in moisture levels between high and low elevations, as well as variation in slope angles, likely influenced fire spread and the amount of vegetation burned. The burn consumed much of the coniferous forest at high elevations where slopes are greatest and moisture is in lower volumes, while low elevation vegetation contained larger forest patches post-fire. As the fire moved north and east, not only did moisture levels change but original vegetation assemblages changed as well. Chief Mountain Highway bisects the northern portion of the burn. The vegetation in this area is largely composed of grasslands and deciduous tree species (Schwanke 1998; Buckler 2012). Grasslands readily ignite and spread fire easily, while deciduous trees generally withstand burns (Brown and Smith 2000). The change in vegetation type in this area may have slowed the spread of the fire.

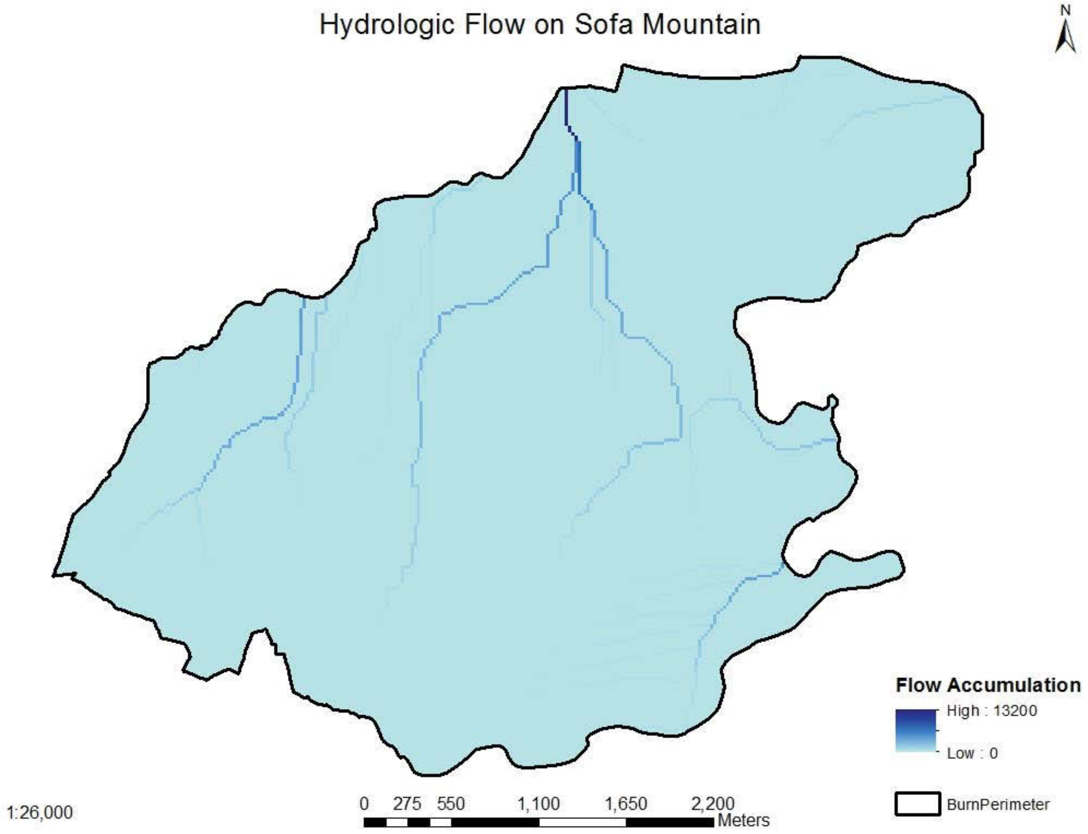

Figure 4.1 - The Hydrologic Flow within the Sofa Mountain Burn Area.

A 3D rendering (Figure 4.2) shows the forested areas that remain post-fire throughout the burn area. These stands were classified as mature. This image is the product of overlaying extracted forest cover classes from an unsupervised classification of a 1999 Landsat image draped over a DEM, allowing visualization of fire movement and subsequent damage across the landscape to be assessed. Delineation of mature tree stands using aerial imagery from 1999 was a subjective process. Tree-core analysis was not undertaken nor was there data available to assess the stand ages. For the purpose of this project, all visible tree stands within the image were considered "mature". It is important, however, to consider that these stands may be of varying ages and reproductive stages.

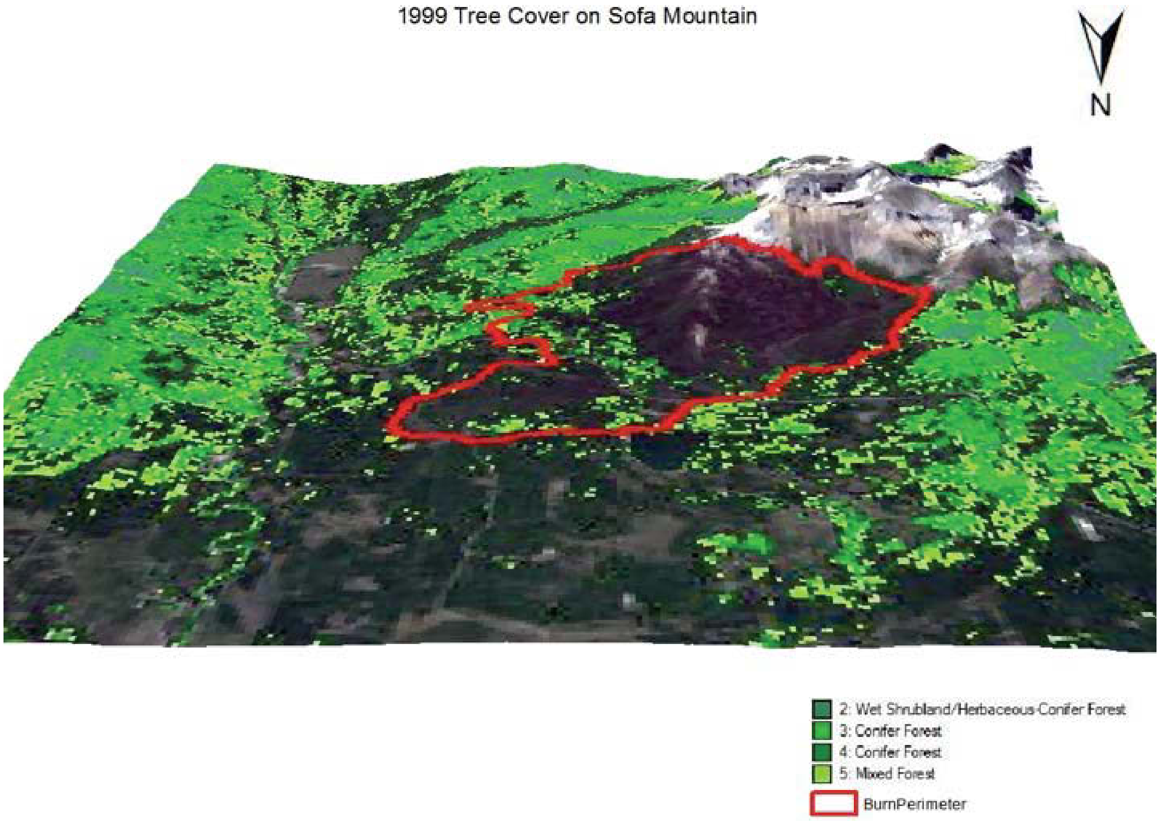

Figure 4.2 – 3D view of the burn and surrounding area produced from a 1999 Landsat image overlaid with forest cover classes from an unsupervised classification of the area one year following the Sofa Mountain fire and draped over a DEM.

4.1.1 Statistical Results

Multiple linear regressions were run with the OLS tool in GIS to determine if topographic features such as elevation, slope, or aspect initiated a positive dependent outcome with the locations of mature tree stands throughout the burn area on Sofa Mountain. Almost all of the OLS results were not statistically significant. The OLS summary report (see Appendix E), however, did show that the Jarque-Bera Statistics output, which tests for normal distribution, was statistically significant with a p value equal to 0.00 for the three variables, elevation, slope, and aspect. If this test is statistically significant ($p < 0.05$) then model predictions are biased in that the residuals, or mature tree stands, are not normally distributed. This test was run with the three topographic variables simultaneously and the output could not be positively correlated to one specific feature. As a result, Gobal Moran's I was run on each topographic feature to determine which, if any, might be causing the mature tree stands to be spatially autocorrelated (see Appendix E). The test indicated that, with a z-score of 0.60 and a p-value of 0.55, elevation was not causing the locations of mature tree stands to be significantly different than random. Testing slope and aspect with Global Moran's I did, however, indicate that there was less than a 1 percent chance that the clustering of mature trees was the result of random chance (Table 4.1). Thus, the location of mature trees in the post-fire environment is influenced by slope and aspect. Therefore, the null hypothesis that no topographic features played a role in the survival of these mature trees was rejected and the hypothesis that topographic features contribute to the survival of these stands was accepted.

Table 4.1 - Results from Global Moran's I cluster analysis indicates that slope and aspect positively influence the successful survival of mature trees within the burn area.

Explanatory Variables	Moran's Index	Expected Index	Variance	z-score	p-value
Elevation	0.022143	-0.012658	0.003357	0.600662	0.548065
Slope	1.133936	-0.012658	0.006221	14.536953	0.000000
Aspect	1.295738	-0.012658	0.00623	16.575995	0.000000

4.2 Mature Trees

The pre-fire composition on Sofa Mountain consisted primarily of conifer forests, which included both pure and mixed stands of lodgepole pine. Thus, because post-fire composition mimics pre-fire composition, it is expected that the post-fire regenerative composition will also consist of primarily conifer forests with prominent stands of Engelmann spruce, Douglas fir, mixed conifer, and lodgepole pine stands. Table 4.2 displays the number and percentage of eighty mature stands sampled and digitized throughout the burn area. Ninety-five percent of the eighty mature tree stands were classified as mixed stands of conifer species, deciduous tree stands, or pure stands of late seral conifer species such as Engelmann spruce and Douglas fir (Table 4.2).

Table 4.2 – Amount and Species Composition of Mature Tree Polygons within the Sofa Mountain Burn Area.

WGMAP Codes	Description	Number of Stands	Percentage
FEP	Mixed Conifer-Deciduous Forest	40	50.00
FFS	Subalpine Fir-Engelmann Spruce Forest	16	20.00
FAP	Poplar-Birch Forest	10	12.50
FSP	Engelmann Spruce Forest	6	7.50
FDF	Douglas-fir Forest	3	3.75
FLP	Lodgepole Pine Forest	3	3.75
FCW	Black Cottonwood Forest	1	1.25
SAM	Mixed-Conifer-Deciduous Shrubland	1	1.25
	Total	**80**	**100.00**

The spatial autocorrelation determined that mature stands located throughout the burn area tend to be clustered due to influences from slope and aspect. Clustering of mature stands is displayed in Figure 4.3 and Table 4.3 lists the stands and stand species present in each cluster (note: GIS polygon descriptions are listed in Appendix D). Many of these stands and clusters are located at low elevations with relatively flat slopes, which appear to be locations better suited to stand survival as typical fire behavior denotes that a fire burns faster upslope. High elevations throughout the area are marked by sparse vegetation, however, while these higher elevations also have steep slopes, the fire may have been retarded due to the low vegetation and fuel present in the area. The impact of aspect on the ecosystem's vegetation is important: north and east facing slopes are generally moister and more supportive of forests, whereas south and west facing slopes are dryer and favor grasslands (Letts et al. 2009; Schwanke 1998). The majority of stands are found at sites with north-, northeast-, and east-facing slopes, which receive less sunlight and have lower microclimate temperatures. There are some stands present on south-, southwest-, and southeast-facing slopes, which receive more sunlight, have higher microclimate temperatures, and are more conducive for species that thrive in dry conditions.

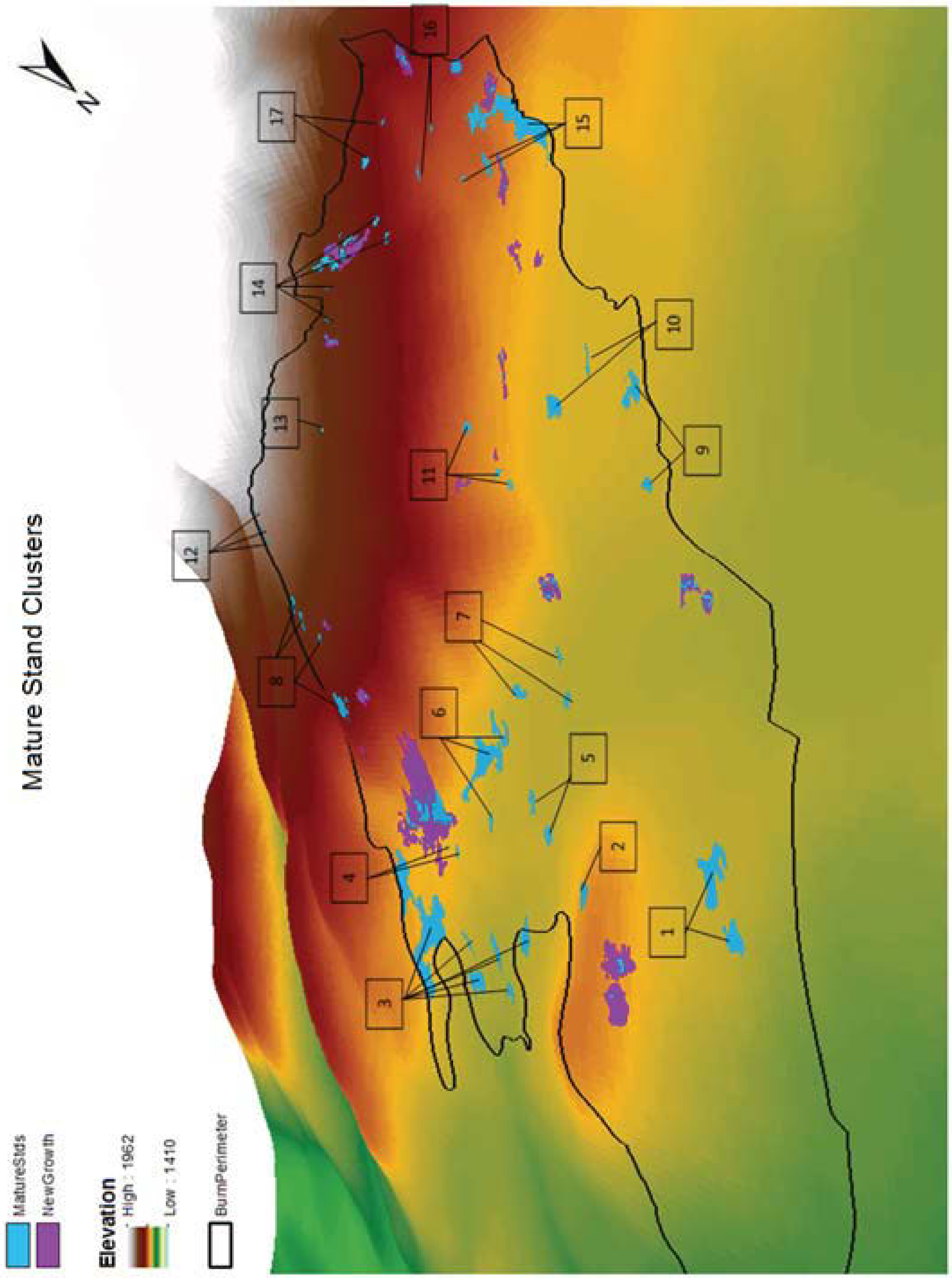

Figure 4.3 - 3D image of clustering of mature stands (blue polygons) across the Sofa Mountain burn area draped over the slope map of the area. Note: purple polygons indicate emergent vegetation associated with mature tree stands, which are discussed later in this section.

Mature stand clusters 3, 4, 5, 6, and 7 are located in areas characterized with a flat slope at the base of the east and west ridges with north- and northeast-facing aspects (Figure 4.3). The hydrologic flow accumulation of this area is also increased due to gradual decline of slope, which creates a consistently wet environment. The mature stands in these clusters are composed of pure stands of lodgepole pine and black cottonwood, mixed stands of Engelmann spruce and subalpine fir, and mixed conifer-deciduous stands (Table 4.3). Stands in clusters 5, 6, and 7 are located near known beaver ponds and permanently wet deciduous/herbaceous shrubland. Interrelated with the hydrologic flow at this location, the deciduous tree species aid in slowing the fire and in the protection of other flammable species. Despite being located in areas that experienced a more intense and severe burn, the moist nature of these sites likely slowed the fire or diminished the damaging effects of the burn allowing for tree survival. Clusters 5, 6, and 7, however, have no new or emergent associated growth. These stands are composed of Engelmann spruce, aspen, and mixed conifer-deciduous tree species. Engelmann spruce and some conifer species, such as subalpine fir, are mesophytic and have tolerance limits for the moisture levels that can and cannot support germination. While the site’s moisture may have contributed to the survival of these patches, it may be too moist to support any new growth.

Table 4.3 – Species composition of mature stand clusters associated with Figure 4.5. See appendix B and C, respectively, for WGMAP code and Class listings.

Cluster #	GIS Polygons in Cluster (FID)	WGMAP Codes	Class
1	8, 56	FAP, FEP	MatAsp, MatMix
2	76	FFS	MatES
3	17, 66, 70, 75, 77, 9	FEP, FCW, FLP	MatMix, MatCon
4	57, 79	FFS, FLP	MatES, MatCon
5	71, 72	FSP	MatES
6	18, 67, 78	FEP, FFS	MatMix, MatES
7	10, 31, 69	FAP, FSP	MatAsp, MatES
8	2, 4, 5, 34, 60	FFS, FLP	MatES, MatCon
9	61, 74	FEP	MatMix
10	11, 62	FFS	MatES
11	7, 26, 28	FEP, FSP	MatESAsp, MatES
12	12, 13, 14	FFS	MatES
13	37	FEP	MatMix
14	19, 48, 39, 42, 43, 44, 49, 68, 73	FEP, SAM, FAP	MatMix, MatAsp
15	1, 6, 20, 54	FEP	MatMix
16	15, 16	FEP	MatMix
17	50, 51	FFS, FEP	MatES, MatMix

Cluster 14, 15, 16, 17 are located on the southwestern extent of the burn (Figure 4.3). These clusters are close to the site of ignition where it was not expected to find mature stands in high numbers. Additionally, exposure to southwest winds at this location may subject vegetation at these sites to extreme drying. Thus, vegetation may be dry regardless of hydrologic flow and slope characteristics. West of the burn extent are a series of ridges. Movement of westerly winds across these features may influence fire behavior by pushing the fire eastward, saving stands from an intense burn on the western edge. Further, the ridges to the west may have provided for these stands from the drying effects of these winds. Cluster 14 also has the added benefit of being located in a near a snowpack with late season snowmelt, as observed from previous field seasons (Cerney 2014). This snow added moisture and slowed the burn at this location. Additionally, these ridges with west aspects will be dry as a result of the prevailing westerly winds that desiccate these stands. Those stands found on the east-facing aspects of the ridges will have higher moisture levels as a result of lessened solar radiance and protection from these winds.

Clusters 1 and 9 are located at lower elevations (Figure 4.3) and are characterized by stands of aspen and mixed conifer-deciduous forest. Aspen is common in lower elevations and susceptible to high severity burns (Brown and Debyle 1989) much like the Sofa Mountain fire. However, these clusters are located in the more northern portion of the burn with low slope angles, high moisture levels, and vegetative assemblages with greater volume of deciduous trees. These conditions essentially created a type of natural break to deter the fire's eastward movement. These stands are also located where it was expected to find high numbers of mature vegetation stands remaining from the pre-fire environment. Thus, the slow moving and less intense fire combined with more resistant tree species, may have resulted in these stands may having an increased chance of survival.

The mature stands that comprise cluster 11 are comprised of Engelmann spruce and mixed conifer-deciduous trees and are located on an environmental transition zone (Figure 4.3). This is significant as it is the only mature stand grouping with no new growth associated that is found in this type of location. These types of transition zones or gradients are areas throughout the landscape with gradual slope change and increased water and organic material runoff from higher elevations, which help to create an environment conducive to stand survival. These transition zones also prove to be beneficial for emergent growth.

Cluster 13 consists of a single mixed conifer-deciduous stand and is somewhat isolated from other mature trees throughout the burn area (Figure 4.3). This stand is also significant in that it is located at a high elevation near the point of ignition. As this stand is one of the few remaining in this part of the burn, it is speculated that the majority of the area surrounding it likely experienced intense and severe burns. This stand is also located in an area characterized by exposed cliff and talus, as well as sparse vegetation. These site conditions indicate that fuel loadings may have been low, regardless of minor disturbances and drought conditions. Further, the deciduous nature of the tree species may have facilitated survival, as these species are known to be more resistant to burn.

Engelmann spruce is quite prolific throughout the burn area: clusters 2, 5, 7, 8, 10, and 12 are predominantly Engelmann spruce (Table 4.3). In relation to Engelmann spruce stands, the influence of aspect on their survival is quite apparent. Every cluster, with the exception of cluster 2, is located on north- and northeast-facing slopes. Cluster 2 is located on a south-, southwest-facing portion of the burn. Engelmann spruce is a mesophytic species that has adapted to dry areas but has a low tolerance for high temperatures (McKenzie and Tinker 2012). South-facing slopes typically receive more sunlight and are, thus, drier with possible higher temperatures. Cluster 12 is located at the upper altitudinal limit of the fire extent, where cluster 8 is located near a late season snow pack (Figure 4.3). Clusters 2, 5, 7, and 10 are at lower elevations and near increased flow accumulation areas. As previously stated, cluster 5 is located in the proximity of beaver ponds and known to have high moisture levels. Since cluster 8 is located near a late season snowpack, the conditions of the site may be conducive to new growth. Much like cluster 12, though, cluster 8 has little opportunity for accumulated soil and seedbed at these high altitudinal extents. There is little to now new growth associated with clusters 8 and 12, which may be a function of soil and seedbed conditions at these higher elevations.

This assessment of mature tree stands also produced some unexpected results. One stand of black cottonwood (FCW) was found in the southeastern portion of the burn flanked by mixed conifer-deciduous forests (Figure 4.4). This is significant in that this species was somewhat rare in the pre-fire composition when compared to the total volume of conifer species found in the area. This species, a member of the willow family, burns very easily (Brown and Smith 2000) and, thus, it was unexpected to identify any remaining stands post-fire. A number of factors exist that may have spared this stand from fire. This stand is on the eastern extent of the burn area on a low slope, high moisture area (Figure 4.4), and is surrounded by four mixed conifer-deciduous stands. These mixed conifer-deciduous stands are more resistant to fire and tend to burn at a slower rate, offering protection by slowing the fire progression.

It was postulated that there might have been increased numbers of mature lodgepole pine stands simply due to the abundance of this species in the pre-fire composition throughout the area. Yet, only three mature lodgepole pine stands (FLP) were found (Figure 4.5).

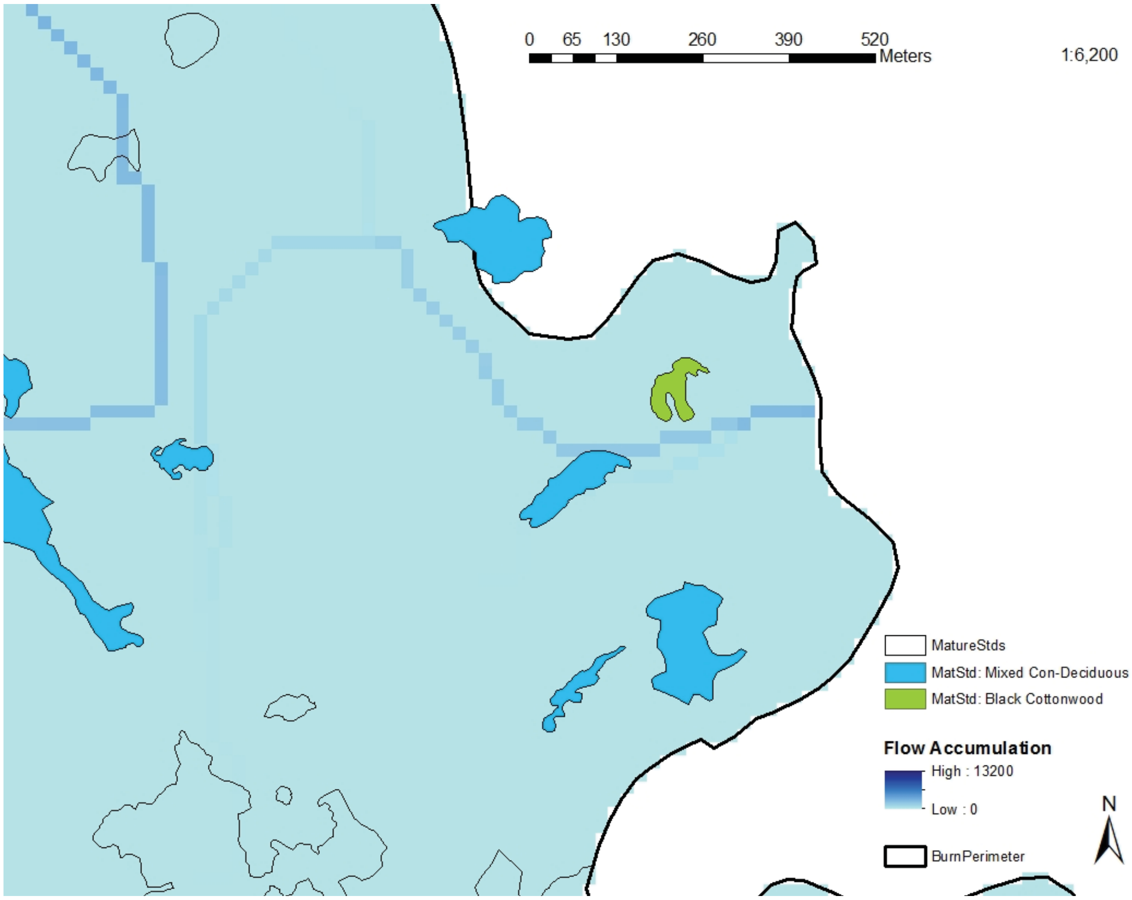

Figure 4.4 - Southeastern portion of the burn containing the mature Black Cottonwood (FCW) stand (green polygon). The black cottonwood is surrounded by mixed conifer-deciduous stands (Mat_Stds_FEP; blue polygons). Mature tree stand polygons are overlaid on the hydrologic flow of the area allowing assessment of spatial association recognition of tree stands and moisture conditions.

These numbers are not unusual for an area that has a stand-replacing fire regime such as Sofa Mountain. If topographic features influence stand survival as hypothesized and fires repeatedly move around these topographic features, it is not unlikely that there would be some amount of hardwood species or late seral conifer species at these locations (Agee 1998). Species that reestablish extremely well post-fire, such as lodgepole pine and aspen, tend to be later outcompeted by shade-tolerant understory species (e.g. Engelmann spruce and subalpine fir) after two to three decades of regrowth (Uchytil 1991a;

McKenzie and Tinker 2012). Therefore, finding the majority of mature stands to be pure or mixed conifer species (i.e. not lodgepole pine) is not unusual.

The three mature stands of lodgepole pine, present in clusters 3, 4, and 8, demonstrate the variability across the landscape of this species (Figure 4.5). While these three clusters have similar aspects (north/northeast/northwest), each of these sites has different elevation, slope, aspect, and moisture levels that may have influenced burn severity and intensity. The lodgepole pine stands in clusters 3 and 4 are similar in elevation, 1555 m and 1552 m respectively, and may have similar percentages of serotiny. Cluster 3 and 4 are likely to have increased moisture levels (Figure 4.3; Figure 4.5) due to the nature of hydrologic flow. These two clusters are located where water accumulation is greatest and, due to the shallow slope, moves more slowly. This allows for a consistently moist environment, which likely attributed to the survival of this stand; the increased moisture aided in the retardation of the fire at these locations and they experience a less severe and intense burn. The lodgepole pine stand found in cluster 3 is the largest mature stand sampled throughout the entire burn area. This is significant in that the surrounding areas would be expected to have increased emergent lodgepole pine stands as well. This is somewhat dependent on the variability of serotiny within this stand. However, the size of the stand implies that even with lower levels of serotiny, the possiblity of propagating that area may be greater than stands of smaller sizes. The lodgepole pine stand found in cluster 8 has an elevation of 1770 m and is located on steep slopes found in the southern portion of the burn area. The fire burned more severe and intense in these higher elevations and moved faster through the drier vegetation. While this cluster is located near the perimeter of the burn, it is still located in the more intensely burned area. This cluster, however, is located near a snowpack close to a topographic bowl feature that may be the reason for snowpack retention.

It is also noteworthy that these three stands of lodgepole pine do not have any new growth associated with them. As these are early seral species that appear in large numbers throughout the post-fire landscape, it was expected to find emergent lodgepole pine adjacent to these mature stands. Again, due to the variability of lodgepole pine stands, this could be the result of varying levels of serotiny or local environmental variables that are producing this anomaly. Further research will be needed to determine exactly why these stands have no emergent growth immediately adjacent.

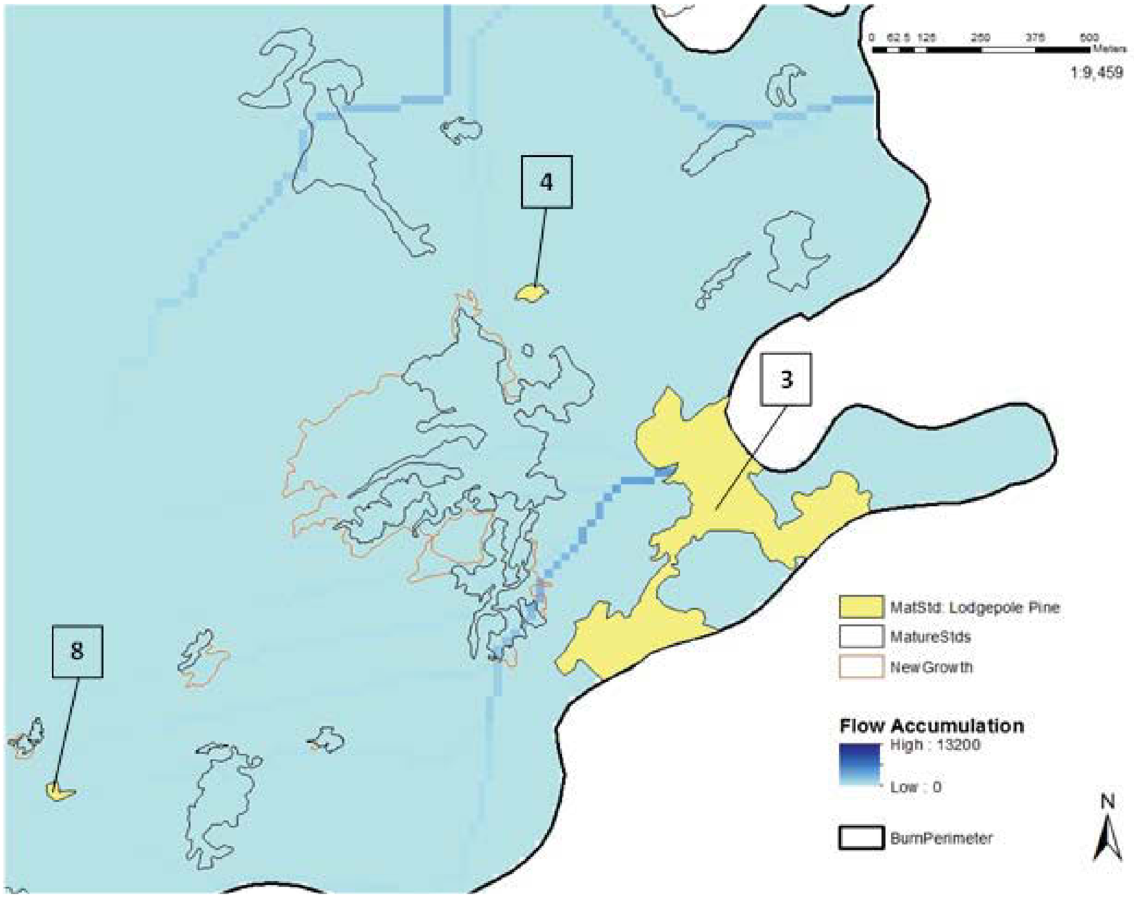

Figure 4.5 – Southeastern portion where three mature lodgepole pine stands (FLP) are found (labeled with cluster association; Figure 4.3). No new growth is associated with these stands. Mature tree stand polygons are overlaid on the hydrologic flow of the area allowing for the assessment of spatial association recognition of tree stands and moisture conditions.

4.3 New Growth Associated with Mature Trees

There was significantly less new growth associated with mature stands than expected. Figure 4.6 displays the identified clusters for the new and emergent growth associated with these mature stands, where Table 4.4 lists the emerging stand and stand species present in each cluster as well as the species of each associated mature stand. All new growth was classified as either FAP – poplar birch forest or FEP – mixed conifer-deciduous forest; eighty-nine percent of this new growth included early seral species lodgepole pine and aspen in some capacity.

Table 4.4 - Amount and Species Composition of Emergent Tree Polygons Associated with Mature Tree Polygons within the Sofa Mountain Burn Area.

WGMAP Code	Class Code	Class Description	Number of Stands (Total: 27)	Percentage
FAP	EmAsp	Emergent Aspen	10	37.04
FEP	EmMix	Emergent Conifer Mix	9	33.33
	EmAspLod	Emergent Aspen and Lodgepole Pine	4	14.81
	EmDF	Emergent Douglas fir	3	11.11
	EmAspLodDFir	Emergent Aspen, Lodgepole Pine, Douglas fir	1	3.7
		Total	**27**	**100.00**

Many of these stands and clusters are located at transition zones throughout the area. Clusters 1, 2, 5, 6, 7, 8, and 9 are all located at these particular areas. Transition zones are optimal for emergent vegetation as there is continuous runoff of water and organic material from steeper slopes. These sites are also well-suited to mature tree patch survival as evidenced by the number of stands with emergent vegetation located at these sites. This relates to Swanson et al.'s (1988) classification of the interactions of landforms. Landform interactions and topographical influences dictate the movement and

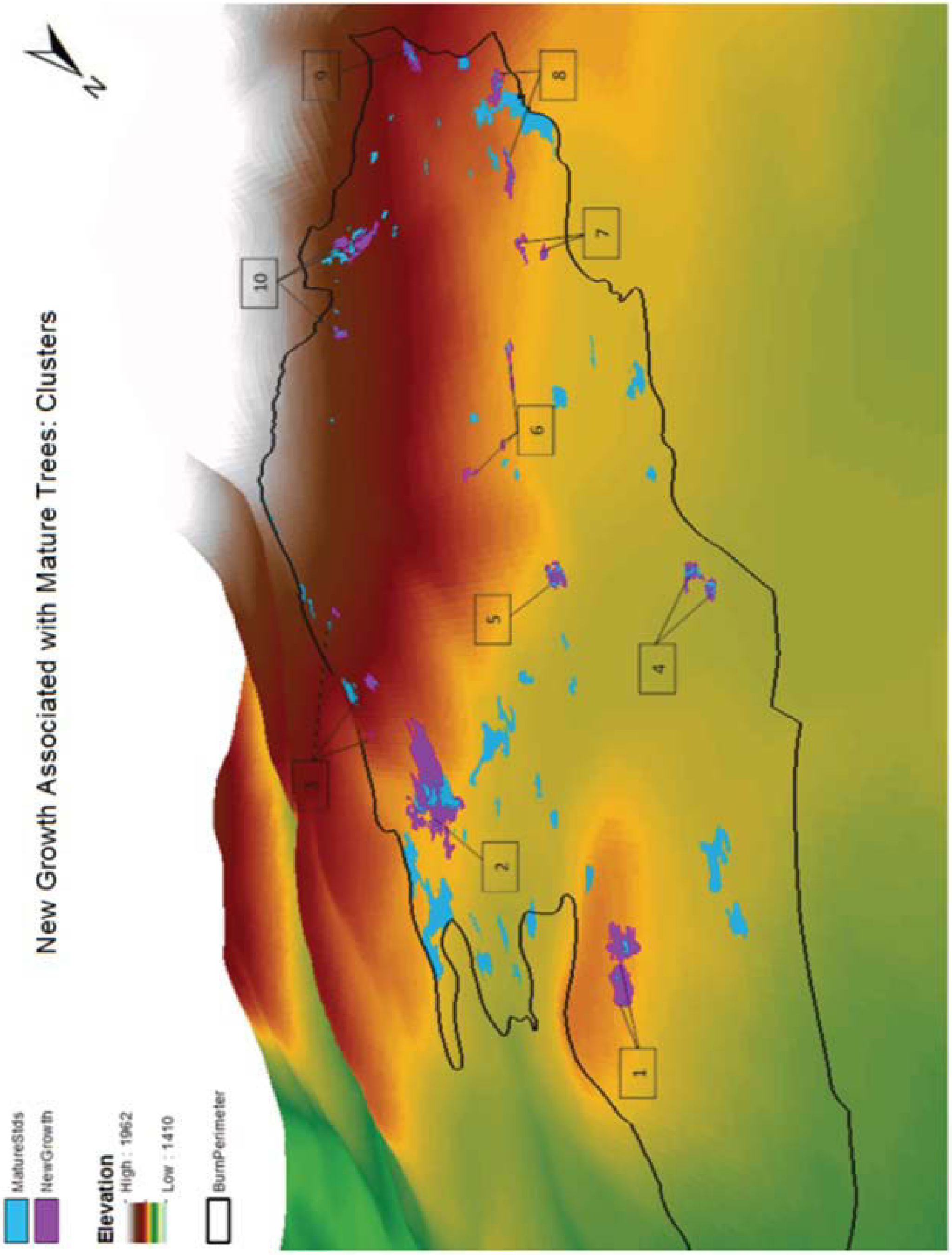

Figure 4.6 - 3D image of clustering of new growth polygons associated with mature stands (purple polygons) across the Sofa Mountain burn area draped over the slope map of the area.

flow of organisms and propagules through a landscape. Throughout the Sofa Mountain burn area, this organic material is continuously moving to and around these sites. Also, no pooling or oversaturation occurs at these sites; the sites are neither extreme – too wet or too dry nor are they nutrient rich or nutrient poor. These transition zones are marked by gradual gradient changes. Stands within clusters 1, 2, 5, 6, 7, 8, and 9 are found near the bottom of ridges that provide protection from intense winds of the area.

There is little new and emergent growth associated with mature tree stands located at lower elevations with flat slopes. As water flows downslope, it reaches sites with little variation in incline and these lower sites become inundated with runoff. As a result, these sites are then unable to promote new growth. Additionally, a less intense, slow-moving fire characterized the sites at low elevations throughout the Sofa Mountain burn area. As this area was not burned as heavily, mineral soils that are essential for prolific germination of lodgepole pine, aspen, white spruce, and black cottonwood were not present.

The varying topography of the area provides protection and dictates the flow of water and nutrients throughout the area, offering unique opportunities for initial vegetation regrowth. Figure 4.7 offers a more detailed view of various clusters and their relation to the landscape. Cluster 1 (Figure 4.7) is located on the northern side of a small hill in the northern portion of the burn area separated from the larger burned portion next to the Chief Mountain Highway. This position of these stands on the north-facing slope of this hill provided protection from desiccating winds. Clusters 8 and 9 are located on the western extent of the burn where westerly winds blow into the area (Figure 4.7). Directly adjacent to this western burn perimeter are a series of ridges. These ridges help to create deep troughs and, thus, act as a wind barrier for these stands effectively causing the wind to move above tree height at this area. As a result, the east slopes provide optimal growing conditions by supplying runoff from higher elevations catches and limiting the drying effect of wind.

The emergent trees belonging to cluster 5 are characterized as emergent aspen associated with mature aspen stands, while cluster 6 consists of mixed conifer and aspen. These sites, located in transition zones, are sheltered by the topography of the area. The ridges located to the south and west of these stands provide shelter from the westerly winds. These ridges also help to create troughs, which act as a moisture and nutrient trap making these locations more conducive to new growth.

At the southern portion of the burn there are snowpacks at two separate locations. While growth directly under the snowpack is not common, clusters 3 and 10 (Figure 4.6) are located in bowl sites that benefit from late-season melt from these snowpacks. In the upper altitudinal limits where moisture, organic material, and seedbed is typically low, snowmelt helps to produce a site that is conducive to new growth (Agee and Smith 1984). Clusters 3 and 6 are the most species diverse clusters. Cluster 3 contains lodgepole pine, Douglas fir, aspen, and some mixed conifer-deciduous forest type while cluster 6 contains Douglas fir, aspen, and some mixed conifer-deciduous forest type (Table 4.5). Both clusters 3 and 6 are in transition zones where water moves through.

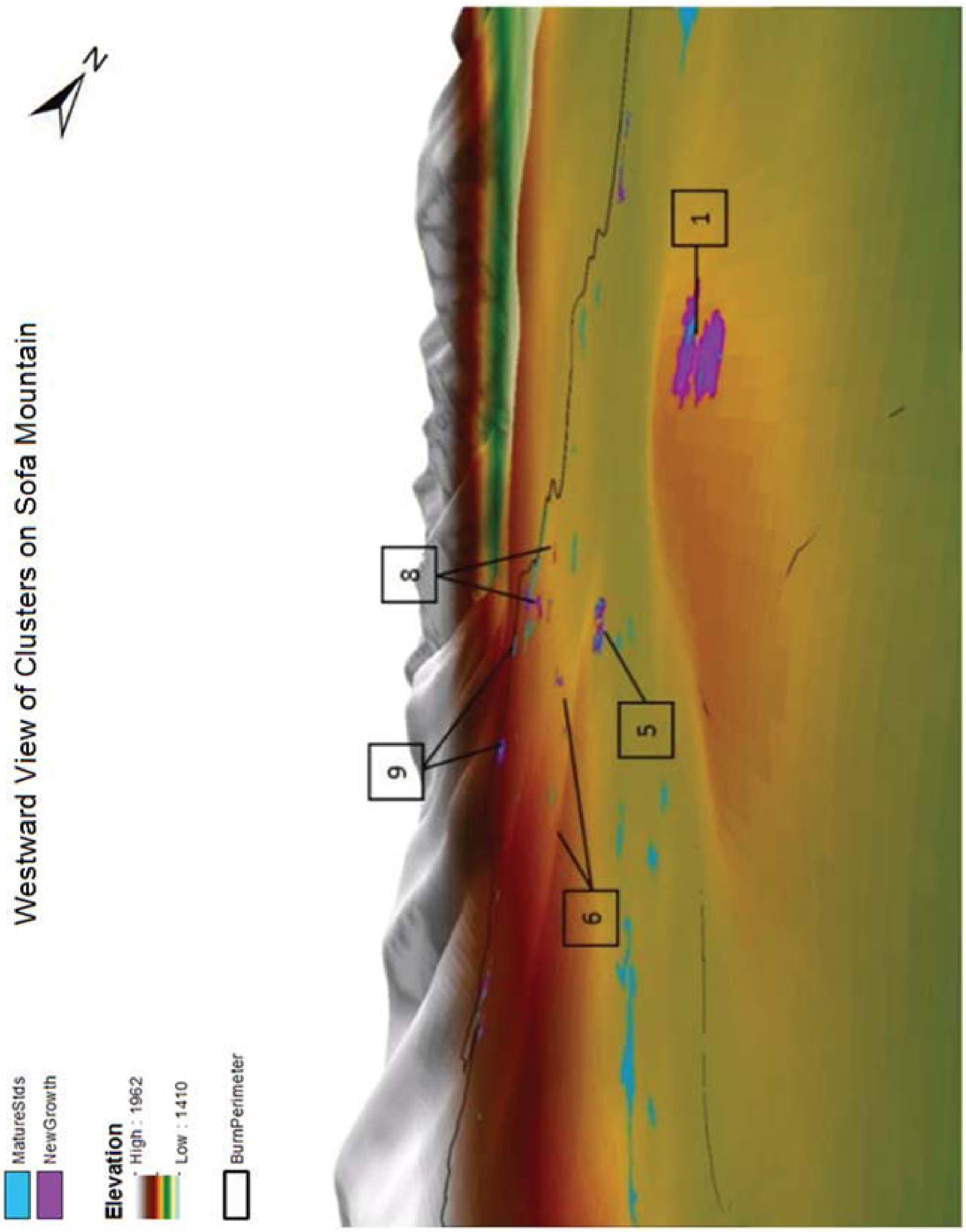

Figure 4.7 – 3D image of the westward view showing clusters protected by ridges throughout the Sofa Mountain burn area.

On the eastern extent of the burn, the largest polygon of new growth was delineated. Cluster 2 is characterized as emergent aspen and lodgepole pine, and is located in an area containing beaver ponds and permanently moist vegetation. This site is also sheltered from the intense winds of the area by ridges that cut through the center of the burn area. Of all the sites sampled throughout the area, this location appears to be most conducive to new growth as it has the largest area of new growth associated with a mature stand. Cluster 4 is not spatially associated with other clusters of new growth. These stands are located in the low elevations of the burn area on the northern portion bisected by the highway, and are characterized by a flat, north-/northeast-facing slope.

Table 4.5 - Reference table associated with new growth clustering in Figures 4.6 and 4.7. This table shows the clustering of new and emergent vegetation as well as the mature stands with which this growth is associated. See appendix B and C, respectively, for full WGMAP code and Class listings.

Cluster #	GIS Polygons in Cluster (FID)		WGMAP Codes		Class	
	Mature Trees	New Growth	Mature Trees	New Growth	Mature Trees	New Growth
1	63, 64	21,22	FFS	FEP	MatES	EmAspLod
2	58, 59	19, 20	FEP, FDF	FAP, FEP	MatMix, MatES	EmAsp, EmAspLod
3	3, 35, 36	10, 11, 25	FAP, FDF	FAP, FEP	MatAsp, MatCon	EmAsp, EmMix, EmAspLodDFir
4	32, 33	8, 9	FEP	FEP	MatMix	EmMix
5	29, 30	6, 7	FAP	FAP	MatAsp	EmAsp
6	23, 24, 25, 27, 55	2, 3, 4, 5, 18	FFS, FEP	FAP, FEP	MatES, MatMix	EmDF, EmAsp, EmMix
7	21, 22	1, 24	FAP, FEP	FAP	MatAsp, MatMix	EmAsp
8	0, 53	0, 17	FEP, FAP	FAP, FEP	MatMix, MatAsp	EmAsp, EmMix
9	52, 65	16, 23	FAP	FAP	MatAsp	EmAsp
10	38, 40, 41, 45, 46	12, 13, 14, 15, 26	FEP	FEP	MatMix	EmMix, EmAspLod

4.4 Regeneration on Sofa Mountain

Regeneration of vegetation following large, infrequent burn events strongly influences forest structure. This initial stage is important because trees are not exhibiting competition with other species, creating a low-stress habitat for early successors (Swanson et al. 2011). While there are some unexpected successional patterns at this burn location, the system is not deviating from the successional pathways common in this environment; there seems to be no divergence from the fire cycle or the vegetative composition at this point in time (2014: 16 years post-fire). Figure 4.8 aids in visualizing the regrowth throughout the burn area as it shows the forest cover from 1999 and the forest cover in 2011, where the new and emergent growth has a large presence. Relating to Nyland's hypothesized successional pathways and patterns of regeneration (1988), the Sofa Mountain burn site is most demonstrating one common successional pathway: a cohort of widely scattered single lodgepole pine seedlings that form as small tree islands and may eventually converge to a more continuous stand with various age classes.

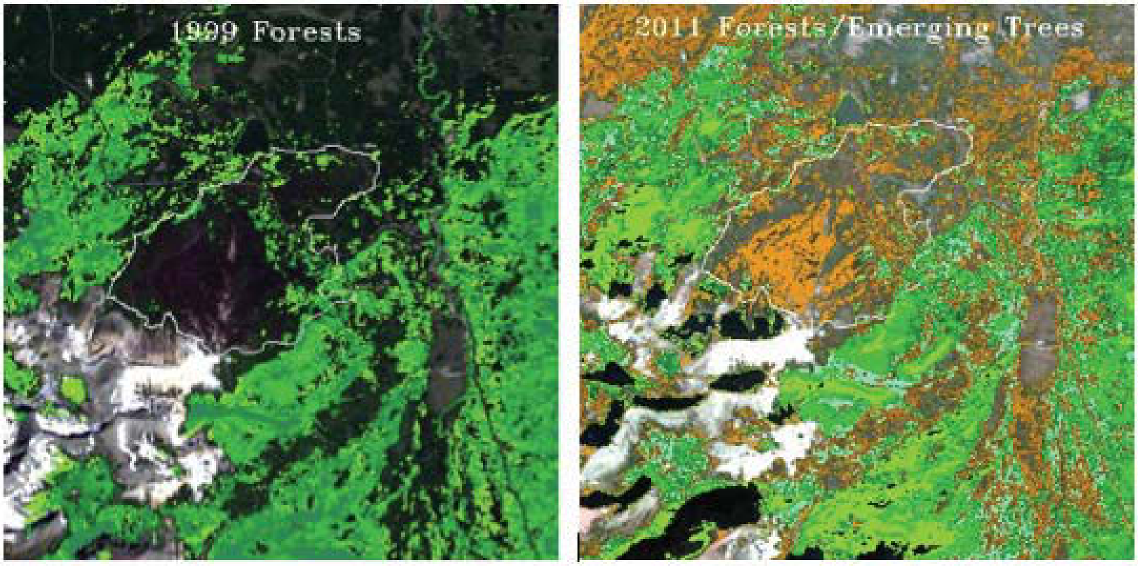

Figure 4.8 - Regrowth of trees over time on Sofa Mountain. Left: 1999, 1 year post-fire, little tree presence (green color) in burn perimeter. Right: 2011, 12 years post-fire, large areas of emergent tree growth (brown color).

Due to the slow successional pathways common in subalpine forest, the impacts of historic fire suppression are likely slight. As of the 2014 field season, it appears that the site is overturning to a new successional stage: shade-tolerant, understory conifer species, most notably Engelmann spruce and Douglas fir, are beginning to emerge, and will eventually compete with lodgepole pine and aspen saplings present throughout the burn area.

4.4.1 NDVI Analysis

An NDVI analysis of the burn area indicates that biomass and vegetation vigor is returning to the area and the site is recovering. The outputs of an NDVI analysis are digital number (DN) values indicating the reflectance of a pixel in the image (see Appendix F for NDVI analysis outputs for each year). Values can range from -1 to 1, where 0 is equal to the absence of vegetation. Water reflects poorly in both the visible red and near-infrared spectral band and corresponds to negative values in the output. Areas of barren rock, sand, or snow also reflect poorly in these spectral bands and generate small values (-0.1 to 0.2). Soils exhibit a near-infrared spectral reflectance and generate small positive values (0.1-0.2). Sparse vegetation (e.g. shrubs and grasslands) generates moderate values (0.2-0.5), while dense vegetation (e.g. forest cover) generates high values (0.6-0.9). Values ranging from 0.8-0.9 indicate the highest possible density of green leaves and a vigorous area. The average values for the NDVI analysis completed for each year are displayed in Table 4.6. (Note: Due to poor image quality from 2011, this image was histogram stretched to offer more contrast for visual purposes. The data is not listed, as the statistics are skewed and indicative of this stretch.) The average pixel value for the image from 1994 was 0.706. In 1999, the same AOI, had an average pixel value of 0.655, while the average for 2014 was 0.769 (Table 4.6). These pixel numbers indicate that while overall vegetative vigor decreased post-fire, the expected drastic change did not occur. These numbers, however, are misleading. Assessing the output numbers individually per year (see Appendix F for NDVI outputs) allows for a more in-depth analysis of the area over time. Values ranging from 0.8-0.9 indicate healthy vegetation throughout the area. In 1994, the highest value was 0.89 where 3,785 pixels reflected values between 0.8-0.9. In 1999, the highest value was 0.93, but only 1,050 pixels reflected values between 0.8-0.9. The highest value in 2014 was 0.92 and a total of 18,513 pixels reflected values between 0.8-0.9. The variations in numbers may be partly due to areas bordering the burn that were included to keep the Landsat images from becoming warped once extracted within ENVI. These surrounding vegetated areas were unaffected by the fire and may be inflating the overall pixel average of the area. The low numbers from 1994 may also be the result of prolonged droughts, which would have decreased vegetation vigor across the area, prior to the Sofa Mountain fire. Despite the highest pixel value from 1999 being equal to 0.93, there was a low frequency of high values, which is expected considering the majority of the image is charred and exposed soil.

Table 4.6 – Numbers results from the NDVI analysis shows total pixel values (DN Total) for each year (1994, 1999, 2014) and the total number of pixels present in the scene (Points Total). Total pixel value was divided by total number of pixels for each year to calculate the average pixel value of the Sofa Mountain burn scene.

	DN Total	Points Total	Average DN
1994	20794.68	29445	0.706
1999	19292.75	29445	0.655
2014	22641.89	29445	0.769

Figure 4.9 displays the analyses run of the Sofa Mountain area across various years following the fire event. The coloring was selected to allow for the visualization of dynamic changes and differences from image to image where dark blue areas are

indicative of high vegetation density and vigor. Green coloring in the images indicate areas covered in sparse vegetation, and red and orange indicate soils. Yellow indicates areas of water, barren rock, sand, or snow.

The 1994 pre-fire image (Figure 4.9, A) portrays a vigorous area with dense forest cover within the burn extent. The fire occurring in 1998 decimated the higher elevations and left vast portions of bare soil and rock. By 1999 (Figure 4.9, B), however, regrowth was already occurring throughout the area. Some perimeter extents, particularly those in the eastern edges of the burn, as well as the northern portion bisected by the Chief Mountain Highway, exhibit the deep blue color indicative of healthy vegetation. 2011 (Figure 4.9, C) is marked by an increase in healthy vegetation and regrowth in the severely burned high elevations. Not only was this upper portion burned severely, but the pre-fire vegetation in this area was sparse as well. Thus, it is expected to see this portion regenerate at a slower rate than the low elevations. Areas of exposed soil are also diminishing as vegetation reestablishes across the landscape. The final analysis year, 2014 (Figure 4.9, D), follows a similar pattern: increased healthy vegetation and regrowth in the more severely burned areas at higher elevations still exhibiting a slower recovery rate with decreased amounts of exposed soil. With this year, the portion to the north of Chief Mountain Highway appears to be similar to the 1994 image and thus, almost fully recovered in vegetation density and vigor.

The variability of weather in this area increased the difficulty of obtaining anniversary Landsat images with minimum cloud cover or other atmospheric interferences. The dates of the images range from July to September. Images from June or July would better reflect conditions and vegetation health and would prove more useful in accurately assessing the vegetation of the area. However, the images used do permit interpretation of ecosystem recovery over time, allowing patterns of regrowth since the time of fire to be recognized.

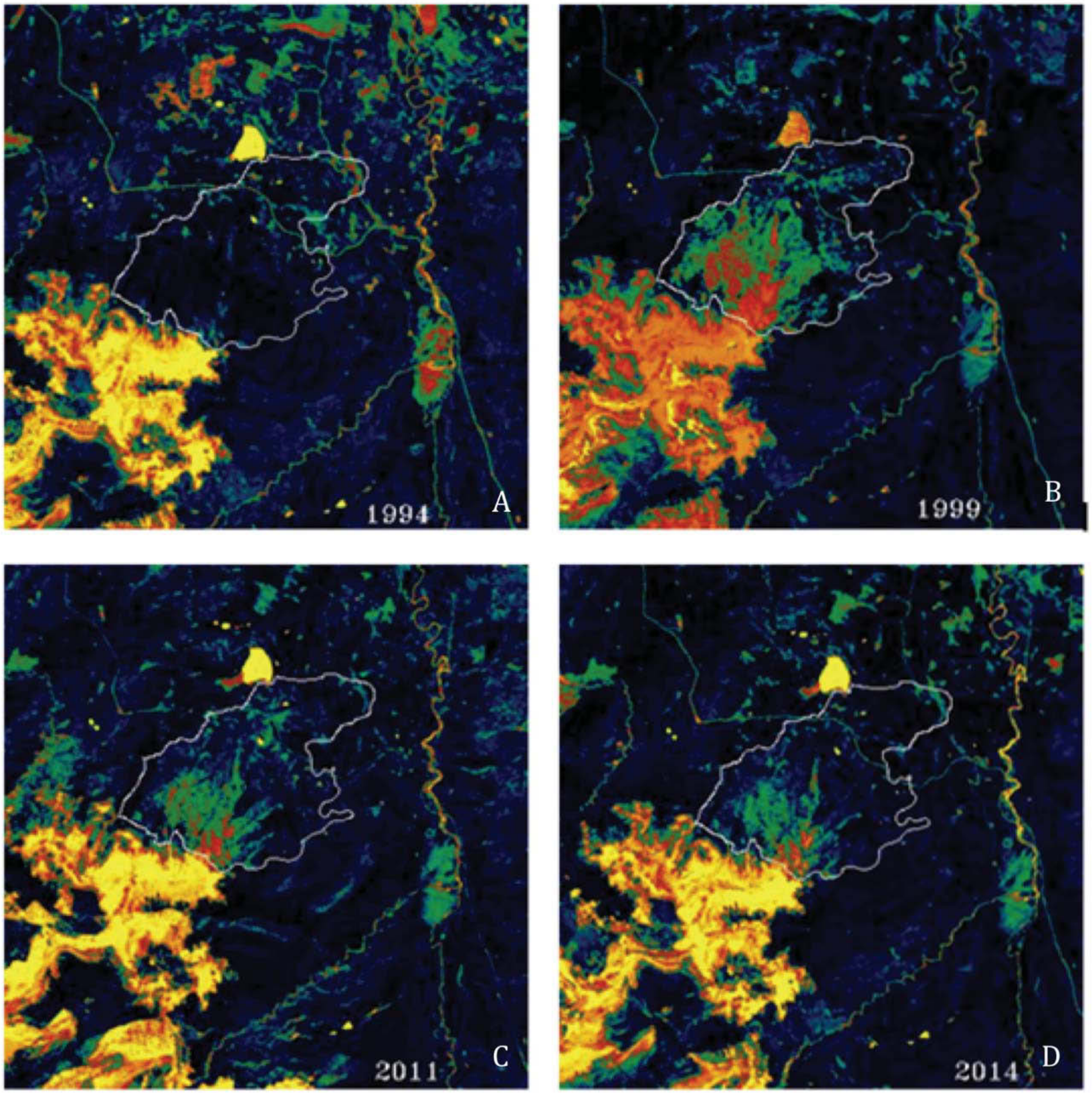

Figure 4.9 - NDVI analysis of vegetation regrowth on Sofa Mountain. Dark blue color indicates healthy vegetation. Images are lettered according to date; A: 1994 - before the fire, B: 1999 - one year following the fire, C: 2011 - twelve years after the fire, and D: 2014 - the most recent summer images.

4.5 Observing Landscape Change Projections

Vegetative assemblages across a landscape vary over time in response to changes in climate. These fluctuations in climate influence distribution as species may evolve and speciate, migrate according to limitations, or become extinct (Turner et al. 2001). Additionally, disturbance events have been shown to be sensitive to fluctuations in climate (Turner et al. 2001). Fire regimes have drastically lengthened with cool, moist temperature or shortened during prolonged warm, dry periods (Clark 1990; Turner et al. 2001). Climate effects are also modified by landform and are important influences on landscape pattern (Turner et al. 2001).

In WLNP, the landscape is climate-driven. Dominated by lodgepole pine, there will be a stable system as long as a seedbed is available. Lodgepole pine trees are reproductively mature at five years of age, an age shorter than the fire interval. Thus, it is expected that this landscape will remain lodgepole pine dominant, as there should be ample seed in the seedbed barring no genetic limitations beyond the capability to adapt to climate fluctuation. Second seral stages are expected as well, given that seed is available and the species can reach maturation. If advanced climate change occurs, then the landscape may undergo a shortened fire interval, which would decrease the presence of late seral species and overall diversity of the landscape, creating a lodgepole pine-grassland dominated landscape.

In Alberta native fescue grasslands as well as a mix of true- and mixed-prairie grasslands with scattered conifer trees at higher elevations have historically dominated the landscape (Levesque 2005). The warming trend following the Little Ice Age produced extended periods of drought, which were conducive to grasslands. Since tree growth is restricted by moisture, a grassland-dominated landscape was the norm (Levesque 2005). Increased future warming may limit moisture in the area, favoring a grassland environment.

Present-day landscapes may be perceived as natural, but most are likely to have been shaped by some human influence (Turner et al. 2001). Pre-European settlement in Canada was marked by low-intensity fire regimes that maintained the grasslands of the area (Reeves and Peacock 2001; Levesque 2005). Fire was common practice for First Nations people, particularly the Blackfoot Indians, in western Canada as a method of regenerating heterogeneity and biodiversity to the landscape (Reeves and Peacock 2001; Levesque 2005). Their nomadic lifestyle helped maintain this ecosystem. European settlement, however, caused indigenous peoples to cease migration and settle (Levesque 2001). They continued, however, to burn the land, which may have changed relative abundances of past plant communities. WLNP fire history suggests that this burning occurred frequently, resulting in vegetation assemblage shifts (Levesque 2005). As of today, large, repeat natural burns regulate the area composition. This assemblage will likely be maintained if the fire cycle is altered to a smaller fire return interval.

Management of large-scale landscapes is increasingly important, particularly for natural, complex landscapes to maintain the integrity of ecosystems and landscapes. Because landscapes have been shaped by human influence, considering traditional activities will also be important in shaping management policies. Current land management is quite specific and tends to focus on harvesting and thinning of biomass (Turner et al. 2001). This, however, cannot substitute for the natural role of fire in a landscape in providing nutrients, heterogeneity, and overall stability (Keeley et al. 2009).

The 2010 WLNP Management Plan states that a goal of the park is the reintroduction of fire to the landscape in order to restore these native grasslands (Park Canada 2010). In the past, mixed fire regimes thinned forests and restored grasslands in montane ecosystems (Cerney 2005). Thus, a future grassland-dominated landscape would not be foreign or new for this landscape. Thus, adaptive management should be undertaken in WLNP. Adaptive management strategies consist of the proposal of management techniques, initiation and implementation of those techniques, monitoring the results, and evaluating the results in order to assess the success of these strategies (Stankey et al. 2006). This process should be reinitiated and altered depending on new and emerging research and knowledge in order to best sustain natural landscapes.

CONCLUSIONS AND RECOMMENDATIONS

5.0 Conclusions

The aim of this thesis was to determine topographic factors influencing tree survival and the associated new growth through a digital analysis of the 1998 Sofa Mountain burn. Topographic features were shown to influence tree survival and may also have some effect on the emergent tree growth. Clustering of surviving stands could not be explained by complete spatial randomness and was determined to be the result of slope and aspect with less than a one percent chance that mature tree clustering was the result of random chance. Eighty mature tree stands were sampled and found primarily in sites with north- and northeast-facing slopes where moisture levels are high, and at sites with lower slope angles. Ridges within the burn area demonstrated the influential nature of topography for stand survival. The west-facing slopes of the ridges will be dry as a result of the prevailing westerly winds that desiccate these stands. Those stands found on the east-facing aspects of the ridges will have higher moisture levels as a result of reduced solar radiance and protection from persistent westerly winds.

Trees remaining after a fire event can and do act as a seed source, and also provide positive plant interactions. Many studies have demonstrated that proximity to these mature stands typically increases the likelihood of emergent vegetation growth (Kikvidze 1996; Ponge et al. 1998; Stueve et al. 2009). It was anticipated that post-fire emergent tree stands would be associated with mature trees. This was not the case, however. The vast majority of new growth was not associated with surviving standing trees but as a product of the *in situ* seedbed and downed trees. Twenty-seven new growth polygons associated with mature tree stands were found. These were located primarily in transition zones where the slope gradient gradually changes directing the flow of water and organic material from higher elevations to these areas making them more conducive for germination and growth.

This thesis project helped to demonstrate the stochastic nature of disturbance throughout a landscape and vegetative patterning in response to these events. Unexpected mature stand survival and new growth patterns further illustrate the variation of fire behavior and the influential effects of topographic features and species' characteristics. Limitations to this study consisted predominantly of human error in the analysis and interpretation of the satellite and aerial imagery used for this project, but also the coarse resolutions of the images and a limited field season. The spatial resolution of Landsat images also attributed to errors within the study. The overall vegetation pattern across the landscape was determined, but the coarseness of the image allowed for the under-estimation of small forest patches and over-estimation of large forest patches. Even with the acquisition of a 30 cm aerial image, decisions were subjective and room for error increased. Previous analysis was useful in determining stand type and characteristics. However, continuous succession and turnover of early seral species throughout the burn area may indicate that a species analysis from 2012 could potentially be outdated. A limited field season reduced the opportunity to survey tree stands. Thus, field work and ground truthed data would be necessary to provide additional data of site conditions for analysis and conclusions, thus, strengthening findings.

5.1 Recommendations for Future Study

Global warming increases fire risk in some areas. The Intergovernmental Panel on Climate Change (IPCC) estimates that by the years 2080-2099 the mean annual temperature will increase by 2.1-5.7 degrees Celsius, a decrease in precipitation during summer months, and decreased snowpack and snowmelt (Christensen et al. 2007; Brown 2009). The changing climate will also have an effect on thunderstorm patterns, drought lengths, and fire seasons and is therefore expected to increase in the frequency of lightning-caused fires (Brown and Smith 2000).

Management of fire-prone landscapes tends to be costly, ineffective, and misdirected (Donovan and Brown 2007; Steelman and Burke 2007). Faced with a rapidly changing climate, many land managers have returned to indigenous burn practices hoping to develop adaptive assemblages (Norgaard 2014). However, before management plans are implemented for WLNP, and particularly the Sofa Mountain area, further analysis should be completed to better understand the ecosystem dynamics and adaptability to a changing climate to ultimately determine if management of these landscapes is necessary at all. A more comprehensive species analysis, which should include understory species composition and serotiny variability among lodgepole pine stands, should be undertaken. This will help to assess the successive pathways occurring in the area. Finally, it would be worthwhile to visit the site in 15-20 years when the ecosystem has moved into a new stage of succession in order to determine if conifer species may be colonizing in close proximity to mature stands and to determine if historic successional pathways are being adhered to at this site.

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APPENDIX A

Fieldwork notes and observations from June 2014 ground truthing.

Site	Perimeter Coordinate		Observations and Notes
	Longitude	Latitude	
1	-113.775784	49.058555	Northeast Slope Aspect; Douglas Fir, Aspen, Lodgepole Pine - More fallen trees
	-113.77355	49.057885	
	-113.773592	49.057856	
	-113.77365	49.057803	
	-113.773623	49.057726	
	-113.773551	49.057769	
	-113.773434	49.05774	
	-113.773381	49.057804	
	-113.773481	49.057821	
2	-113.772316	49.057709	Mature Mix; North-Northeast-facing Slope
	-113.772408	49.057685	
	-113.772472	49.057698	
	-113.772474	49.057691	
	-113.772527	49.057563	
	-113.772361	49.057551	
	-113.772119	49.057729	
	-113.772108	49.057726	
	-113.77232	49.05783	
	-113.772309	49.057943	
3	-113.771808	49.057663	Northeast-facing Slope; Mature Mix
	-113.771753	49.057712	
	-113.771586	49.057703	
	-113.771502	49.057721	
	-113.771539	49.057631	
	-113.77161	49.057608	
4	-113.770981	49.057294	Animal Activity - island not recorded; coordinates taken at 'mouth' of island

APPENDIX B

WGMAP codes and descriptions of vegetation in WLNP.

Map Code	Description
CSA	Dwarf-shrub/Herbaceous Complex: Dry - Mesic
CSW	Dwarf-shrub/Herbaceous Complex: Mesic - Wet
FAP	Poplar-Birch Forest
FCW	Black Cottonwood Forest
FDF	Douglas-fir Forest
FEP	Mixed Conifer-Deciduous Forest
FFS	Subalpine Fir-Engelmann Spruce Forest
FLP	Lodgepole Pine Forest
FSP	Engelmann Spruce Forest
FSW	Engelmann Spruce-Wet Shrub Forest
HGL	Herbaceous Grassland
HPF	Permanently Flooded Herbaceous
HSF	Semi-permanently Flooded Herbaceous
HWM	Wet Meadow Herbaceous
NLP	Natural or Artificial Lake/Pond
SAM	Mixed Conifer-Deciduous Shrubland: Avalanche/Snow Burial
SDS	Deciduous Shrubland: Dry-Mesic
SMR	Mixed Regenerate Shrubland
SWL	Deciduous Wet Shrubland
VCT	Cliff/Talus - Sparse Vegetation
WDF	Douglas-fir Woodland
WFS	Subalpine Fir-Engelmann Spruce Woodland
WLP	Lodgepole Pine Woodland

APPENDIX C

GENCLASS and CLASS classifications as characterized and designated by Dan Buckler (2012).

GENCLASS	Description
MatTree	Mature Tree
EmTree	Emergent Tree
CLASS	Description
EmAsp	Emergent Aspen
EmLod	Emergent Lodgepole Pine
EmAspLod	Emergent Aspen and Lodgepole Pine
EmAspLodDFir	Emergent Aspen, Lodgepole Pine, and Douglas-fir
EmAspLodWil	Emergent Aspen, Lodgepole Pine, and Willow
EmLodWil	Emergent Lodgepole Pine and Willow
EmShr	Emergent Shrubland
Grass	Grassland
GraShr	Grassland with Shrubs
WetShr	Wet Shrubland
Wil	Willow
MatAsp	Mature Aspen
MatCon	Mature Conifer
MatES	Mature Spruce-Fir
MatAspES	Maure Aspen and Spruce-fir
MatMix	Mature Mix
Water	Water

APPENDIX D

ArcGIS attribute table for mature tree stands including WGMAP codes, GENCLASS codes, and CLASS codes.

FID	WGMAP	GENCLASS	CLASS
0	FEP	MatTree	MatMix
1	FEP	MatTree	MatMix
2	FFS	MatTree	MatES
3	FDF	MatTree	MatCon
4	FFS	MatTree	MatES
5	FFS	MatTree	MatES
6	FEP	MatTree	MatMix
7	FEP	MatTree	MatESAsp
8	FAP	MatTree	MatAsp
9	FLP	MatTree	MatCon
10	FAP	MatTree	MatAsp
11	FFS	MatTree	MatES
12	FFS	MatTree	MatES
13	FFS	MatTree	MatES
14	FFS	MatTree	MatES
15	FEP	MatTree	MatMix
16	FEP	MatTree	MatMix
17	FEP	MatTree	MatMix
18	FEP	MatTree	MatMix
19	SAM	MatTree	MatMix
20	FEP	MatTree	MatMix
21	FAP	MatTree	MatAsp
22	FEP	MatTree	MatMix
23	FEP	MatTree	MatMix
24	FEP	MatTree	MatMix
25	FEP	MatTree	MatMix
26	FSP	MatTree	MatES
27	FFS	MatTree	MatES
28	FSP	MatTree	MatES
29	FAP	MatTree	MatAsp
30	FAP	MatTree	MatAsp
31	FSP	MatTree	MatES
32	FEP	MatTree	MatMix
33	FEP	MatTree	MatMix
34	FFS	MatTree	MatES
35	FAP	MatTree	MatAsp
36	FDF	MatTree	MatCon

FID	WGMAP	GENCLASS	CLASS
37	FEP	MatTree	MatMix
38	FEP	MatTree	MatMix
39	FAP	MatTree	MatAsp
40	FEP	MatTree	MatMix
41	FEP	MatTree	MatMix
42	FEP	MatTree	MatMix
43	FEP	MatTree	MatMix
44	FEP	MatTree	MatMix
45	FEP	MatTree	MatMix
46	FEP	MatTree	MatMix
47	FEP	MatTree	MatMix
48	FEP	MatTree	MatMix
49	FEP	MatTree	MatMix
50	FFS	MatTree	MatES
51	FEP	MatTree	MatMix
52	FAP	MatTree	MatAsp
53	FEP	MatTree	MatMix
54	FEP	MatTree	MatMix
55	FEP	MatTree	MatMix
56	FEP	MatTree	MatMix
57	FFS	MatTree	MatES
58	FEP/FDF	MatTree	MatMix/MatES
59	FDF/FEP	MatTree	MatES/MatMix
60	FLP	MatTree	MatCon
61	FEP	MatTree	MatMix
62	FFS	MatTree	MatES
63	FFS	MatTree	MatES
64	FFS	MatTree	MatES
65	FAP	MatTree	MatAsp
66	FEP	MatTree	MatMix
67	FEP	MatTree	MatMix
68	FEP	MatTree	MatMix
69	FSP	MatTree	MatES
70	FCW	MatTree	MatCon
71	FSP	MatTree	MatES
72	FSP	MatTree	MatES
73	FAP	MatTree	MatAsp

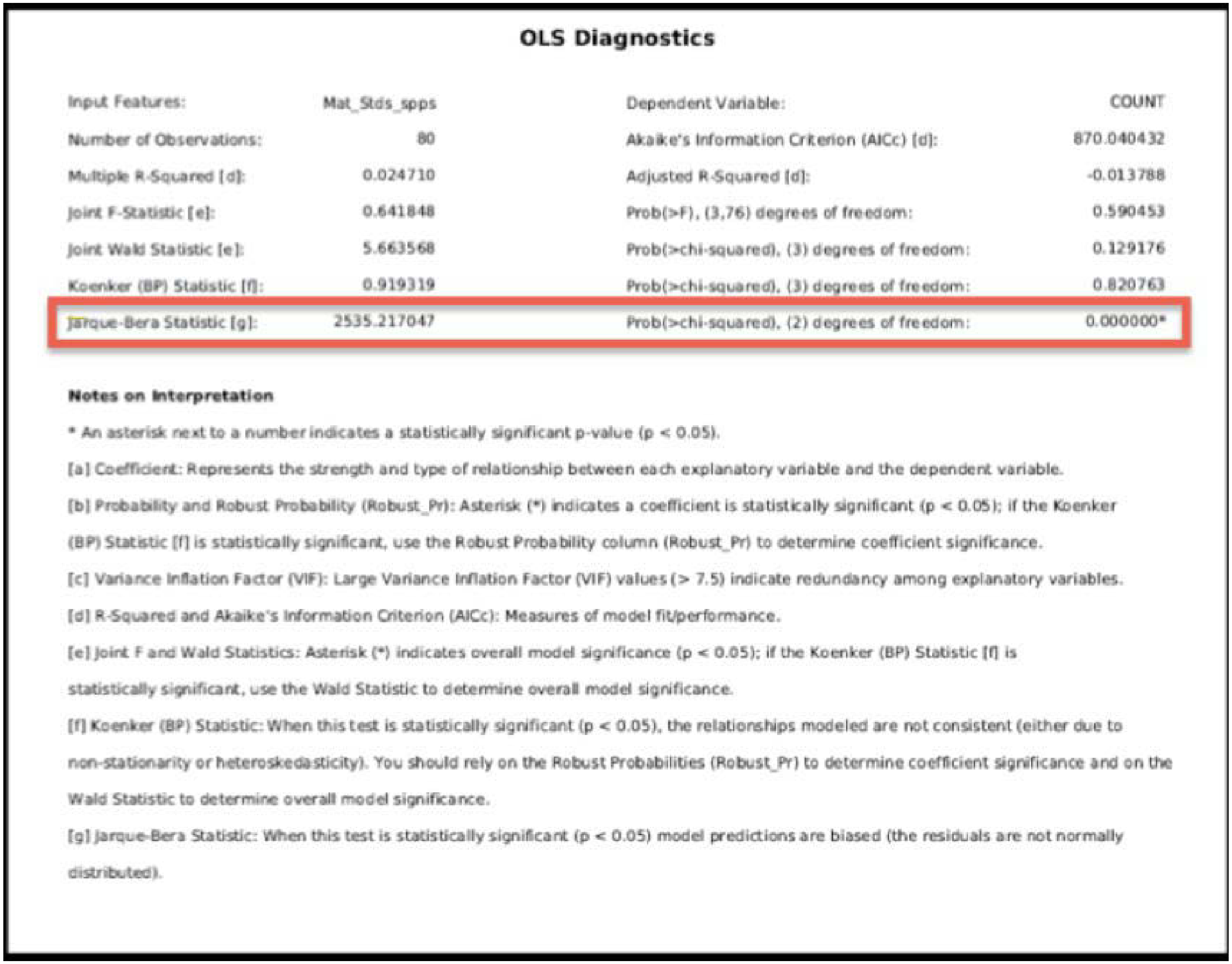
FID	**WGMAP**	**GENCLASS**	**CLASS**
74	FEP	MatTree	MatMix
75	FEP	MatTree	MatMix
76	FFS	MatTree	MatES
77	FEP	MatTree	MatMix
78	FFS	MatTree	MatES
79	FLP	MatTree	MatCon

ArcGIS attribute table for new growth vegetation including code listings and mature tree stand associations.

FID	WGMAP Code	GENCLASS	CLASS	MatStd_Association
0	FAP	EmTree	EmAsp	0
1	FAP	EmTree	EmAsp	21
2	FEP	EmTree	EmDF	23
3	FEP	EmTree	EmDF	24
4	FEP	EmTree	EmDF	25
5	FAP	EmTree	EmAsp	27
6	FAP	EmTree	EmAsp	29
7	FAP	EmTree	EmAsp	30
8	FEP	EmTree	EmMix	32
9	FEP	EmTree	EmMix	33
10	FAP	EmTree	EmAsp	35
11	FEP	EmTree	EmMix	36
12	FEP	EmTree	EmMix	38
13	FEP	EmTree	EmMix	40
14	FEP	EmTree	EmMix	41
15	FEP	EmTree	EmMix	45
16	FAP	EmTree	EmAsp	52
17	FEP	EmTree	EmMix	53
18	FEP	EmTree	EmMix	55
19	FEP	EmTree	EmAspLod	59
20	FAP	EmTree	EmAsp	58
21	FEP	EmTree	EmAspLod	63
22	FEP	EmTree	EmAspLod	64
23	FAP	EmTree	EmAsp	65
24	FAP	EmTree	EmAsp	22
25	FEP	EmTree	EmAspLodDFi	3
26	FEP	EmTree	EmAspLod	48

APPENDIX E

OLS diagnostics report



OLS Diagnostics

Input Features:	Mat_Stds_spps	Dependent Variable:	COUNT
Number of Observations:	80	Akaike's Information Criterion (AICc) [d]:	870.040432
Multiple R-Squared [d]:	0.024710	Adjusted R-Squared [d]:	-0.013788
Joint F-Statistic [e]:	0.641848	Prob(>F), (3,76) degrees of freedom:	0.590453
Joint Wald Statistic [e]:	5.663568	Prob(>chi-squared), (3) degrees of freedom:	0.129176
Koenker (BP) Statistic [f]:	0.919319	Prob(>chi-squared), (3) degrees of freedom:	0.820763
Jarque-Bera Statistic [g]:	2535.217047	Prob(>chi-squared), (2) degrees of freedom:	0.000000*

Notes on Interpretation

* An asterisk next to a number indicates a statistically significant p-value ($p < 0.05$).

[a] Coefficient: Represents the strength and type of relationship between each explanatory variable and the dependent variable.

[b] Probability and Robust Probability (Robust_Pr): Asterisk (*) indicates a coefficient is statistically significant ($p < 0.05$); if the Koenker (BP) Statistic [f] is statistically significant, use the Robust Probability column (Robust_Pr) to determine coefficient significance.

[c] Variance Inflation Factor (VIF): Large Variance Inflation Factor (VIF) values (> 7.5) indicate redundancy among explanatory variables.

[d] R-Squared and Akaike's Information Criterion (AICc): Measures of model fit/performance.

[e] Joint F and Wald Statistics: Asterisk (*) indicates overall model significance ($p < 0.05$); if the Koenker (BP) Statistic [f] is statistically significant, use the Wald Statistic to determine overall model significance.

[f] Koenker (BP) Statistic: When this test is statistically significant ($p < 0.05$), the relationships modeled are not consistent (either due to non-stationarity or heteroskedasticity). You should rely on the Robust Probabilities (Robust_Pr) to determine coefficient significance and on the Wald Statistic to determine overall model significance.

[g] Jarque-Bera Statistic: When this test is statistically significant ($p < 0.05$) model predictions are biased (the residuals are not normally distributed).

APPENDIX F

NDVI Statistics Report. DN refers to the digital number, or brightness value, of each pixel and Pixel Count refers to the frequency each DN is found in the image.

1994:

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
-0.454545	1	0.058711	23
-0.401632	3	0.064002	30
-0.338137	10	0.069294	24
-0.274641	1	0.074585	37
-0.253476	23	0.079876	25
-0.232311	2	0.085167	24
-0.200563	11	0.090459	39
-0.168815	5	0.09575	36
-0.14765	8	0.101041	21
-0.115902	10	0.106333	27
-0.094737	6	0.111624	23
-0.078863	5	0.116915	23
-0.06828	1	0.122207	20
-0.062989	1	0.127498	19
-0.057698	3	0.132789	9
-0.047115	4	0.13808	37
-0.041824	1	0.143372	8
-0.036533	1	0.148663	16
-0.031241	9	0.153954	15
-0.02595	3	0.159246	10
-0.020659	12	0.164537	10
-0.015367	8	0.169828	12
-0.010076	5	0.17512	17
-0.004785	72	0.180411	22
0.005798	6	0.185702	13
0.011089	26	0.190994	16
0.016381	23	0.196285	25
0.021672	25	0.201576	9
0.026963	14	0.206867	11
0.032254	29	0.212159	13
0.037546	27	0.21745	7
0.042837	19	0.222741	18
0.048128	34	0.228033	10
0.05342	16	0.233324	10

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
0.238615	10	0.423811	40
0.243907	13	0.429102	12
0.249198	9	0.434393	25
0.254489	11	0.439685	27
0.25978	10	0.444976	28
0.265072	9	0.450267	19
0.270363	9	0.455559	27
0.275654	5	0.46085	36
0.280946	14	0.466141	41
0.286237	9	0.471433	23
0.291528	12	0.476724	35
0.29682	16	0.482015	43
0.302111	12	0.487306	19
0.307402	9	0.492598	45
0.312693	22	0.497889	59
0.317985	7	0.50318	55
0.323276	16	0.508472	39
0.328567	36	0.513763	49
0.33915	27	0.519054	53
0.344441	6	0.524346	50
0.349733	20	0.529637	47
0.355024	29	0.534928	67
0.360315	16	0.54022	62
0.365607	24	0.545511	53
0.370898	18	0.550802	53
0.376189	20	0.556093	51
0.38148	20	0.561385	79
0.386772	17	0.566676	73
0.392063	23	0.571967	56
0.397354	30	0.577259	86
0.402646	23	0.58255	72
0.407937	20	0.587841	86
0.413228	28	0.593133	82
0.41852	19	0.598424	98

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
0.603715	83	0.74658	1021
0.609006	99	0.751872	995
0.614298	90	0.757163	1223
0.619589	67	0.762454	1239
0.62488	133	0.767746	1262
0.630172	105	0.773037	1555
0.635463	148	0.778328	784
0.640754	164	0.783619	1131
0.646046	173	0.788911	1253
0.651337	166	0.794202	773
0.656628	195	0.799493	1064
0.661919	331	0.804785	975
0.667211	132	0.810076	626
0.672502	274	0.815367	614
0.677793	298	0.820659	411
0.683085	309	0.82595	392
0.688376	374	0.831241	264
0.693667	411	0.836532	180
0.698959	433	0.841824	151
0.70425	535	0.847115	68
0.709541	772	0.852406	51
0.714833	447	0.857698	15
0.720124	631	0.862989	17
0.725415	753	0.86828	14
0.730706	925	0.873572	4
0.735998	860	0.878863	2
0.741289	1110	0.894737	1

1999:

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
-0.25	1	-0.101503	0
-0.245359	0	-0.096863	0
-0.240719	0	-0.092222	6
-0.236078	0	-0.087582	0
-0.231438	0	-0.082941	0
-0.226797	0	-0.078301	5
-0.222157	0	-0.07366	0
-0.217516	0	-0.06902	6
-0.212876	0	-0.064379	0
-0.208235	0	-0.059739	0
-0.203595	0	-0.055098	0
-0.198954	0	-0.050458	0
-0.194314	0	-0.045817	0
-0.189673	0	-0.041176	0
-0.185033	0	-0.036536	0
-0.180392	0	-0.031895	0
-0.175752	0	-0.027255	0
-0.171111	1	-0.022614	0
-0.166471	0	-0.017974	0
-0.16183	0	-0.013333	2
-0.15719	0	-0.008693	7
-0.152549	0	-0.004052	54
-0.147908	0	0.000588	0
-0.143268	1	0.005229	5
-0.138627	0	0.009869	5
-0.133987	0	0.01451	10
-0.129346	1	0.01915	11
-0.124706	0	0.023791	9
-0.120065	0	0.028431	14
-0.115425	0	0.033072	21
-0.110784	0	0.037712	19
-0.106144	0	0.042353	17

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
0.046993	28	0.204771	57
0.051634	26	0.209412	48
0.056275	33	0.214052	36
0.060915	36	0.218693	60
0.065556	42	0.223333	43
0.070196	25	0.227974	50
0.074837	30	0.232614	61
0.079477	37	0.237255	50
0.084118	40	0.241895	75
0.088758	60	0.246536	89
0.093399	49	0.251176	35
0.098039	45	0.255817	75
0.10268	32	0.260458	60
0.10732	57	0.265098	83
0.111961	36	0.269739	78
0.116601	48	0.274379	84
0.121242	39	0.27902	55
0.125882	45	0.28366	48
0.130523	33	0.288301	90
0.135163	49	0.292941	152
0.139804	44	0.297582	50
0.144444	47	0.302222	44
0.149085	32	0.306863	95
0.153725	41	0.311503	213
0.158366	35	0.316144	78
0.163007	39	0.320784	17
0.167647	35	0.325425	9
0.172288	42	0.330065	331
0.176928	29	0.334706	0
0.181569	39	0.339346	16
0.186209	40	0.343987	44
0.19085	41	0.348627	200
0.19549	66	0.353268	108
0.200131	3	0.357908	37

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
0.362549	77	0.515686	91
0.36719	115	0.520327	115
0.37183	122	0.524967	105
0.376471	97	0.529608	74
0.381111	49	0.534248	161
0.385752	85	0.538889	68
0.390392	96	0.543529	103
0.395033	43	0.54817	109
0.399673	128	0.55281	115
0.404314	71	0.557451	102
0.408954	124	0.562092	123
0.413595	56	0.566732	60
0.418235	113	0.571373	137
0.422876	19	0.576013	109
0.427516	142	0.580654	129
0.432157	91	0.585294	70
0.436797	85	0.589935	149
0.441438	125	0.594575	36
0.446078	83	0.599216	168
0.450719	128	0.603856	131
0.455359	95	0.608497	136
0.46	91	0.613137	120
0.464641	57	0.617778	91
0.469281	171	0.622418	126
0.473922	88	0.627059	122
0.478562	65	0.631699	81
0.483203	115	0.63634	162
0.487843	127	0.64098	144
0.492484	24	0.645621	128
0.497124	233	0.650261	116
0.501765	16	0.654902	110
0.506405	77	0.659542	156
0.511046	155	0.664183	135

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
0.668824	138	0.803399	493
0.673464	161	0.808039	603
0.678105	166	0.81268	528
0.682745	149	0.81732	604
0.687386	145	0.821961	589
0.692026	204	0.826601	514
0.696667	160	0.831242	563
0.701307	228	0.835882	552
0.705948	186	0.840523	594
0.710588	235	0.845163	563
0.715229	152	0.849804	594
0.719869	219	0.854444	587
0.72451	200	0.859085	611
0.72915	263	0.863725	536
0.733791	226	0.868366	456
0.738431	236	0.873007	461
0.743072	298	0.877647	337
0.747712	239	0.882288	376
0.752353	349	0.886928	198
0.756993	316	0.891569	128
0.761634	365	0.896209	78
0.766275	371	0.90085	42
0.770915	441	0.90549	31
0.775556	342	0.910131	10
0.780196	496	0.914771	1
0.784837	568	0.919412	0
0.789477	463	0.924052	0
0.794118	460	0.928693	0
0.798758	585	0.933333	1

2014:

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
-0.676127	1	-0.38137	1
-0.651041	2	-0.343742	2
-0.619684	1	-0.33747	1
-0.613413	2	-0.324927	2
-0.607141	1	-0.318656	2
-0.60087	1	-0.312384	1
-0.594598	6	-0.306113	1
-0.588327	6	-0.287299	1
-0.582056	7	-0.281027	2
-0.575784	3	-0.274756	1
-0.569513	6	-0.268485	1
-0.563241	8	-0.262213	1
-0.55697	3	-0.255942	1
-0.550698	1	-0.237127	2
-0.538156	2	-0.218313	1
-0.531884	1	-0.174413	1
-0.525613	2	-0.16187	1
-0.51307	4	-0.136785	2
-0.506799	2	-0.124242	2
-0.494256	2	-0.111699	1
-0.46917	1	-0.099156	1
-0.450356	3	-0.092885	1
-0.444084	3	-0.080342	1
-0.437813	2	-0.036442	2
-0.431541	1	-0.030171	1
-0.42527	2	-0.023899	1
-0.418999	1	-0.011356	1
-0.406456	2	-0.005085	1
-0.393913	1	0.013729	1

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
0.026272	1	0.295943	25
0.032544	1	0.302215	22
0.051358	1	0.308486	24
0.057629	1	0.314758	22
0.070172	3	0.321029	30
0.082715	1	0.3273	18
0.088986	4	0.333572	25
0.095258	6	0.339843	23
0.101529	6	0.346115	34
0.107801	13	0.352386	20
0.114072	14	0.358658	29
0.120344	23	0.364929	26
0.126615	25	0.3712	28
0.132886	23	0.377472	23
0.139158	27	0.383743	11
0.145429	21	0.390015	26
0.151701	28	0.396286	33
0.157972	27	0.402558	24
0.164244	29	0.408829	28
0.170515	37	0.4151	32
0.176786	43	0.421372	35
0.183058	54	0.427643	42
0.189329	35	0.433915	27
0.195601	35	0.440186	21
0.201872	38	0.446457	40
0.208143	38	0.452729	34
0.214415	27	0.459	25
0.220686	28	0.465272	44
0.226958	27	0.471543	29
0.233229	37	0.477815	29
0.239501	29	0.484086	33
0.245772	30	0.490357	36
0.252043	32	0.496629	50
0.258315	25	0.5029	33
0.264586	22	0.509172	34
0.270858	29	0.515443	47
0.277129	28	0.521715	58
0.283401	21	0.527986	32
0.289672	21	0.534257	44

Digital Number (DN)	Point Total	Digital Number (DN)	Point Total
0.540529	43	0.734943	232
0.5468	56	0.741214	292
0.553072	59	0.747486	295
0.559343	72	0.753757	391
0.565614	58	0.760029	380
0.571886	66	0.7663	400
0.578157	74	0.772571	413
0.584429	105	0.778843	474
0.5907	96	0.785114	510
0.596972	95	0.791386	560
0.603243	80	0.797657	687
0.609514	91	0.803928	688
0.615786	104	0.8102	842
0.622057	135	0.816471	873
0.628329	121	0.822743	1039
0.6346	125	0.829014	1130
0.640872	149	0.835286	1432
0.647143	124	0.841557	1635
0.653414	136	0.847828	1777
0.659686	147	0.8541	1744
0.665957	136	0.860371	1698
0.672229	170	0.866643	1653
0.6785	155	0.872914	1451
0.684771	186	0.879186	1148
0.691043	173	0.885457	741
0.697314	191	0.891728	411
0.703586	215	0.898	176
0.709857	220	0.904271	59
0.716129	224	0.910543	14
0.7224	258	0.916814	1
0.728671	234	0.923085	1