SIMULATING HISTORIC LANDSCAPE PATTERNS OF FIRE IN THE SOUTHERN APPALACHIAN MOUNTAINS: IMPLICATIONS FOR FIRE HISTORY AND MANAGEMENT

A Thesis

by

ELLEN R. GASS

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Chair of Committee,	Charles W. Lafon
Committee Members,	David M. Cairns
	Fred E. Smeins
Head of Department,	Vatche Tchakerian

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ABSTRACT

Fire suppression policies implemented in the early 20th century led to a decrease in fire-associated species and ecosystems in the southern Appalachian Mountains. As managers work towards restoration, a greater understanding of the pre-suppression fire regime is needed. Fire frequency and seasonality can be determined from physical fire records, such as fire scars, but fire size, fire cycle, ignition density, and ignition source are more difficult to ascertain. Using FARSITE, a spatially explicit fire model, I predicted past fire spread in the western Great Smoky Mountains National Park (GSMNP). Results showed a mean pre-suppression fire size of over an order of magnitude larger than fires on current landscape conditions (567 ha vs. 45 ha). Large fire sizes would have encouraged fire-associated vegetation and continuous flammable fuelbeds. In addition, the current lightning ignition rate within the study area resulted in a 120-135 year pre-suppression lightning fire cycle, which indicates that natural fires were influential on the landscape. This fire cycle is shorter than the lightning fire cycle experienced today (approx. 25-30,000 years). Using the mean fire return interval from previous research, I determined the potential contribution of lightning and anthropogenic ignitions to the fire cycle. This contributes to the debate on the importance of lightning versus anthropogenic ignitions to the pre-suppression fire regime. Most importantly, the estimation of mean fire size, fire cycle, and ignition density for lightning and anthropogenically ignited fires may aid federal resource managers as they use lightning ignitions and prescribed burns to restore fire-associated ecosystems in the GSMNP and other areas of the southern Appalachians.

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1. INTRODUCTION

Knowledge of pre-suppression landscape patterns of fire will help managers make better land management decisions concerning the southern Appalachian Mountains, especially through more effective use of lightning-ignited fires and controlled burns. Improved management practices will lead to ecosystems that more closely resemble the landscape before fire suppression. In at least some parts of the Appalachian Mountains, the pre-suppression landscape had open canopy woodlands with grass understories that were maintained by frequent fire (Harrod et al. 2000). Fire suppression practices in the early 20th century led to drastic changes on the North American landscape (Harrod et al. 2000; Bond and Keeley 2005; Nowacki and Abrams 2008). In the southern Appalachian Mountains, effects of suppression include a loss of biodiversity and fire-associated species (Nowacki and Abrams 2008). Also, increased moisture content and decreased flammability of fuels resulting from fire suppression has changed how fire can spread on the current landscape (Harrod et al. 1998; Lafon 2010).

Resource managers now understand that fire is necessary for the maintenance of many landscapes in the United States. Fire acts to encourage fire-associated species and remove competitors. It can lead to a more open landscape structure that allows for an increased herbaceous understory. Managers increasingly use fire in restoration efforts, but a more complete understanding of pre-suppression fire patterns is needed to help mangers make the most effective use of fire as a tool. Current fire history research in this area demonstrates that fires occurred frequently before the early 20th century and leads to questions about the spatial extent of fires, ignition density, and ignition source necessary to generate the frequent fire record that researchers have found (Harmon 1982; Hoss et al. 2008; Aldrich et al. 2010; Lafon 2010).

My study enhances our understanding of the spatial extent of fires on the complex terrain of the southern Appalachian Mountains, where researchers have only recently begun to recognize the importance of fire prior to suppression. An increased understanding of fires' spatial extent will allow us to draw conclusions about ignition density and sources. Both lightning and anthropogenic ignitions occurred in the southern Appalachian Mountains (Brose et al. 2001; Lafon 2010). However, the relative importance of anthropogenic versus lightning ignitions is debated (Nowacki and Abrams 2008; Lafon 2010). Historic accounts provide evidence for anthropogenic ignitions (Pyne 1982; Denevan 1992; Nowacki and Abrams 2008), but they do not tell us what percentage of pre-suppression ignitions was anthropogenic. Likewise, lightning ignitions were important actors on the landscape (Petersen and Drewa 2006; Lafon 2010), but without information on the spatial extent of fires, their relative importance cannot be determined. As managers try to determine the frequency, size, and ignition considerations for burns in the southern Appalachian Mountains, an increased understanding of the historic frequency, size, and ignition sources can be used to create more effective management plans in order to reverse some of the undesired vegetation effects that fire suppression has caused.

1.1 Hypotheses and objectives

The overall objective of my research is to expand our understanding of the spatial extent and ignition density of pre-suppression fires by modeling pre-suppression fire behavior and spread using FARSITE. Two hypotheses drive this study:

1) Pre-suppression fire sizes predicted by fire modeling will be larger than those on the current landscape.
2) Ignition density required to support the pre-suppression fire regime for the western Great Smoky Mountains National Park (GSMNP) will be greater than can be accounted for by lightning ignitions alone.

To test my two hypotheses, I pursued three research objectives:

1) Calibrate FARSITE to accurately model fires in the western GSMNP.
2) Simulate the spatial extent of fires on a pre-suppression landscape.
3) Estimate the percentage of pre-suppression fire frequency that could be accounted for by lightning and anthropogenic ignitions.

2. BACKGROUND

2.1 Fire in the southern Appalachian Mountains

Wildfires, both anthropogenic and natural in origin, have been actors on the southern Appalachian Mountains landscape dating back at least 4,000 years ago (Delcourt et al. 1986; Delcourt and Delcourt 1997). Evidence for the presence of fire comes from multiple sources. Historical records, including eye-witness accounts and survey witness tree records, indicate that fire was a significant shaper of the southern Appalachian landscape prior to European settlement up until the early 20th century (Pyne 1982; Nowacki and Abrams 2008; Lafon 2010). Native Americans in the eastern deciduous forests used fire as a tool for managing their landscape and manipulating the vegetation composition of the area (Pyne 1982; Denevan 1992; Delcourt and Delcourt 1997; Nowacki and Abrams 2008). As European settlers moved into the area in the mid-18th to early 19th century, they displaced the Native American population (Brose et al. 2001). Many maintained the practice of burning they had observed from the Native Americans (Pyne et al. 1996). Some areas experienced periods of depopulation between Native American habitation and European settlement. Industrialized logging had a large economic and ecological impact in the region ca. 1880-1930 (Pyne 1982; Brose et al. 2001). The slash left behind was easily ignited, often causing large, intense, stand-replacing wildfires that were difficult to control (Brose et al. 2001; Lafon 2010). Starting in the 1920s and 1930s, the United States Forest Service (USFS) and other agencies instituted a policy of fire suppression and prevention to avert the catastrophic fires that were occurring due to logging activity. The attempt during most of the 20th century to extinguish all wildfires immediately significantly altered the southern Appalachian landscape.

2.2 Vegetation and landscape conditions in the southern Appalachian Mountains

Current landscapes in the southern Appalachians reflect the fire suppression policies of the 20th century. Both the structure and composition of the vegetation is different than what was found on the landscape prior to suppression and logging (Bond and Keeley 2005; Nowacki and Abrams 2008). The pre-suppression landscape apparently was a pyrogenic landscape with flammable patches of open woodlands (Denevan 1992; Harrod et al. 1998; Harrod et al. 2000; Nowacki and Abrams 2008). Frequent fires promoted many fire-associated species prior to European settlement (Wright and Bailey 1982; Abrams 1992; Lafon 2010). These species remain on the current landscape, providing evidence for the historic role of fire on the southern Appalachian landscape.

Fire-associated species found in the southern Appalachians include plants such as Peters Mountain mallow (*Iliamna corei*) and mountain golden heather (*Hudsonia montana*). Peters Mountain mallow requires fire for seed germination (Buttrick 1992). Fires remove the competitor sand myrtle (*Leiophyllum buxifolium*) and promote mountain golden heather seedling establishment by removing surface litter and exposing mineral soil (Frost 1990). Fire-associated species also include several pine (*Pinus*) and oak (*Quercus*), which formed the greater composition of the pre-suppression landscape (Abrams 2003).

2.2.1 Pine forests

Pine-dominated forests are commonly associated with fire (Agee 1998). Many pines have specific adaptations that allow them to survive and thrive in fire-associated ecosystems (Agee 1998). Four pine species found in the southern Appalachians show adaptations associated with fire, but Table Mountain pine (*P. pungens*) and pitch pine (*P. rigida*) are considered the most fire-dependent. Pitch pine and shortleaf pine (*P. echinata*) experience basal resprouting after fire (Keeley and Zedler 1998; Williams 1998; Brose and Waldrop 2006). Adult Table Mountain pine and pitch pine have thick bark that protects them from fires and self-prune lower branches to prevent fire from moving up into the canopy (Williams 1998; Brose and Waldrop 2006). Table Mountain pine, an endemic species to the central and southern Appalachians, and pitch pine have serotinous cones (Lamont et al. 1991; Williams 1998). They remain closed past maturity, sealed with resins that prevent the cones from opening and releasing seeds until melted by heat (Barden 1979; Williams 1998). In the southern Appalachians, forests dominated by Table Mountain pine and pitch pine are typically found on xeric, exposed ridgetops and south-facing slopes (Whittaker 1956; Williams 1998; Lafon 2010). Table Mountain pine and pitch pine are shade-intolerant; require open, scarified sites to establish and germinate; and thrive on nutrient-poor soils or areas where competitors have been removed (Williams and Johnson 1992; Williams 1998). Fires trigger regeneration for

Table Mountain pine and pitch pine in several ways (Williams 1998; Brose and Waldrop 2006). Fires open serotinous cones, which distributes seeds onto the mineral soil, where seedlings can establish. Seedlings are more successful at establishing on exposed soils where fires have removed leaf litter and duff. By removing competitors, fires allow existing pines to have access to resources.

2.2.2 Oak forests

Oaks have been dominant in the deciduous forests of the eastern U.S. for 10,000 years (Abrams 1992). Oak dominated forests cover a wide range of topographic positions, from dry upper slopes to submesic lower slopes. As early to midsuccessional species, oaks are typically not a dominant species in later successional forests due to their low to intermediate shade tolerance (Abrams 1992). The presence of oak species in the southern Appalachians is thought to be associated with frequent fires (Abrams 1992). Frequent burning maintains stands of species such as chestnut oak (*Quercus prinus*) and white oak (*Quercus alba*) by removing competing species that are less resistant to fire (Nowacki and Abrams 2008; Lafon 2010). Many oak species have adaptations that allow them to survive on a landscape that experiences frequent fire. Fire adaptations include thick, protective bark, which can compartmentalize fire damage to prevent decay from spreading, and the ability to resprout after fire (Lorimer 1985; Abrams 1992; Lafon 2010). Fire also creates a more favorable seedbed for seed germination and establishment (Lorimer 1985; Abrams 1992).

2.2.3 Historic conditions

Prior to European settlement, frequent fires appear to have maintained oak and pine stands in open woodland conditions with flammable herbaceous understories (Wright and Baily 1982; Abrams 1992; Frost 1998; Harrod et al. 2000; Nowacki and Abrams 2008). Fires restricted woody fuel accumulation and maintained low basal area and density of canopy trees (Harrod et al. 2000). Open conditions allowed shade-intolerant, fire-dependent species, such as oaks, pines, and grasses, to thrive. Pine-dominated forests probably expanded following the fires associated with logging in the late 19th century and early 20th century, establishing on more mesic sites than may have been typical historically (Williams 1998; Williams and Johnson 1992; Harrod et al. 1998).

2.2.4 Fire exclusion effects and mesophication

Fire suppression has resulted in a shift from open woodlands to dense forests and shrub thickets; from shade-intolerant, fire-associated species to shade-tolerant, fire-sensitive species in many areas. The forest experienced a rapid increase in canopy density and basal area in the first decades of fire exclusion (Harmon 1980). The current forest structure is significantly denser than what was found prior to suppression (Harrod et al. 1998; Nowacki and Abrams 2008). Harrod et al. (1998) found that stem density had increased almost threefold, and basal area almost twofold, after 40 years of fire exclusion in xeric forests in the western GSMNP. As density and basal area increase, so do canopy cover and shading. Shade-intolerant oak and pine species cannot survive on the forest floor and are being outcompeted by shade-tolerant, fire-sensitive species. Thus, oak and pine regeneration and recruitment have declined (Abrams 1992; Brose and Waldrop 2006; Nowacki and Abrams 2008).

Pine forests are being replaced by oaks and other hardwoods, especially on mesic sites (Harmon 1982; Williams and Johnson 1992; Williams 1998; Nowacki and Abrams 2008). Oak forests are being replaced by mixed mesophytic species (Nowacki and Abrams 2008). Instead of open pine and oak stands, the region is now dominated by more mesophytic, closed canopy stands with little herbaceous cover (Harrod et al. 2000; Nowacki and Abrams 2008). Fire-sensitive, shade-tolerant species like red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), black cherry (*Prunus serotina*), white pine (*Pinus strobus*), hemlock (*Tsuga*), beech (*Fagus* spp.), birch (*Betula* spp.), sassafras (*Sassafras albidum*), tulip poplar (*Liriodendron tulipifera*), and black gum (*Nyssa sylvatica*) are found in many areas previously dominated by fire-associated, shade-intolerant species (Harmon 1980; Harmon 1982; Harrod et al. 1998; Abrams 1992; Nowacki and Abrams 2008). Much of this replacement has taken place within one tree generation after the removal of fire (Nowacki and Abrams 2008; Abrams 1992; Abrams 2003). While many fire-sensitive, shade-tolerant species were historically found in coves and on mesic sites (Whittaker 1956; Harrod et al. 1998), their spread onto xeric sites and mesic sites that had historically been burned is a product of fire exclusion. Nowacki and Abrams (2008) termed this process “mesophication.”

The moist, shaded conditions that encourage fire-sensitive species also discourage fire ignitions and spread, providing positive feedback loops for the mesophication process (Nowacki and Abrams 2008). The dense configuration and high leaf area of fire-sensitive species causes little light to reach the forest floor to dry fuels, decreases drying winds, and increases relative humidity. Fire-sensitive species also tend to produce fuels that hold more moisture and decay more rapidly than fuels produced by fire-associated species. Higher fuel moisture reduces the flammability of the understory, limiting fire spread (Nowacki and Abrams 2008).

2.3 Fire regimes in the southern Appalachian Mountains

While the presence of fire-associated species and historical accounts indicate the existence of fire on the southern Appalachian landscape, they do not provide a complete picture. A single fire can affect current conditions, but landscapes are shaped by the occurrence (or nonoccurrence) of multiple fires over time. Fire regimes are a "generalized description of the role fire plays in an ecosystem" (Agee 1993). They are defined by a list of typical parameters. Depending on the available evidence, the parameters listed can vary (Krebs et al. 2010). Fire regimes generally include temporal, magnitude, and spatial characteristics of fire within the ecosystem. Three distinct fire regimes are thought to have existed in the southern Appalachian mixed oak forests during recent centuries: 1) frequent, low-intensity surfaces fires ignited during the period of Native American and then European settler habitation; 2) stand-replacing, high-intensity fires caused by logging and industrial activities during the late 19th and early 20th centuries; 3) 'no-fire' regime that has led to the replacement of oaks and pines by mesophytic species under modern fire prevention policies since the 1930s (Brose et al. 2001; Lafon 2010).

2.4 Fire frequency and seasonality

Little is known about the fire regime(s) prior to logging and fire suppression. Fire history reconstructions can help illuminate the fire regime that existed during Native American habitation and European settlement. Researchers have used fire-scarred trees and charcoal in pond/bog sediments and soils to determine the presence, density, and frequency of fires (Abrams 1992; Delcourt and Delcourt 1998; Hoss et al. 2008; Aldrich et al. 2010; Bowman et al. 2011). Sediment cores from the southern Appalachians show charcoal, indicating the presence of fire, as far back as 4,000 years ago (Delcourt and Delcourt 1998). Pollen records from cores indicate that fire corresponded with open oak, pine, and chestnut forests (Delcourt et al. 1986; Delcourt et al. 1998). To answer more detailed questions about the frequency and seasonality of pre-suppression fires in the southern Appalachians, researchers have reconstructed fire histories from fire-scarred trees, which is the most suitable way to determine fire history in fire regimes dominated by surface fires (Swetnam and Baisan 1996)

The three physiographic regions of the southern Appalachian Mountains show similar fire frequencies using reconstructed fire histories from fire scars for years prior to logging and suppression (Tables 1 and 2). Fire frequency is often reported using mean fire return interval (MFI) for a specific area and time period (Pyne et al. 1996). MFI is the average interval for all trees, or the sum of all intervals from all trees divided by the

Table 1. Fire history reconstructions in the southern Appalachian Mountains

Author	Physiographic Province	Community	Study Location	Logging history	Elevation (m)
Harmon 1982	BR	Pine forests	9,100 ha in westernmost part of GSMNP, Eastern TN	Relatively unlogged	260–942
Flatley et al. 2013	BR and RV	Pine stands within an oak-hickory forest	TN and NC	Unlogged	520-1115
Aldrich et al. 2010	RV	Xerophytic pine-oak stands with hardwood understory	Mill Mountain, George Washington National Forest, VA	Apparently unlogged	ca. 785
Hoss et al. 2008	RV	Oak dominated forest with some pines and other hardwoods	Narrows Preserve Peters Mountain, VA	Previously logged and apparently unlogged	610-820
Sutherland et al. 1993	RV	Oak dominated forest with Table Mountain Pine	Northern flank of Brush Mountain, Southwestern VA	Apparently unlogged	750-840
Schuler and McClain 2003	RV	Oak-pine forest, northern hardwood forest, grass balds, and the southernmost stands of red-pine	Southwest aspect near Pike Knob, North Fork Mountain, near Circleville, WV		1224
McEwan et al. 2007	AP	Mixed oak forest	Southeastern OH and eastern KY	Large-scale land clearing ca. 1870	
Shumway et al. 2001	AP	Old-growth mixed oak forest	Big Savage Mountain Savage River State Forest, Western MD	Apparently unlogged	600-670
Sutherland 1997	AP	Mixed-oak stand	Raccoon Ecological Management Area, Vinton Co, OH	Uncut after 1850s	

*BR = Blue Ridge, AP = Appalachian Plateau, RV = Ridge and Valley

Table 2. Mean return fire intervals from fire history reconstructions

Author	Physiographic Province	Range of Dates Used	Fire Interval	Interval Method	Number of stands	Number of dated cross sections	Number of scars	Number of fire years
Harmon 1982	BR	1856-1940	12.7	Arithmetic MFI	26	43	115	
Flatley et al. 2013								
Licklog Ridge	BR	1773-fire suppression	4.6/4.4	MFI/WMI**	3	116	593	91
Linville Mountain	BR	1756-fire suppression	6.5/5.8	MFI/WMI**	2	44	181	30
House Mountain	RV	1797-fire suppression	7.9/6.5	MFI/WMI**	3	82	304	37
Aldrich et al. 2010	RV	1726-1930	7.8/7.5	MFI/WMI**	4	63	209	42
Hoss et al. 2008	RV	1867-1976	12.5/12.3	MFI/WMI**	1	73	171	53
Sutherland et al. 1993	RV	1798-1944	9-11		2	14		
Schuler and McClain 2003	RV	1869-1962	15.5/14.8	MFI/WMI	1	20	17	7
McEwan et al. 2007	AP	1875-1954	7.3/6.6	MFI/WMI	9	225		33
	AP	1917-1936	2.1/1.7	MFI/WMI	1	26		10
Watch Rock	AP	1875-1934	8.4/8.2	MFI/WMI	1	33		8
Ball Diamond	AP	1878-1931	6.6/6.3	MFI/WMI	1	22		9
Arch Rock	AP	1900-1936	9.0/8.1	MFI/WMI	1	31		5
Raccoon Creek	AP	1889-1931	6.4/5.7	MFI/WMI	1	25		6
Shawnee	AP	1889-1931	5.3/4.7	MFI/WMI	1	20		9
Road Branch	AP	1885-1954	8.6/6.7	MFI/WMI	1	20		9
Dickerson Hollow	AP	1893-1954	12.2/11.1	MFI/WMI	1	20		6
Silver Creek	AP	1879-1900	n/a	MFI/WMI	1	28		2
Shumway et al. 2001	AP	1616-1959	7.6	WMI	1	19	121	42
Sutherland 1997	AP	1856-1995	5.4/3.6	MFI/WMI	1	14	48	23

*BR = Blue Ridge, AP = Appalachian Plateau, RV = Ridge and Valley **MFI and WMI calculated using filtered composite fire interval.

number of intervals (Innes et al. 2000). MFI is most representative when fires are normally distributed (Pyne et al. 1996). Many studies also report the Weibull median fire interval (WMFI), which is the median fire return interval modeled by fitting a Weibull distribution to the observed fire intervals (Grissino-Mayer 2001). Reconstructions in the Appalachian Plateau show an MFI of 5.4-7.1 years and a WMFI of 3.6-7.6 years (Sutherland 1997; Shumway et al. 2001; McEwan et al. 2007). Reconstructions in the Ridge and Valley show a MFI and WFMI of 7.8-12.5 years and 6.5-12.3 years (Sutherland et al. 1993; Hoss et al. 2008; Aldrich et al. 2010; Flatley et al. 2013). Reconstructions in the Blue Ridge show a MFI and WFMI of 4.6-12.7 years and 4.4-5.8 years (Harmon 1982; Flatley et al. 2013). It should be noted that Harmon (1982) only calculated the MFI. Across the regions of the southern Appalachians, there is agreement from reconstructions that fires occurred frequently. Reconstructions can underestimate fire frequency since not all fires cause scars (Abrams 1985). Low intensity fires might not cause scarring, whereas higher intensity fires are more likely scar trees (Mutch 1980; Guyette and Cutter 1991; Pyne et al. 1996).

Seasonality of fire events can often be determined from the position of the scar within the annual ring. If the fire scar is in the earlywood, the fire occurred early in the growing season (spring). If the fire scar is in the latewood, the fire occurred late in the growing season (late spring to summer). If the fire scar is in the dormant area, the fire occurred in the dormant season (fall or before wood growth was initiated in spring).

As with frequency, the three physiographic regions of the southern Appalachians show relatively consistent fire seasonalities (Table 3). Most fires occurring in the

Table 3. Fire seasonality from fire history reconstructions

Author	Physiographic province	Dormant Season (%)	Early season (%)	Late season (%)
Harmon 1982	BR	not determined	not determined	not determined
Flatley et al. 2013**				
Licklog Ridge	BR	90.6	9.0	0.4
Linville Mountain	BR	75.2	24.8	0.0
House Mountain	RV	75.4	23.7	0.9
Aldrich et al. 2010**	RV	89.6	9.7	0.7
Hoss et al. 2008	RV	93.6	1.8	4.6
Sutherland et al. 1993	RV	majority	not determined	not determined
Schuler and McClain 2003	RV	majority	not determined	not determined
McEwan et al. 2007	AP	84	13	3
Shumway et al. 2001	AP	91	6.4	2.9
Sutherland 1997	AP	69	25	6

*BR = Blue Ridge, AP = Appalachian Plateau, RV = Ridge and Valley
**Seasonality could not be determined for all trees.

Appalachian Plateau took place during the dormant season (69-91%), as did most fires occurring in the Ridge and Valley (75.4-93.6%) and Blue Ridge (75.2-90.6%). Early season fires accounted for 6.4-25% of fires in the Appalachian Plateau, 1.8-23.7% of fires in the Ridge and Valley, and 9.0-24.8% of fires in the Blue Ridge. Late season fires accounted for 2.9-6% of fires in the Appalachian Plateau, 0.7-4.6% of fires in the Ridge and Valley, and 0-0.4% of fires in the Blue Ridge. Burning conditions in the southern Appalachians are best during the dormant season, when there is the highest amount of dry, dead fuel on the ground due to leaf-off, low precipitation, and high winds (Lafon et al. 2005). Growing season fires are the least common due to moist fuel conditions and increased canopy cover (Lafon et al. 2005).

2.5 Spatial extent, ignition density, and fire cycle

Although its presence and frequency have been established, the spatial extent and ignition density of pre-suppression fires remain elusive. An understanding of both frequency and mean spatial extent is needed to determine the ignition density. If the mean fire sizes are smaller, then more ignitions, or a higher ignition density, are needed to maintain the observed frequency. Likewise, a larger mean spatial extent requires a smaller ignition density. While pre-suppression fires are thought to have grown larger than fires on the current landscape (Harrod et al. 2000), determining the magnitude of the change has proven difficult because paleo-ecological evidence has limited ability to inform about fire size and ignition density. Without an awareness of pre-suppression fire size, our understanding of the influence of fire on the landscape is limited. Fire size influences vegetation and fuel configuration. Burned-over areas provide exposed soil and more favorable seedbeds for early successional plants to establish (Lorimer 1985; Abrams 1992), influencing the patch shape and size of vegetation communities. As fires encourage highly flammable, herbaceous fuel beds, these fuel beds in turn encouraged more fire spread (Harrod et al. 2000). Areas of continuous fuels and no natural fire breaks have the potential to burn unimpeded from one or few ignitions (Frost 1998). If large fires created large areas of continuous fuel beds, they could influence the size of subsequent fires.

The influence of fire size is often interpreted through fire cycle. Fire cycles are generally more effective at conveying the ecological importance of fire than fire frequency. The fire cycle, or natural fire rotation, is defined by Heinselman (1973) as "the average number of years required in nature to burn-over and reproduce an area equal to the total area under consideration." Fire cycle differs from fire rotation in that fire cycle is calculated using tree cross-sections and fire scars, while fire rotation is typically determined through historical records (Innes et al. 2000). Fire cycle is useful for both scientist and managers because it provides a measure of the amount of fire within a system that can be used to elucidate the age structure of a forest stands (Heinselman 1973). It allows direct comparisons between ecosystems or between time periods within the same ecosystem (Heinselman 1973). While useful, it must be remembered that fire's impact on any landscape is the combination of many factors including fire size, fire size distribution, ignition source, ignition location, intensity, severity, fuel patterns, vegetation, topography, climate, prior disturbance history, etc.

(Heinselman 1973). While fire cycle gives us a useful quantification, scientists and managers must also investigate the patterns that compose the fire cycle to understand how fire is interacting with the landscape. Fire cycles can be determined using the average stand age of a forest (Wagner 1978) or by dividing the study area by the total area burned and multiplying that by the number of years observed (Cleland et al. 2004).

Fire cycle = (Study Area / Total Area Burned) x Years Observed

For example, if fires that burned unimpeded for 100 years at a rate of approximately 0.5 ignitions a year for a 35,000 ha study area produced a 0.1 ha mean fire size, the fire cycle would be (35,000 ha / 5 ha) x 100 years, or 700,000 years. In other words, it would take 700,000 years for an area equivalent to that of the study area to burn. If the mean fire size were 7,000 ha, the area would have a 10 year fire cycle. It should be noted that fire cycles do not imply that every hectare of the area will burn during that time. Some areas will burn multiple times and some will not burn, but the total area burned will equal the size of study area. Considering a reconstructed MFI of approximately 10 years, the 10 year fire cycle would be consistent with historic fire frequencies. The 700,000 year fire cycle would not be consistent with the reconstructed MFI, indicating that the role of fire for the 100 year observational period is different than its role historically. During the time period of the reconstructed fire history, the landscape must have experienced either fires with a larger mean size, more ignitions, or both.

Current fire cycles have been calculated for areas of the central and southern Appalachians (Table 4) using current fire size and ignition density information (Tables 5 and 6). The long fire cycles found on the current landscape do not reflect the fire

Table 4. Current fire cycle in the southern Appalachians

	Fire Cycle (years)			Physiographic		
Author	Lightning	Anthropogenic	Both	province	Area	Years
Flatley et al. 2011	25,397	1,257	1,197	BR	Great Smoky Mountains National Park	1930-2003
	-	-	204	BR	Shenandoah National Park	1930-2003
Harmon 1982	30,000	840	2,000+	BR	Western Great Smoky Mountains National Park	1940-1979
Harmon 1981	30,400	844	-	BR	Great Smoky Mountains National Park	1942-1979
Lafon and Grissino-Mayer 2007	96,637	12,216	10,845	AP	Monongahela National Forest	1970-2003
	9,461	1,472	1,274	RV	George Washington and Jefferson National Forests	1970-2003
	1,560	347	284	BR	Shenandoah National Park	1970-2003
Lafon et al. 2005	6,138	1,196	1,001	AP, RV, BR	Central Appalachians (same as Lafon and Grissino-Mayer 2007	1970-2003

*BR = Blue Ridge, AP = Appalachian Plateau, RV = Ridge and Valley**Includes suppressed fires.

Table 5. Current fire sizes in the southern Appalachians

Author	Mean Fire Size (ha) Lightning	Anthropogenic	Both	Physiographic province	Area	Years
Flatley et al. 2011	8.2	28.3	25.6	BR	Great Smoky Mountains National Park	1930-2003
	-	-	42.7	BR	Shenandoah National Park	1930-2003
Harmon 1982	3.4	5.4	-	BR	Western Great Smoky Mountains National Park	1940-1979
Harmon 1981	3.3	17.6	-	BR	Great Smoky Mountains National Park	1940-1979
Lafon and Grissino-Mayer 2007	7.8	5.3	5.5	AP	Monongahela National Forest	1970-2003
	9.1	12.6	36.9	RV	George Washington and Jefferson National Forests	1970-2003
	27.2	40.0	12.0	BR	Shenandoah National Park	1970-2003
Lafon et al. 2005	16.7	19.6	19.1	AP, RV, BR	Central Appalachians (same as Lafon and Grissino-Mayer 2007	1970-2003

*BR = Blue Ridge, AP = Appalachian Plateau, RV = Ridge and Valley

**Includes suppressed fires.

Table 6. Current ignition density in the southern Appalachians

Author	Ignition Density (N/100,000 ha/year) Lightning	Anthropogenic	Both	Physiographic Province	Area	Years
Flatley et al. 2011	0.9	5.5	6.3	BR	Great Smoky Mountains National Park	1930-2003
	-	-	13.5	BR	Shenandoah National Park	1930-2003
Harmon 1982	2.8	7.3	-	BR	Western Great Smoky Mountains National Park	1940-1979
Harmon 1981	0.1	0.6	-	BR	Great Smoky Mountains National Park	1940-1979
Lafon and Grissino-Mayer 2007	0.1	1.5	1.6	AP	Monongahela National Forest	1970-2003
	1.0	4.7	5.7	RV	George Washington and Jefferson National Forests	1970-2003
	2.0	6.3	8.3	BR	Shenandoah National Park	1970-2003
Lafon et al. 2005	1.0	4.5	5.5	AP, RV, BR	Central Appalachians (same as Lafon and Grissino-Mayer 2007	1970-2003

*BR = Blue Ridge, AP = Appalachian Plateau, RV = Ridge and Valley

**Includes suppressed fires.

frequency determined through fire history reconstructions (Lafon et al. 2005). Either the mean fire size today is smaller; there are fewer current ignitions; or a combination of both. If the mean spatial extent of fires was larger on the pre-suppression landscape, then a lower density of ignitions was required to burn the same area. By determining pre-suppression mean fire size, researchers can ascertain how dense ignitions would have to have been to burn at observed frequencies. Ignition density will also help illuminate the contribution of lightning and anthropogenic ignitions. In light of changing human activities in the southern Appalachians, was lightning alone sufficient to maintain the observed frequency? If not to what extent did humans affect the structure of the landscape through fire?

2.6 Anthropogenic and lightning ignitions

Debate exists around historic fire ignition sources in North America. Some researchers argue that anthropogenic ignitions were not a significant source of fire (Russell 1983; Vale 1998; Barrett et al. 2005). Historical accounts, fire suppression effects, and fire history reconstructions provide evidence for anthropogenic use of fire (Denevan 1992; Delcourt et al. 1998; Nowacki and Abrams 2008) with some authors even suggesting that lightning was an insignificant ignition source (Kay 2007). Both lightning and anthropogenic ignitions are seen on the current landscape (Table 7). If lightning ignitions cannot account for the reconstructed fire frequencies, then other ignition sources must have been acting on the pre-suppression landscape, most likely anthropogenic ignitions. Current lightning ignitions are an important ignition source in

Table 7. Current ignition source in the southern Appalachians

Author	Lightning	Anthropogenic	Physiographic province	Area	Years
Flatley et al. 2011	13.6%	86.4%	BR	Great Smoky Mountains National Park	1930-2003
	-	-	BR	Shenandoah National Park	1930-2003
Harmon 1982	27.7%	72.3%	BR	Western Great Smoky Mountains National Park	1940-1979
Harmon 1981	13.6%	86.4%	BR	Great Smoky Mountains National Park	1940-1979
Lafon and Grissino-Mayer 2007	7.5%	92.5%	AP	Monongahela National Forest	1970-2003
	17.6%	82.4%	RV	George Washington and Jefferson National Forests	1970-2003
	24.3%	75.7%	BR	Shenandoah National Park	1970-2003
Lafon et al. 2005	16.5%	83.5%	BR	Central Appalachians (same as Lafon and Grissino-Mayer 2007	1970-2003

*BR = Blue Ridge, AP = Appalachian Plateau, RV = Ridge and Valley

**Includes suppressed fires

some parts of the eastern deciduous forest, though they are less frequent than anthropogenic ignitions (Harmon 1981; Harmon 1982; Lafon et al. 2005; Cohen et al. 2007; Lafon and Grissino-Mayer 2007; Flatley et al. 2011). Lightning fires can cause more mortality than dormant fires since they are more likely to ignite during summer months (Sutherland et al. 1993; Lafon et al. 2005). Thus, lightning fires may cause more lasting effects than anthropogenic fires.

Lightning ignitions are most common in the growing season when the weather supports thunderstorm activity (Lafon 2010). Anthropogenic fires are most common in the dormant season when fuel conditions are most conducive to fire ignition and spread (Lafon 2010; Hoss et al. 2008). Lightning and anthropogenic fires can overlap during the spring when conditions are conducive to burning and lightning activity is increasing (Lafon 2010). The seasonality found in southern Appalachian fire history reconstructions is consistent with the current understanding of the importance of anthropogenic ignitions in the pre-logging, pre-suppression fire regime in the southern Appalachians. The reconstructed fire-scar seasonality matches what is seen in anthropogenic fires today (Lafon 2010).

The majority of the fire history reconstructions performed in the southern Appalachians includes periods of European population. However, several include periods of Native American habitation and subsequent depopulation (Aldrich et al. 2010; Shumway et al. 2001; Flatley et al. 2013). There does not appear to be a difference in fire frequency and seasonality during the depopulated periods. It is possible that lightning ignitions were more of a factor during the depopulated period (Lafon 2010).

2.7 Re-introduction of fire

The recognition of the negative consequences of fire exclusion has led managers within some areas of the southern Appalachians to reintroduce fire (Brose et al. 2001). Managers use prescribed burns and some lightning ignited fires. Under current Wildland fire use (WFU) policies, lightning ignited fires that achieve resource management objectives are allowed to burn unsuppressed (Lafon and Grissino-Mayer 2007; Cohen et al. 2007). Management objectives include promoting the fire-associated landscape and vegetation that existed prior to fire suppression (Brose et al. 2001). With the recognition that the landscape cannot be restored to exactly its pre-suppression conditions, knowledge of the pre-suppression fire regimes is still used to help inform management decision (Lafon 2010). An understanding of what fire behaviors maintained the pre-suppression landscape will allow managers to use fire more effectively. While previous research described several characteristics including frequency and seasonality, questions of fire size, ignition density, and ignition source still need to be answered. With this information, managers can draw a more complete picture about the pre-suppression role of fire on the southern Appalachian landscape and use fire more effectively as a restoration tool.

3. STUDY AREA

GSMNP is approximately 209,000 ha within the Unaka Range of the Blue Ridge physiographic province. The Blue Ridge province forms the eastern part of the Appalachian Mountains and experiences infrequent heavy precipitation events and its lowest relative humidity during the spring and summer that encourage lightning ignitions (Whittaker 1956; Lafon and Grissino-Mayer 2007). GSMNP is located in western Tennessee and eastern North Carolina, running along part of the border between the two states. It has highly variable topography, characterized by steep slopes, deep valleys, and little flat area (Whittaker 1956) with elevations ranging from 265 to 2025 meters (National Park Service 2014b). It is one of the world's most diverse temperate forests (Madden et al. 2004). The GSMNP has a generally humid climate, but the high relief of the topography causes microclimatic variation that result in many different species finding niches in which to thrive (Whittaker 1956). Vegetation ranges from xeric pine stands to oak-dominated submesic to subxeric forests to mesic and cove areas with mesophytic conifers and hardwoods (Flatley et al. 2011). At the Gatlinburg 2 SW weather station, the National Climatic Data Center reports 1981-2010 mean annual precipitation of 1404 mm, mean annual temperature of 13.39°C, mean January maximum and minimum temperatures of 10°C and -3.89° C, and mean July maximum and minimum temperatures of 30°C and 16.11° C. (1981-2010 US Normals Data, 2013). At higher elevations, the annual precipitation can reach more than 2032 mm (Whittaker 1956) and temperatures decrease 10-20°F between the base of the mountains to the top

(National Park Service 2014b). My study area is 34609.27 ha of the western GSMNP (Fig. 1). It includes the study areas of Harmon (1982), Harrod et al. (1998), and Flatley et al. (2013). I used the findings from these three studies as inputs within this project.

Evidence of human settlement in the western GSMNP goes back as far as 6000 BC (Bass and Quentin 1977). An increase in charcoal in bog sediments southeast of GSMNP corresponds to the Cherokee arrival between 1450 and 1600 AD (Lynch and Clark 1996). Euro-Americans settled the Cades Cove area as early as the 1820s (Shields 1977; Dunn 1988). While not all areas of GSMNP were affected, settlers engaged in logging, clearing, agriculture, and grazing (Pyle 1988). Between 40 and 80% of the park was cleared by settlers or logged in the logging boom of the late nineteenth century (National Park Service 2014a; Pyle 1988) and that 20-40% of GSMNP has experienced no non-fire anthropogenic disturbance (Braun 1950; Pyle 1988). GSMNP was officially established as a national park in 1934 (Pyle 1988; MacKenzie and White 1998). With the establishment of GSMNP, policies of fire exclusion were enacted, changing many areas from fire-associated to fire-sensitive landscapes. In addition to fire use or non-use and other anthropogenic disturbances, the GSMNP vegetation also experienced changes due to the chestnut blight of the 1920s and 1930s that resulted in almost no living chestnuts by the early 1940s (Whittaker 1956).

Throughout European settlement (1820s-1934), many areas in the GSMNP were relatively unlogged (Shields 1977; Pyle 1988).This means that prior to suppression we can assume that these areas looked much as it had prior to European settlement. This is

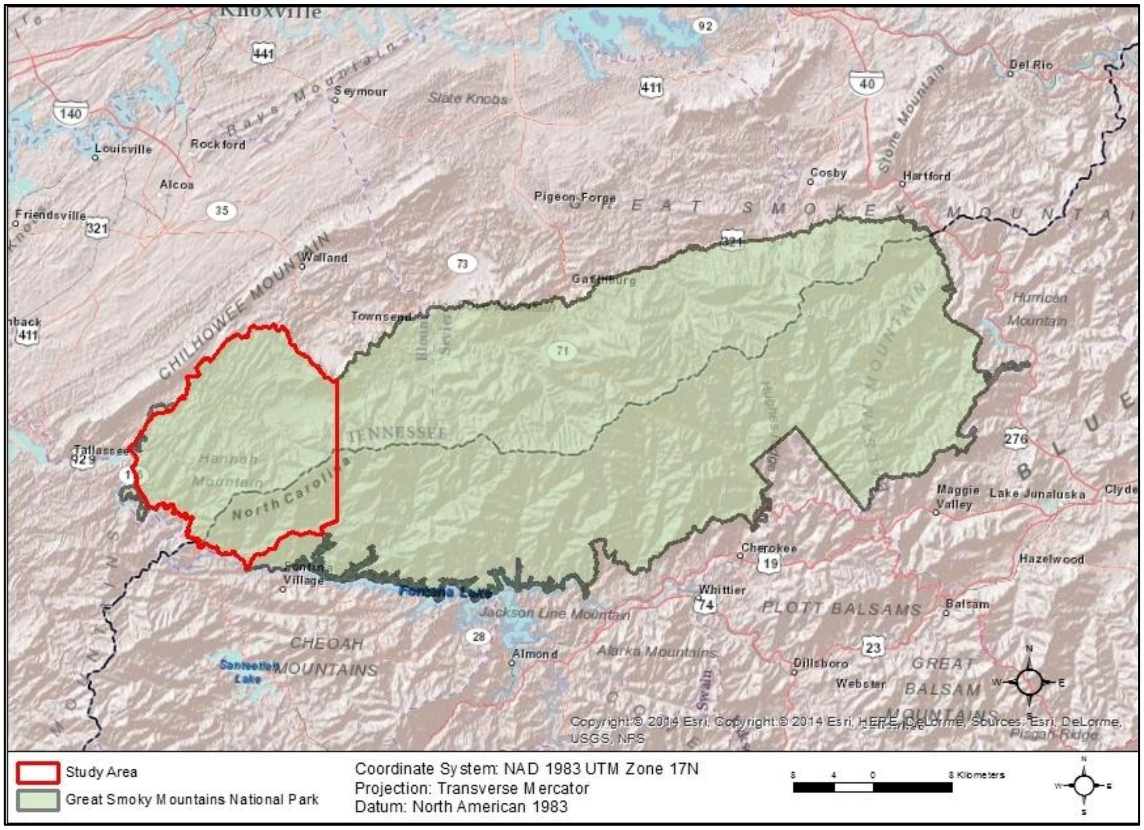

Figure 1. Study area in the western GSMNP.

important because after GSMNP was established, from 1935-1937, Frank H. Miller conducted a vegetation survey and sampling of GSMNP (MacKenzie and White 1998). Therefore, Miller's work provides a record of the landscape and vegetation that can be assumed to be relatively similar to the historic landscape. Harrod et al. (1998) used Miller's data to investigate the effects of fire suppression on the western GSMNP.

The fire history within the western GSMNP has been reconstructed from fire-scarred trees, returning a MFI of 12.7 years from 1856-1940 (Harmon 1982) and 9.1 years from 1773-fire suppression (Flatley et al. 2013). Flatley et al. (2013) includes the period of Cherokee habitation, which did not have significantly different mean fire scars per recording tree per decade than the Euro-American settlement period or the Industrial period. Therefore, we know that fire was frequent and active on their site. Current lightning ignitions within GSMNP are 0.9 ignitions per 1000 km^2 per year (Flatley et al. 2011), and for the study area are 0.463 ignitions per year. Because anthropogenic and lightning ignitions have been historically active within this area, it is an appropriate site to use as a model for pre-suppression fires and to explore the influence of anthropogenic and lightning ignitions.

4. METHODS

4.1 FARSITE

Our knowledge of historic fire regimes in the southern Appalachian Mountains has expanded through fire history reconstructions such as dendroecological and pollen analysis, but these are not able to explain all aspects of historic fire behavior. The introduction and calibration of the Fire Area Simulator model (FARSITE) as a research tool on the southern Appalachian landscape provides the opportunity to add to the understanding of the spatial extent of historic fires, ignition density, and ignition source that cannot be easily garnered through other means.

FARSITE is a 2-dimensionsal fire modeling system that simulates fire spread spatially and temporally on the landscape based on topography, weather, and fuels (Finney and Ryan 1995; Finney et al. 1997; Missoula Fire Sciences Laboratory 2010a; Stratton 2006). It is a deterministic model using defined mathematical relationships to predict fire behavior (Finney and Ryan 1995; Phillips et al. 2006). Released in 1995, FARSITE was developed to predict fire spread, shape, and intensity in real time to aid fire managers and firefighters make more informed suppression and management decisions (Finney and Ryan 1995; Finney et al. 1997; Phillips et al. 2006). It is currently used by the USFS, NPS, and other federal and state land management agencies to inform management decisions about fire spread in both wild and prescribed fires (Missoula Fire Sciences Laboratory 2010a).

Fire spread within FARSITE is based on Rothermel's fire spread equation (Finney 1998). As a vector model based on the Huygens' principle of wave propagation, FARSITE generates fire spread at different timesteps as expanding polygons (Finney and Ryan 1995). Huygens' principle considers fire spread as a wave generated at each vertex on the outer edge of a fire expansion polygon independently of the other vertexes (Finney and Ryan 1995; Finney 1998). Thus, mathematical relationships are applied to each vertex individually, then the outputs at each vertex are combined to predict the behavior of the fire as a whole (Finney 1998). FARSITE outputs time of arrival, intensity, flame length, rate of spread, heat per area, and direction in table, vector, or raster formats (Finney 1998; Stratton 2006). One of the advantages of FARSITE is that its vector and raster outputs are spatial and ready to be input into a GIS to perform spatial analysis and produce maps that capture the temporal and spatial change of the fire.

As its use became more widespread, managers began to implement FARSITE for more than just real time fire management and control. FARSITE has been effectively used to plan prescribed burns and evaluate proposed fuel treatments (Finney et al. 1997; Duguy et al. 2007). In addition it can be used to provide cause and effect relationships between inputs and fire behavior to better understand fire behavior (Finney et al. 1997; Andrews and Queen 2001; Duncan and Schmalzer 2004). Spatial outputs are analyzed to see how different landscapes produce different fire behavior and spread (Phillips et al. 2006; Ryu et al. 2007). Recently, researchers have begun to investigate historic fire regimes through FARSITE (Bean and Sanderson 2008). Using FARSITE as a research tool has expanded our understanding of fire behavior. With its proven predictive ability, FARSITE’s use on historic landscapes is a promising new application.

4.2 FARSITE limitations and assumptions

All modeling systems are simplifications or generalizations of the real world. To appropriately use any model, its limitations and assumptions must be understood to accurately use and interpret the model outputs (Stratton 2006). As Box et al. (1978) said “All models are wrong, but some are useful.” While FARSITE’s validity as a tool has been demonstrated, there are a few limitations that need to be acknowledged in consideration of this study.

If a simulation is inaccurate in the beginning, that error will increase as the simulation continues. To avoid compounding errors, researchers should use the maximum spatial and temporal resolution and appropriately calibrate FARSITE (Missoula Fire Sciences Laboratory 2010b). In addition, all inputs to be used with FARSITE should be carefully examined for accuracy and appropriateness. The quality of the topography, weather, and fuel characteristic inputs will affect the quality of FARSITE’s outputs (Finney and Ryan 1995). The southern Appalachians are a complex landscape. While research has shown FARSITE’s predictive ability on this landscape (Phillips et al. 2006), FARSITE’s limitations and assumptions documentation acknowledges the need for further research to determine how well FARSITE operates on complex landscapes (Missoula Fire Sciences Laboratory 2010b).

FARSITE has difficulty accounting for large dead fuels that can maintain fire activity through smoldering after the fire has moved beyond that area (Andrews and Queen 2001). The fuel loads used within FARSITE are 1 hour, 10 hour, 100 hour, and live. With large dead snags, the smoldering effects could be longer than 100 hours and could contribute to re-ignition. Thus, FARSITE has a limited ability to model fires with a long timespan but minimum conditions for burning (Finney and Ryan 1995). FARSITE's limited ability to account for smoldering large dead fuels should have little effect on its use for suppression (Finney and Ryan 1995), but these fuels could be an important ignition factor when modeling historic fires or determining appropriate fuel treatments to minimize fire hazard.

FARSITE's "Limitations and Assumptions" (2010b) states that "The FARSITE model is not designed to determine if a fire will spread or not." It can be used for this purpose when additional parameters are set to determine when environmental conditions would logically stop fire spread. Forcing fire spread to stop under certain conditions or after certain timespans could lead to an underprediction of fire spread, however, due to large dead snags that cannot be accounted for by FARSITE or by the researchers. No model is perfect or able to accurately make predictions at all scales and for all purposes. With an understanding of the assumptions underlying the FARSITE, it can be used to elucidate our understanding of fire behavior on the Southern Appalachian landscape (Missoula Fire Sciences Laboratory 2010b).

4.3 FARSITE inputs

FARSITE requires spatial inputs of elevation, slope, aspect, canopy cover, and fuel models (Finney 1998). The spatial inputs affect fire behavior in several ways. Slope is the elevation change over varying horizontal location (Bolstad 2005). It can increase the fire spread rate when the fire is moving upslope by pre-heating the upslope fuels that are in closer contact to the flames than they would be on a flat landscape (Whelan 1995). Therefore, slope affects the rate at which fire spreads. Aspect is the "steepest downhill direction" from a particular point (Bolstad 2005). It affects fire spread by influencing the amount of solar radiation a particular site receives thus influencing fuel moisture (Bolstad 2005). Fuel moisture has a significant effect on the rate of fire spread (Pyne et al. 1996). Before fuels can ignite, the water must be vaporized by heat in the pre-ignition phase of combustion (Pyne et al. 1996). Thus, high fuel moisture content means that it takes longer for those fuels to dry out and then ignite, thus slowing fire spread (Pyne et al. 1996). Increased solar radiation decreases the amount of time it takes to dry fuels prior to ignition, thus leading to higher rates of spread. Elevation can affect weather conditions, including temperature and humidity (Finney 1998; Phillips et al. 2006), which influences fuel moisture. Temperature and humidity are adjusted within FARSITE based on elevation (Phillips et al. 2006). Canopy cover refers to the amount of ground that is blocked from view of the sky by the canopy, or the percentage of the ground that is shaded (Finney 1998). Canopy cover affects fuel moisture similar to aspect in that it influences the amount of solar radiation that reaches fuels, contributing to how quickly they dry out, affecting speed of ignition and rate of spread (Finney 1998). Higher canopy cover also decreases wind speeds, thus decreasing rate of spread (Finney 1998).

FARSITE also requires wind and weather data, composed of daily minimum and maximum temperature and humidity, precipitation, wind speed and direction, cloud cover, and initial fuel moisture, as well as ignition location and burn duration (Finney 1998). Temperature and humidity influence fire behavior primarily through their influence on fuel moisture (Finney and Ryan 1995). Precipitation data, including amount, type, and duration influences fuel moisture as well as moisture of extinction. Moisture of extinction is the fuel moisture at which fire spread will no longer be uniform (Rothermel 1983; Pyne et al. 1996). When fuel moisture exceeds the moisture of extinction, the fire will not continue to spread until conditions decrease fuel moisture below the moisture of extinction. Wind is a major factor in fire behavior influencing the direction, rate, and distance of fire spread (Whelan 1995).

4.4 Fuel models

Fuel models are representations of the vegetation structure and fire-carrying capacity of the landscape. They are classified by vegetation type (e.g. grass, brush, timber, slash) and described by live fuel load, dead fuel load (1 hr, 10 hr, and 100 hr), surface-area-to-volume (SAV) ratio, heat content, fuel bed depth, and dead fuel moisture of extinction (Anderson 1982; Rothermel 1983; Scott and Burgan 2005). Based on these characteristics, fuel models are expected to produce certain fire behaviors, including rate of spread and flame length (Anderson 1982; Scott and Burgan 2005).

There are 13 commonly used fuel models developed by Anderson and Brown (Rothermel 1972) and Albini (1976) that are used within FARSITE and other fire modeling systems to predict fire behavior (Anderson 1982; Rothermel 1983). These modeling systems were designed based on fire behavior in the western US and “for the severe period of the fire season when wildfires pose greater control problems” (Anderson 1982). Thus, when used outside of a “severe period of the fire season” or in high-humidity areas, they tend to overpredict fire spread (Rothermel 1972; Scott and Burgan 2005).

The 13 fuel models listed by Rothermel (1972) and Albini (1976) do not accurately represent the fuel conditions of the southern Appalachian Mountains due to the high moisture content of fuels in this area (Andrews and Queen 2001; Phillips et al. 2006; Waldrop et al. 2007; Stottlemyer et al. 2009). Fuel moisture is the primary limitation on fire in the southern Appalachian Mountains (Lafon et al. 2005) and needs to be accurately represented when modeling fire behavior on this landscape. In the southern Appalachian Mountains, Phillips et al. (2006) produced reasonable results with FARSITE using 3 of the 13 fuel models listed by Rothermel (1972) and Albini (1976) and customized fuel models created for their study. However, Phillips et al. (2006) had to adjust the spread rates for the fuel models used beyond an acceptable range according to the parameters recommended by Stratton (2006). They are, therefore, not considered suitable fuel models to use for the southern Appalachian landscape. Phillips et al. (2006) emphasized that while they generated reasonable results using a combination of adjusted and customized fuel models to represent an area within the southern Appalachian

Mountains, the fuel conditions of the landscape are not fully represented and new fuel models need to be developed.

In 2005, Scott and Burgan published “Standard Fire Behavior Fuel Models” which introduced 45 new fuel models to account for differences in climate and vegetation and to improve our ability to model fire behavior. While these models appear to better predict fire behavior in more humid climates, they need additional verification for use on the southern Appalachian landscape.

4.5 Objective 1: Calibrate FARSITE to accurately model fires in the western GSMNP

To appropriately generate and interpret their results, researchers must first calibrate FARSITE for their study area (Stratton 2006). Calibration is accomplished by comparing FARSITE outputs to known fire behavior and adjusting inputs so the simulation more closely matches the observed (Finney 2000; Phillips et al. 2006; Stratton 2006). When calibrating, researchers choose the output that is the most relevant for their research question as FARSITE may simulate different outputs with different accuracy (Stratton 2006). Since my research hypotheses are related to fire size, I am using fire size for my calibration.

4.5.1 Acquire and process inputs

Elevation, slope, aspect, canopy cover, and fuel models are input as ASCII grid files and incorporated into one FARSITE landscape file (.lcp) (Finney 1998; Stratton 2006). I derived elevation, slope, and aspect from USGS National Elevation Dataset

(NED) 1/3 arc-second raster elevation files for the western GSMNP downloaded from the U.S. Geological Survey (U.S. Geological Survey 2012; Finney 1998; Phillips et al. 2006; Stratton 2006). National Elevation Datasets are a type of Digital Elevation Model (DEM). The NED is in NAD83, NAVD883 at 1/3 arc-second, or approximately 10 meters, of resolution. I projected and resampled the NED to NAD 83, UTM Zone 17N at 10 meter resolution using a bilinear technique in ArcGIS 10 (ESRI Inc. 2011). I derived slope and aspect in ArcGIS 10 using Spatial Analyst tools. I used the percent estimates of canopy cover produced by Welch et al. (2002) and provided to GSMNP as GIS vector shapefiles. Canopy cover is divided into the following four classes: 1 (0-25%), 2 (26-50%), 3 (51-75%), 4 (76-100%). Welch et al. (2002) determined percent canopy cover for both leaf-on and leaf-off conditions from a combination of remotely sensed data and field verification (Welch et al. 2002). FARSITE allows for the inclusion of barriers to fire growth. I added road, stream, and trail shapefiles for the GSMNP (National Park Service 2012). These vector files act to stop fire growth and are overlayed on top of the existing landscape inputs.

I acquired weather, wind, and fuel moisture data through Fire Family Plus (FFP) version 4.1 (Bradshaw and Tirmenstein 2010). FFP summarizes and analyzes daily weather observations and can be used to generate weather (.wtr), wind (.wnd), and fuel moisture (.fms) files for use in FARSITE (Bradshaw and Tirmenstein 2010). FARSITE weather files include daily minimum and maximum temperature and humidity, and precipitation amount and timing (Finney 1998). FARSITE wind files include hourly wind speed, wind direction, and cloud cover (Finney 1998). FARSITE fuel moisture files include initial fuel moisture (Finney 1998). Using FFP, I obtained remote automated weather station (RAWs) weather data for the western GSMNP from Indian Grave weather station. Indian Grave weather station is located at 35°37’25” N, 83°48’30” W, 823 meters of elevation, with mid slope position (26-40%), a southern aspect, and an average precipitation of 114.3 centimeters (Fig. 2). From FFP, I also downloaded the Wildland Fire Management Information (WFMI) data on all fires occurring in the GSMNP from 1972-2011, including ignition location, burn period, and total acres burned (Bradshaw and Tirmenstein 2010).

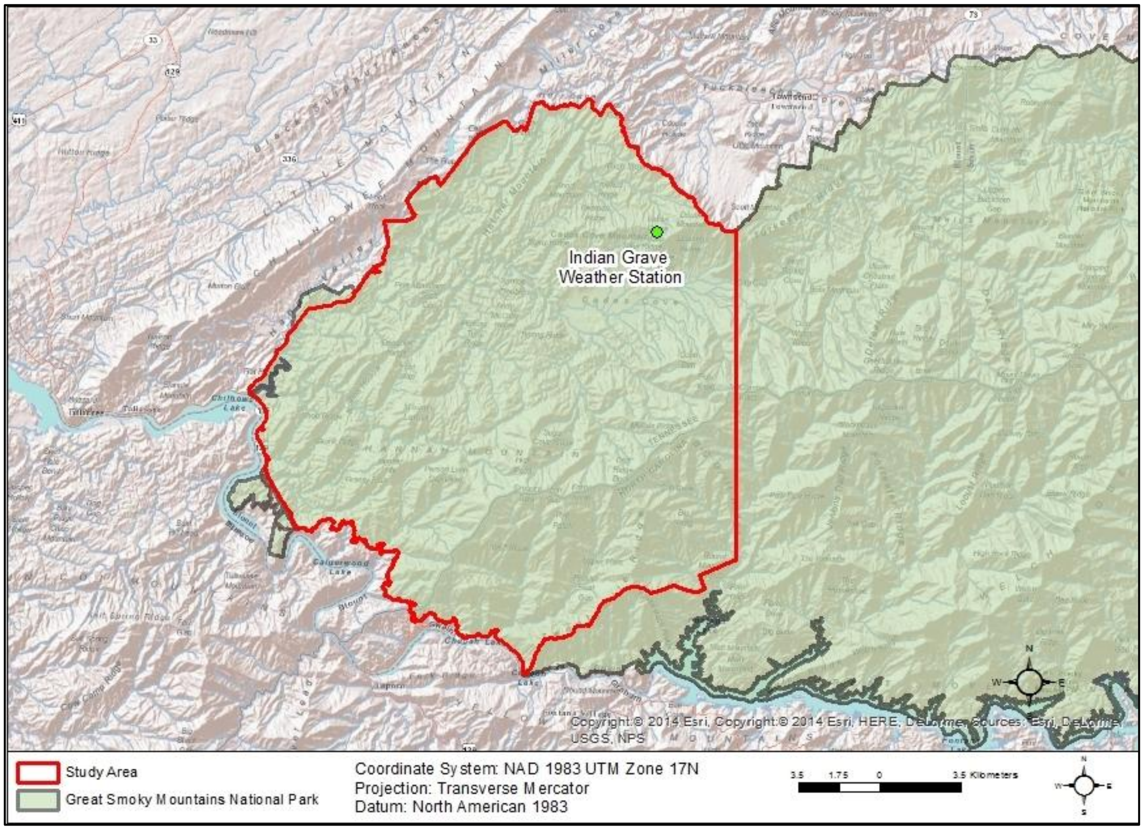

Figure 2. Location of Indian Grave weather station.

4.5.2 Select fuel models

The most commonly adjusted inputs during calibration are fuel models due to their tendency to cause FARSITE to overpredict fire spread (Rothermel 1972; Scott and Burgan 2005). Welch et al. (2002) produced digital vegetation maps as GIS vector shapefiles for GSMNP. These were created based on a combination of remotely sensed data and field identification and verification (Welch et al. 2002). In addition to classifying the general vegetation for the GSMNP, Welch et al. (2002) also classified the area into the 13 fuel models listed by Rothermel (1972) and Albini (1976). Instead of using the fuel model map classified by Welch et al. (2002), I used the reclassification of Welch et al. (2002) vegetation map using Scott and Burgan (2005) fuel models conducted by Munoz (2009) with some alterations and clarifications. Fuel models were selected for an area by considering 1) the general fire-carrying fuel type - nonburnable, grass, grass-shrub, shrub, timber-understory, timber litter, slash-blowdown, 2) the dead fuel extinction moisture (based on climate), 3) fuel characteristics such as depth, size, and amount of living fuel, and 4) an evaluation of predicted fire spread compared to the expected or observed fire spread (Scott and Burgan 2005).

Fuel models are selected based on vegetation maps and researchers' knowledge of the areas and fuel models in question (Duncan and Schmalzer 2004; Duguy et al. 2007; Bean and Sanderson 2008). Selecting fuel models that agree with observed fire behavior is the most important factor (Scott and Burgan 2005).

Once appropriate fuel models are selected spread rate adjustment factors are assigned to the different fuel models (Rothermel and Rinehart 1983). Adjustment factors adjust the spread rate to more accurately reflect observed fire behavior (Phillips et al. 2006; Duguy et al. 2007; Missoula Fire Sciences Laboratory 2010b). If a fuel model is overpredicting fire spread, an adjustment factor of 0.9 (90%) can be applied to reduce its fire spread by 10%. FARSITE has a specific adjustment file to hold the adjustment factors.

FARSITE's "Limitations and Adjustments" (2010b) states that adjustment factors should be based on fire spread at the head of the fire. When using FARSITE for suppression purposes, it is evident why it is most important for head fires to be accurately represented. FARSITE's "Limitations and Assumptions" (2010b) also states that adjustment factors may change throughout a fire. However, for my study, I based adjustment factors on spread in all directions over the entire fire because I am most interested in the total fire size simulated. Using fire spread at the head of the fire to inform adjustment factors would lead to an overprediction of fire size.

4.5.3 Simulate recent unsuppressed wildland fires in the western GSMNP

To calibrate FARSITE for the western GSMNP, I obtained fire information and perimeters from GSMNP for recent, lighting-ignited unsuppressed wildland fires (Rob Klein, personal communication 11/9/2012). I received perimeters for five fires, but determined that only Cattail 2 was appropriate to use for calibration (Table 8). Cattail 2 was a 185 acre lightning-ignited fire in the western part of GSMNP. It ignited at 35.513237°N, 83.981908°W at 1800 hours on 8/5/2007 and was extinguished at 1830 hours on 8/18/2007. The elevation of the burned area ranged from 299 to 463 m. I received nine fire NPS perimeter shapefiles (Rob Klein, personal communication 11/9/2012). Cattail 2 did have minor holding actions taken at the end of the fire (Rob Klein, personal communication 11/9/2012), so I did not use the final perimeter (timestep 9) in my calibration.

The other four fires I received from NPS were not appropriate for the current calibration for multiple reasons (Table 8). Beard Cane burned over an area that had previously burned and been hit by a tornado (Rob Klein, personal communication 11/9/2012). Therefore, its fuels were not reflective of the rest of the western GSMNP. Calderwood was outside of GSMNP so I did not have vegetation data for the area burned with which to determine fuel models. Chilly Springs did not have complete perimeters, and several of the perimeters were contradictory. With only two perimeters, there were not enough timesteps to get an accurate picture of how fire spread was affected by fuel model selection and adjustment factors for Big Medicine. Therefore, I eliminated Big Medicine from my calibration as well.

Three landscape compositions were tested for Cattail 2 to determine the appropriate fuel models for the western GSMNP. I first grouped Welch et al. (2002) vegetation ecogroups into three forest groups – mesophytic forest, oak forest, and pine forest (Table 9). I then assigned fuel models to these forest groups to create different landscape scenarios (A, B, C) reflecting current vegetation cover (Table 10 and 11, Fig. 3-5). All fuel models for the three forest groups were chosen from the Timber Litter (TL) fuel type models. Within the GSMNP, the understory does not typically carry fire (Rob Klein, personal communication 2/12/13). Therefore, Timber Litter fuel models,

Table 8. Western GSMNP fires considered for calibration

Fire Name	Date & Time of Ignition	Date & Time of Extinction	Days Active	NPS Perimeter Shapefiles	Total Acreage Burned	Appropriate for Calibration	Notes
Beard Cane	7/25/2011 0245	9/12/2011 1500	50	3	316	No	Fuels not reflective of western GSMNP
Big Medicine	8/17/2007 1600	8/27/2007 0800	10	2	34	No	Too few perimeters
Cattail 2*	8/5/2007 1800	8/18/2007 1830	13	9	185	Yes	Minor holding action taken at end of fire
Calderwood	08/17/2010 1709	09/23/2010 1800	38	9	291	No	No vegetation data
Chilly Springs	4/5/2006 0800	4/18/2006 0800	13	6	913	No	Perimeters incomplete and contradictory

*Fire chosen for calibration

Table 9. Vegetation Ecogroups and Short Names from Welch et al. (2002) grouped into forest groups for fuel model assignment

Forest Groups	Ecogroup	Short Name
Mesophytic Forest	Alluvial vegetation	Alluvial vegetation (non-forested)
Mesophytic Forest	Floodplain forests	Floodplain forests
Mesophytic Forest	Hemlock forests	Hemlock forest (typic type)
Mesophytic Forest	Montane cove forests	Acid cove forest (typic type)
Mesophytic Forest	Montane cove forests	Cove forest (rich type)
Mesophytic Forest	Montane cove forests	Cove forest (typic type)
Mesophytic Forest	Montane cove forests	Red oak cove forest
Mesophytic Forest	Successional hardwood forests	Successional hardwood forest
Oak Forest	Chestnut oak forests	Chestnut oak forest
Oak Forest	Montane oak-hickory forests	Oak-hickory forest (red oak type)
Oak Forest	Montane oak-hickory forests	Oak-hickory forest (rich type)
Oak Forest	Montane oak-hickory forests	Oak-hickory forest (typic acidic type)
Pine Forest	Hemlock forests	Hemlock forest (white pine type)
Pine Forest	White pine forests	White pine forest
Pine Forest	White pine forests	White pine-xeric oak forest
Pine Forest	White pine-mesic oak forests	White pine-mesic oak forest
Pine Forest	Yellow pine forests	Yellow pine forest
Ericaceous shrubs	Ericaceous shrubs (non-heath bald type)	Ericaceous shrubs (non-heath bald type)
Nonburnable Surface	Human influence	Human influence
Nonburnable Surface	Roads	Roads
Nonburnable Surface	Rock	Rock
Nonburnable Surface	Sparse vegetation	Sparse vegetation
Nonburnable Water	Water	Water

*Fuel models not calibrated

Table 10. Landscape scenarios tested by calibration

Landscape Scenario	Mesophytic Forest	Oak Forest	Pine Forest	Ericaceous Shrubs	Nonburnable Surface	Nonburnable Water
Landscape A	182 (TL2)	186 (TL3)	183 (TL3)	143 (SH3)*	99 (NB9)*	98 (NB8)*
Landscape B	182 (TL2)	182 (TL2)	181 (TL1)	143 (SH3)*	99 (NB9)*	98 (NB8)*
Landscape C	182 (TL2)	182 (TL2)	188 (TL8)	143 (SH3)*	99 (NB9)*	98 (NB8)*

*Fuel models not calibrated

Table 11. Fuel Model Descriptions from Scott and Burgan (2005)

Fuel Model	Fuel Model Name	Spread Rate	Flame Length	Fuel Load	Primary Carrier of Fire
143 (SH3)	Moderate Load, Humid Climate Shrub	Low	Low	Moderate	Woody shrubs and shrub litter
181 (TL1)	Low Load Compact Conifer Litter	Very Low	Very Low	Light to moderate	Compact forest litter
182 (TL2)	Low Load Broadleaf Litter	Very Low	Very Low	Low	Compact broadleaf (hardwood) litter
183 (TL3)	Moderate Load Conifer Litter	Very Low	Low	Moderate	Moderate load conifer litter, light load of coarse fuels
186 (TL6)	Moderate Load Broadleaf Litter	Moderate	Low	Moderate	Broadleaf litter, less compact than TL2

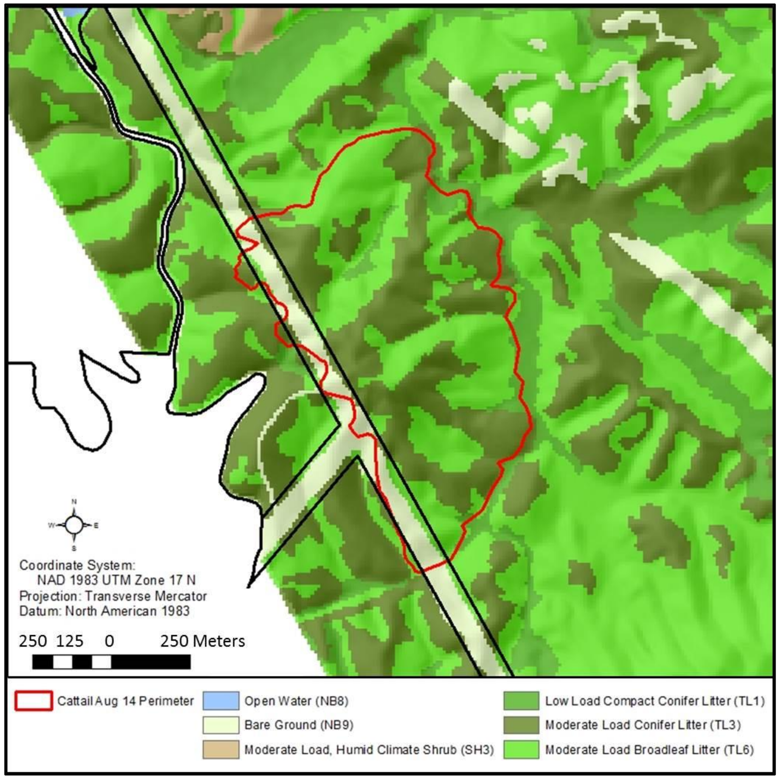

Figure 3. Landscape A fuel model configuration.

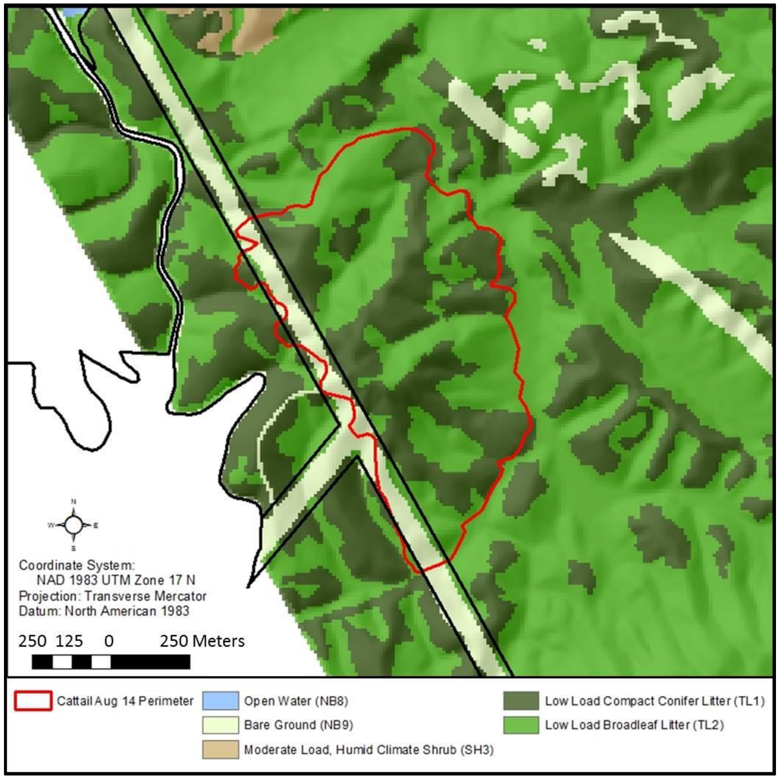

Figure 4. Landscape B fuel model configuration.

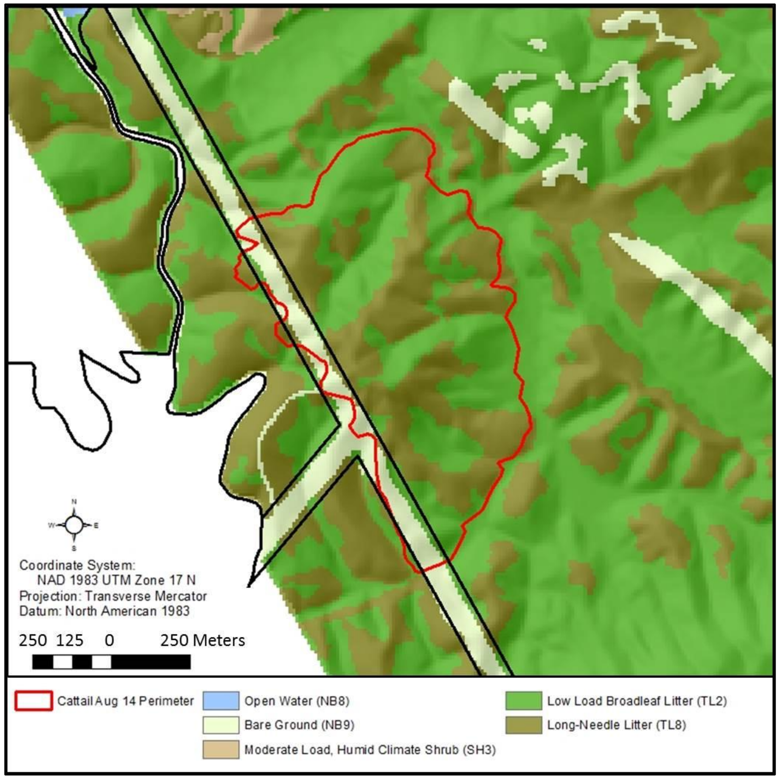

Figure 5. Landscape C fuel model configuration.

where “the primary carrier of fire in the TL fuel models Is dead and down woody fuel” (Scott and Burgan 2005, p 56) is the most appropriate type of fuel model for the study area.

I used each fire perimeter as the ignition location and ran the simulation until the next perimeter. Each of these I will refer to as a simulation timestep (Table 12). Using timesteps instead of the entire fire length is a unique way to attempt calibration of FARSITE, as most previous research used only an initial ignition location and final fire perimeter (Finney and Ryan 1995). This calibration method should avoid compounding errors (Stratton 2006) and result in more accurate fuel model and adjustment file selection.

Table 12. Cattail 2 Timesteps

Timestep	Ignition Location	Burn Start	Burn End	Final Perimeter Comparison
1	CT_Ign_1.shp	8/5 1800	8/6 2300	6Aug07_perimeter
2	6Aug07_perimeter	8/7 0000	8/8 0000	7Aug07_perimeter
3	7Aug07_perimeter	8/8 0000	8/9 0000	8Aug07_perimeter
4	8Aug07_perimeter	8/9 0000	8/10 0000	9Aug07_perimeter
5	9Aug07_perimeter	8/10 0000	8/11 0000	10Aug07_perimeter
6	10Aug07_perimeter	8/11 0000	8/12 0000	11Aug07_perimeter
7	11Aug07_perimeter	8/12 0000	8/14 0000	13Aug07_perimeter
8	13Aug07_perimeter	8/14 0000	8/15 0000	14Aug07_perimeter
9	14Aug07_perimeter	8/15 0000	8/18 1830	Final

I ran simulations for each landscape scenario adjusting the spread rate for each fuel model from a factor of 0.6 to 1.4. Stratton (2006) recommends that for a fuel model to be appropriate, it should not need an adjustment of more than 0.3 to 0.4 in either direction. Therefore, during calibration the adjustment files were not altered past 0.6 or 1.4. I compared the size of the simulated fire to the size of the next timestep's actual perimeter and the amount of overlap between the simulated and actual fire. I calculated the area of the simulated fire relative to the actual fire ("Percent Area"). I also calculated "Percent Overlap" based on the portion of the actual burned polygon that was burned in the simulation. I used Percent Area and Percent Overlap to compare the different landscape scenarios and determine the appropriate adjustment factors.

4.5.4 Calibrate FARSITE to best match burn perimeter

FARSITE overpredicted fire size for Landscapes A and C. Landscape B consisted of only two fuel models: 181 (TL1) for pine forest and 182 (TL2) for both mesophytic forest and oak forest. Landscape B most accurately simulated the actual fire size. The primary carrier of fire for both fuel models was compact litter, and they had the lowest fire spread within Timber Litter fuel models for conifer and broadleaf fuel types respectively.

I ran 81 simulations of Landscape B to include every adjustment file combination from 0.6 to 1.4 for fuel models 181 (TL1) and 182 (TL2). To determine the appropriate adjustment factors, I selected the timesteps where the Percent Area was within 10% and the Percent Overlap was greater than 75%. Eight simulations out of 81 had three timesteps where the Percent Area was between 90 and 110% (Table 13). I calculated the median and mean adjustment factors using only these eight simulations to determine the final fuel model adjustment factors. The results were fuel model 181 (TL1) with an adjustment factor of 0.8 and fuel model 182 (TL2) with an adjustment factor of 0.6. In other words, calibration shows that fuel model 181 (TL1) spreads at a rate that is 80% of its default spread rate. Fuel model 182 (TL2) spreads at a rate that is 60% of its default spread rate.

4.6 Objective 2: Simulate the spatial extent of fires on a pre-suppression landscape

After calibrating FARSITE, I then used it to explore the spatial extent of fires on the pre-suppression GSMNP landscape. I selected a 36,964 ha area of the western GSMNP as my study area (Fig. 1). Because the vegetation composition of the western GSMNP is different from the eastern portion, the calibration I performed and the fuel models and adjustments selected are most appropriately applied to the western GSMNP. Eighty-nine percent of the study area is composed of vegetation ecogroups from Welch et al. (2002) that were calibrated during Objective 1. Also, within the GSMNP, most lightning ignitions occur in the western portion of the park. I ran multiple simulations within the study area on different potential pre-suppression landscape scenarios to estimate the range of fire sizes that could have occurred on the pre-suppression landscape in the southern Appalachian Mountains.

Table 13. Landscape B simulations used to determine the final adjustment factors

Simulation No.	181 (TL1)	182 (TL2)	Timestep 1	Timestep 2	Timestep 3	Timestep 4	Timestep 5	Timestep 6	Timestep 7	Timestep 8
033	0.8	0.7	10.7%	73.5%	110.2%	121.3%	129.0%	98.3%*	123.6%	107.7%*
034**	0.7	0.7	9.3%	72.4%	108.9%*	120.1%	127.6%	97.2%*	122.5%	107.3%*
035**	0.6	0.7	8.0%	71.3%	107.7%*	118.9%	126.3%	96.0%*	121.3%	106.9%*
141**	1.1	0.6	15.3%	73.7%	109.8%*	119.4%	127.3%	98.2%*	124.0%	107.5%*
041**	1	0.6	13.6%	72.6%	108.5%*	118.2%	126.0%	97.1%*	123.1%	107.1%*
042**	0.9	0.6	12.0%	71.5%	107.5%*	117.1%	124.8%	96.0%*	122.2%	106.7%*
043**	0.8	0.6	10.5%	70.4%	106.1%*	116.1%	123.5%	95.0%*	121.1%	106.3%*
044**	0.7	0.6	9.1%	69.3%	104.8%*	115.0%	122.3%	93.9%*	119.9%	105.9%*
045**	0.6	0.6	7.9%	68.2%	103.5%*	113.8%	121.0%	92.8%*	118.7%	105.5%*
Average Adjustment Factor	*0.8*	*0.63*								
Median Adjustment Factor	*0.75*	*0.6*								

* Percent Area between 90% and 110%

**Used for calculation of final adjustment factors

4.6.1 Set FARSITE inputs

I used the same digital elevation model for the simulations as used for the calibration. I derived elevation, slope, and aspect from USGS National Elevation Dataset (NED) 1/3 arc-second raster elevation files for the western GSMNP downloaded from the U.S. Geological Survey (U.S. Geological Survey 2012; Finney 1998; Phillips et al. 2006; Stratton 2006). I used the adjustment factor from calibration (Table 13). I included the current stream vector shapefile as a barrier to fire growth. Unlike during calibration, I did not include roads or trails as barrier files, because these are recent modifications to the landscape.

I acquired 16 years (1997-2013) of weather and fuel moisture data through Fire Family Plus (FFP) version 4 (Bradshaw and Tirmenstein 2010). In cases where FARSITE could not account for the gaps in the recorded weather data, I used the mean from the other recorded years (Table 14).

Table 14. Percent of simulations in which at least one weather, wind, or fuel moisture input was based on averaged values from the other years.

Weather Input	% of Simulations with Averaged Inputs*
Weather	1.20%
Wind	12.00%
Fuel Moisture	7.40%
Total	13.80%

*Simulations were included in count if any inputs were averaged.

4.6.2 Create pre-suppression landscape scenarios

To estimate the pre-suppression landscape, I created three potential pre-suppression landscape scenarios by modifying the current fuel models and canopy cover (Table 15). The first scenario (Hx1) assumes the pre-suppression landscape is exactly the same as the current landscape but without Roads and areas of Human Influence. I used the fuel model crossovers created during calibration (Table 9 and 10), to assign fuel models for Hx1 based on the Welch et al. (2002) vegetation map. I then reclassified any areas defined as “Roads” or “Human Influence” to the fuel model making up its largest border. I used the current measure of percent canopy cover produced by Welch et al. (2002).

I then created the second and third scenarios (Hx2 and Hx3) to represent vegetation conditions of the western GSMNP prior to fire suppression in the 1930s (MacKenzie and White 1998, Harrod et al. 1998). The pre-suppression landscape was characterized by yellow pine and oak stands and patches of open-canopy woodlands with flammable grass understories (Harrod et al. 2000). Scenario Hx2 is a conservative estimate of the pre-suppression landscape conditions. I assumed the fuel models are the same as Hx1, but I adjusted the canopy cover to accommodate more open vegetation. Harrod et al. (1998) found canopy density (stems/ha) increased by 272% and basal area (m^2/ha) increased by 196% from the 1930s to the 1970s in the western GSMNP. While no direct measurements of canopy cover were made, I used Harrod et al. (1998) as a guide for the proportion of change applied to the current canopy cover from Welch et al. (2002). Canopy cover is divided into the following four classes and their corresponding

Table 15. Fuel model and canopy cover description of pre-suppression scenarios. For each scenario (Hx1, Hx2, Hx3), the % of Study Area lists the percentage of the total study area this forest type and its associated fuel model compose. Canopy Cover lists the percentage of the total study area this canopy cover class (1: 0-25%, 2: 26-50%, 3: 51-75%, 4: 76-100%) composes under leafon and leafoff conditions.

	Oak Forest (Fuel Model: 182)			Pine Forest (Fuel Model: 181)			Grass/shrub Understory (Fuel Model: 163)			Other (Fuel Models: 98, 99, 143, 150, 202)		
Scenario	% of Study Area	Canopy Cover (leafon)	Canopy Cover (leafoff)	% of Study Area	Canopy Cover (leafon)	Canopy Cover (leafoff)	% of Study Area	Canopy Cover (leafon)	Canopy Cover (leafoff)	% of Study Area	Canopy Cover (leafon)	Canopy Cover (leafoff)
Hx1	72.85%	1: 0.17% 2: 10.69% 3: 9.71% 4: 52.27%	1: 61.40% 2: 9.82% 3: 0.01% 4: 1.61%	24.04%	1: 0.04% 2: 11.21% 3: 11.35% 4: 1.44%	1: 0.15% 2: 12.90% 3: 9.63% 4: 1.36%	n/a	n/a	n/a	3.11%	1: 3.11% 2: 0.00% 3: 0.00% 4: 0.00%	1: 3.11% 2: 0.00% 3: 0.00% 4: 0.00%
Hx2	72.85%	1: 10.87% 2: 38.75% 3: 1.98% 4: 21.25%	1: 66.49% 2: 4.75% 3: 0.00% 4: 1.61%	24.04%	1: 11.25% 2: 12.79% 3: 0.00% 4: 0.00%	1: 13.05% 2: 10.99% 3: 0.00% 4: 0.00%	n/a	n/a	n/a	3.11%	1: 3.11% 2: 0.00% 3: 0.00% 4: 0.00%	1: 3.11% 2: 0.00% 3: 0.00% 4: 0.00%
Hx3	46.06%	1: 5.01% 2: 17.81% 3: 1.98% 4: 21.25%	1: 39.70% 2: 4.74% 3: 0.00% 4: 1.61%	11.07%	1: 5.17% 2: 5.90% 3: 0.00% 4: 0.00%	1: 6.00% 2: 5.07% 3: 0.00% 4: 0.00%	39.77%	1: 11.94% 2: 27.82% 3: 0.00% 4: 0.00%	1: 33.83% 2: 5.93% 3: 0.00% 4: 0.00%	3.11%	1: 3.11% 2: 0.00% 3: 0.00% 4: 0.00%	1: 3.11% 2: 0.00% 3: 0.00% 4: 0.00%

canopy cover percentages: 1 (0-25%), 2 (26-50%), 3 (51-75%), 4 (76-100%). I divided the percent canopy cover by 2 for the areas classified as Oak Forest and Pine Forest. Therefore, I reclassified classes 4 (76-100%) and 3 (51-75%) to class 2 (26-50%), and classes 2 (26-50%) and 1(0-25%) to class 1 (0-25%). I left the Mesophytic Forest, Ericaceous Shrubs, and Nonburnable Surface canopy cover percentages unchanged.

Scenario Hx3 assumes open Oak and Pine Forests characterized by grass/shrub understories. I used the same canopy cover values as in Scenario Hx2, but altered the fuel models to represent the grass/shrub understory. Harrod et al. (2000) measured herbaceous and shrub cover 3, 4, and 8 years following fires on xeric sites in the western GSMNP. They found a mean herbaceous cover of 22% and a mean shrub and woody vine cover of 32% (Harrod et al. 2000). I therefore randomly reclassified 54% (i.e. 22% + 32%) of the Oak and Pine Forest vegetation to fuel model 163 (TU3) in ArcGIS 10 (ESRI Inc. 2011). TU3 is the “Moderate Load, Humid Climate Timber-Grass-Shrub” fuel model. Fire is primarily carried in the moderate forest litter, grass, and shrubs of TU3 (Scott and Burgan 2005). Therefore, TU3 appears to appropriately reflect the fuel conditions found on the pre-suppression landscape. I used the canopy cover percentages determined for Hx2 within the Hx3 landscape.

4.6.3 Run multiple simulations

I ran 500 simulations on each pre-suppression landscape scenario (Hx1, Hx2, and Hx3) to determine the mean fire size for each landscape. I randomly generated 500 ignition locations within the study area using ArcGIS 10 Create Random Points tool

(ESRI Inc. 2011). Ignition locations located on nonburnable fuel models were eliminated. Using R statistical software (R Development Core Team 2008), I randomly generated which year of weather and fuel moisture to use for each simulation. Cohen et al. (2007) determined the frequency of lightning-caused fires by month within GSMNP for 1940-2006. I randomly generated start month for each simulation based on the monthly fire frequency distribution from Cohen et al. (2007). Within each month, I randomly generated the starting day and beginning and end time (0-2300) of each simulation.

FARSITE will not end a simulation on its own. Li (2000) stopped simulations when non-flammable land cover was encountered, when the fire ran into the boundary of the region, or when rainfall exceeded a critical amount. Li (2000) defined the critical amount as 30 mm within west-central Alberta, Canada. After investigating the weather data for the Cohen et al. (2007) fires I could find no critical amount of rainfall that led to extinction. Several fires burned through periods of 30+ mm of rainfall, and several fires extinguished without rainfall. This led me to decide that picking a critical rainfall at which to extinguish fires was an inappropriate way to determine duration.

Instead of using previously set criteria to stop my simulations, I set the duration for each simulation based on the frequency distribution for the durations of 35 unsuppressed fires from the GSMNP during 1985 to 2008, compiled from the Wildland Fire Management Information (WFMI) database (Table 16) (Cohen et al. 2007). These fires were listed as unsuppressed in the WFMI database and/or included in Cohen et al. (2007), which contained an analysis of the ten GSMNP fires managed under the

Table 16. Unsuppressed fires used to determine duration.

Fire Name	Duration (days)	Extent (acres)	Year	Duration known	Cohen et al. 2007
Barnes	1	0.1	1987	no	
Big Medicine	11	34	2007	yes	
Blacksmith	35	523	1999	yes	yes
Butterfl6	1	0.1	2002	no	
Cane	1	0.1	2000	no	
Cattail 2	14	185	2007	yes	
Cave Ridge	6	0.1	2000	yes	yes
Chestnut	1	0.1	1985	yes	
Chilly Spring Knob	38	913	2006	yes	yes
Chimney Top	7	0.1	2008	yes	
Collins 2	9	130	1999	yes	yes
Dinky	1	0.1	1987	yes	
Ekaneetlee	13	6	2001	yes	yes
Enloe Ridge	3	0.1	1998	yes	yes
February	1	0.1	1988	no	
Fizzle	1	0.1	1987	no	
Foothills	1	0.1	1991	no	
Fork Snag	1	0.1	1988	no	
Forney	1	1	1992	no	
Forney Creek	22	370	1998	yes	yes
Fort Harry	8	0.2	2000	yes	yes
Jet Fire	1	0.1	1992	no	
Johns Ridge	2	0.1	2008	yes	
Mitchell Branch	13	35	2008	yes	
Overlook	1	0.1	1987	no	
Parkview	1	0.1	2000	no	
Purchase1	1	0.1	1994	no	
Shot Beech	35	0.1	2004	yes	yes
Small	1	0.1	1994	no	
Snag	1	0.1	1989	no	
Spring	1	0.1	1990	no	
Tarkiln Ridge	28	16	2008	yes	
Thunderhead	1	1	1995	no	
Turtle	1	1	1988	no	
Wolfpen	5	3	2001	yes	yes

wildland fire use policy from 1998 to 2006. In cases where the duration or extent differed between Cohen et al. (2007) and the WFMI database, Cohen et al. (2007) was used because they had error-checked the WFMID data. Seventeen of the 35 fires had an unknown duration because only the start time was reported in the WFMI database. Therefore, I listed the duration for these fires as 1 day because the probability of a fire lasting longer than 1 day but not being discovered was low (Rob Klein personal correspondence 9/23/13).

The unsuppressed fires were binned into durations of 5 days, and an exponential curve was fitted using a nonlinear least-squares estimation performed with R Statistical Software for all except the first bin (Fig. 6) (R Development Core Team 2008). The first bin, which contained fire durations of 1-5 days, included 62.86% of all the fires (22/35). The first bin was not used in the nonlinear regression because it would skew the line to such an extent it no longer accurately reflected the distribution of durations. The nonlinear regression model equation is:

$y = \exp(a + b * x)$ where $a = -0.73517$ and $b = 0.07084$

This equation was used to solve for y until the number of fires predicted was less than 0.01% of the total number of fires (Table 17). Sixty-three percent of the durations were within the first bin (1-5). I generated random durations between 1 and 5 for 63% of the simulations using R statistical software (R Development Core Team 2008). The remaining 37% of the durations were based on the nonlinear regression. For each bin, I generated random numbers within that bin that were used for the corresponding percentage of simulations (e.g. approximately 11% of the simulations had randomly generated durations between 6 and 10) using R statistical software (R Development Core Team 2008). While I acknowledge that using only 35 fires on which to base my durations is not as many as would be preferred, but it was the most reasonable solution based on the information available.

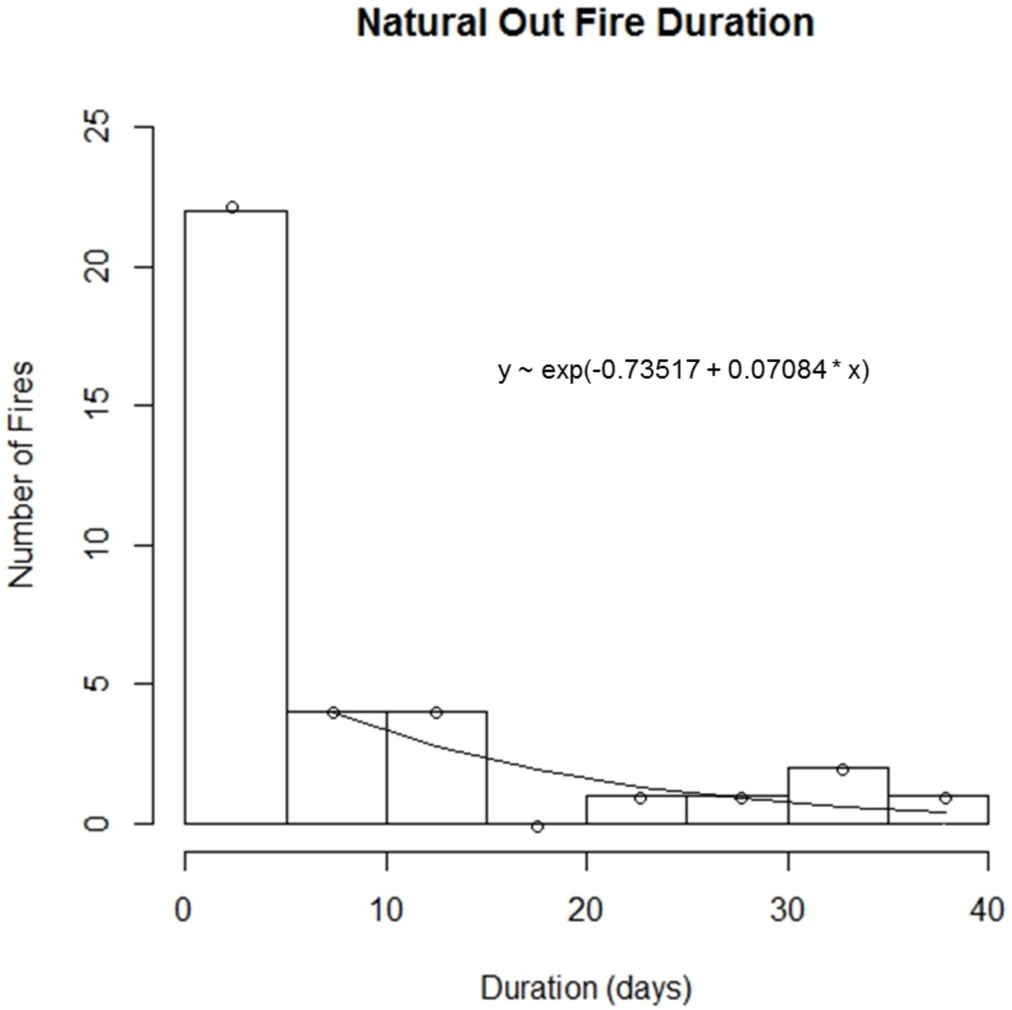

Figure 6. Unsuppressed fires from 1985 – 2008 within GSMNP that were used to determine simulation durations.

Table 17. Fire duration percentages.

Bin	Number of fires from nonlinear regression formula	Percentage of total fires within bin
1-5*	5.721494*	62.86%
6-10	4.014971	11.47%
11-15	2.817444	8.05%
16-20	1.977098	5.65%
21-25	1.387398	3.96%
26-30	0.9735851	2.78%
31-35	0.6831984	1.95%
36-40	0.4794239	1.37%
41-45	0.3364284	0.96%
46-50	0.2360834	0.67%
51-55	0.1656679	0.47%
56-60	0.1162549	0.33%
61-65	0.08158009	0.23%
66-70	0.05724757	0.16%
71-75	0.0401726	0.11%
76-80	0.02819051	0.08%
81-85	0.01978225	0.06%
86-90	0.01388189	0.04%
91-95	0.009741404	0.03%
96-100	0.00683588	0.02%
101-105	0.004796974	0.01%
106-110	0.003366203	0.01%
111-115	0.002362181	0.01%

* Bin 1-5 percentage was not determined using line function.

4.7 Objective 3: Estimate the percentage of pre-suppression fire frequency that could be accounted for by lightning and anthropogenic ignitions

With the spatial extent of fires on the three landscape scenarios, I then explored the implications for fire cycle and ignition density. An understanding of ignition density and fire cycle is needed to determine the contributions of lightning and anthropogenic ignitions to the observed fire frequency on the pre-suppression landscape.

4.7.1 Determine total area burned and lightning fire cycle

Using the simulations on the three different pre-suppression landscape scenarios, I next determined the fire cycle for the study area. Fire cycle can be calculated by dividing the study area by the total area burned and multiplying that by the number of years observed for the study area.

Fire cycle = (Study area / Total area burned) x Years observed

To determine the total area burned, I created overlays of the simulation areas and calculated the number of fires per 10m cell (resolution and location of cells matched FARSITE inputs). I determined the number of years represented for the study area based on current lightning ignition observations. From 1942 to 2008, there were 124 recorded lightning ignitions in GSMNP. Of those, 31 were within the study area. Lightning ignitions (31) divided by the number of years recorded (67) equals a rate of 0.463 lightning ignitions per year. At that ignition rate, five-hundred lightning fires (i.e. the number of simulations run) would require a span of 1080 years. Twenty-two of the simulations showed no fire growth, but they were still included in the calculations. Eliminating those 22 simulations would lead to a 1033 year time span of observed fires.

During the 1080 years observed for this study, fires would have ignited outside of the study area and burned into the study area. Fires with ignitions outside the study area are not represented by my simulations. This leads to an underestimation of the total area burned. To account for this underestimation I created a subset of the landscape. The subset landscape experienced fires ignited within the subset landscape and fires that ignited outside of the subset landscape and burned into it, giving us a better representation of the amount of fire experienced within this area. I created buffers at 500 meter intervals from the study area boundary and determined the mean number of fires per cell for each 500 meter buffer. The mean number of fires per cell increased until the 2500-3000 meter buffer (Fig. 7). Therefore, I subset the study area by 2500 meters (Fig. 8). I then calculated the number of fires for each 10m cell for just the subset area, and I calculated the lightning fire cycle for the subset study area.

After calculating fire cycle for the total and subset study area, I tested if topographic position affected fire cycle. I used the slope position classification Flatley et al. (2011) calculated for the GSMNP using the GIS application LANDFORM (Klingseisen et al. 2008). The landscape was classified based on topographic wetness into ridge (driest), upper slope, lower slope, and bottom (wettest). I calculated fire cycle for each topographic position.

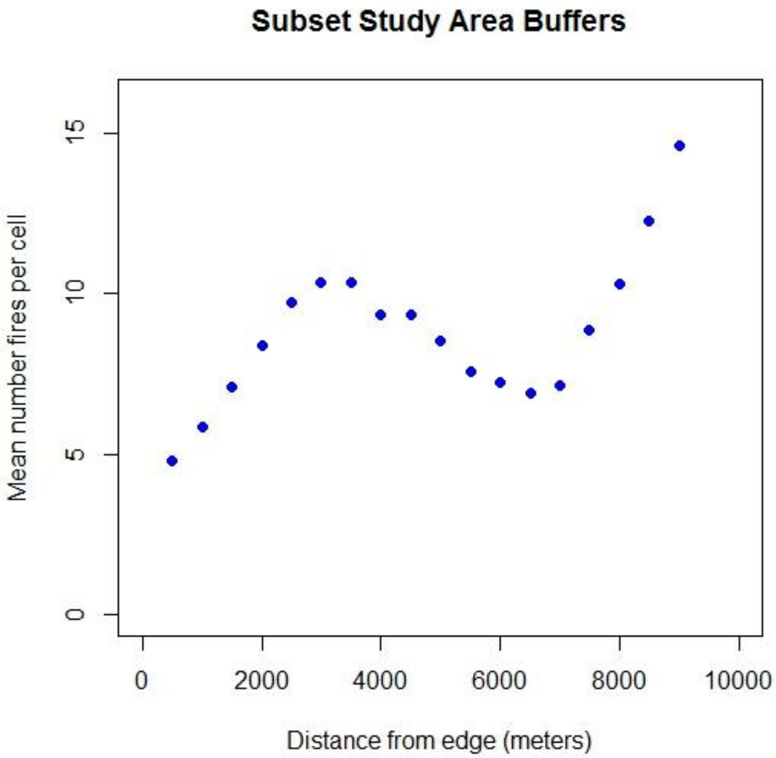

Figure 7. Mean number of 10 m grid cell fire occurrence count for each 500 meter buffer for the Hx3 landscape.

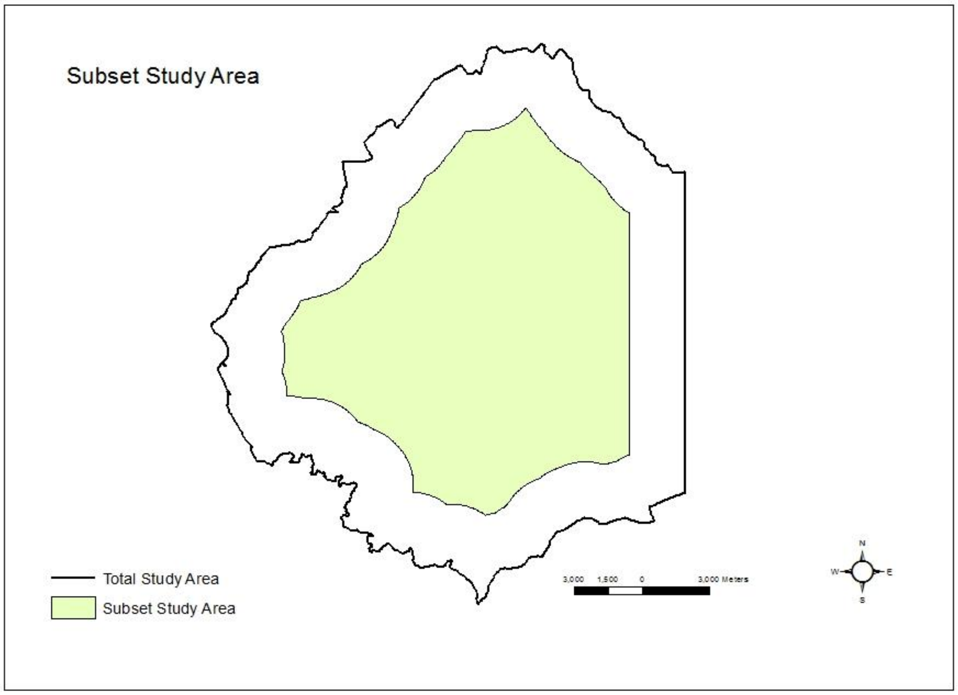

Figure 8. Subset study area compared to total study area. Subset study area boundary is 2500 meters from total study area boundary.

4.7.2 Determine ignition density

Using two different MFIs calculated from fire scarred trees, I then calculated the ignition density for the study area. Flatley et al. (2013) found a point MFI of 9.1 years for Licklog Ridge. Point MFI is calculated based on individual trees as opposed to other MFI calculations that create composites (Hoss et al. 2008). Point MFI is a useful, but conservative, estimate of the frequency of fire at any point on the landscape since fires do not usually scar every tree they burn (Hoss et al. 2008). Since point MFI represents how often any point on the landscape burned, it should approximately equal the fire cycle (Larsen 2000). Harmon (1982) found an arithmetic MFI of 12.7 years for the westernmost portion of GSMNP. I determined the average hectares that would have to burn yearly to maintain the recorded MFI by dividing the study area by 9.1 and 12.7. To determine the ignition density, I then divided the average acres by the mean burned area per fire. The mean burned area is the area per study area or topographic region that would burn during a fire. It was determined by dividing the total area burned per study area or topographic region by 500.

Ignition density = (Study area / MFI) / (Total area burned / 500)

Flatley et al. (2013) collected most samples on the ridge and upper slope, but a few were in the lower slope (Flatley personal communication 3/6/2014).Therefore, I determined the ignition density per topographic region because the 9.1 MFI is most appropriate to compare to the ridge, upper slope, and lower slope regions. Since I do not have the topographic position data for the sampling sites from Harmon (1982), I chose to only apply the 12.7 MFI to the total study area and the subset study area.

4.7.3 Determine percentage of pre-suppression lightning fire frequency

With the ignition density and fire cycle determined above, I calculated the percentage of ignitions that could be accounted for by lightning. Two formulas that return the same results can be used to determine the percentage of lightning ignitions. The first formula divides the current lightning ignition density for the study area by the ignition density required to maintain the total burned area generated by the different landscape scenarios.

Lightning ignitions (%) = Current lightning ignition density / Ignition density

The second formula divides the MFI by the lightning fire cycle to determine the potential percentage of lightning ignitions that acted on the pre-suppression landscape. It uses the MFI from Flatley et al. (2013) or Harmon (1982), and both formulas assume that anthropogenic ignitions have the same mean fire size as lightning ignitions.

$$\text{Lightning ignitions (\%)} = \text{MFI} / \text{Lightning fire cycle}$$

The ignitions that are not accounted for by lightning must be anthropogenic in origin.

$$\text{Anthropogenic ignitions (\%)} = 1 - \text{Lightning ignitions (\%)}$$

5. RESULTS

5.1 Spatial extent of fires on pre-suppression landscape

Most simulated fires on Hx1 and Hx2 were of small sizes, with 57% less than 10 hectares, whereas 54% of Hx3 fires were between 100 and 1000 ha (Fig. 9-12). Fire size differed among the historic scenarios (Friedman's test, $x^2 = 860.1248$, $df = 2$, $p < 0.01$) (Table 18). Post-hoc Nemenyi tests yielded significant differences in mean fire sizes generated among all three landscapes (Table 19). The mean fire size of scenario Hx3 is an order of magnitude larger than either of the other two scenarios. However, the mean fire size generated by averaging the simulated fire sizes for the total study area is an underestimation of what would have been seen on the landscape historically because the study area boundary truncated some of the fires (Fig. 12). Hx1 had 5.6 % of the total simulations stopped by the study area boundary. Hx2 had 6.0%, but Hx3 had 25.4% because the mean fire size for Hx3 was much larger than Hx1 or Hx2. The study area boundary, therefore, led to an underestimation of the mean fire size.

5.2 Total area burned and lightning fire cycle for the study area

The overlays generated by counting the number of fires each 10m cell burned showed a much larger range of times burned for Hx3 than for the Hx1 or Hx2 scenarios (Fig. 13-15). The number of fires per 10m cell ranged from 0 to 6 for Hx1 and Hx2 and 0 to 32 for Hx3. The total area burned created from overlays was slightly higher than if I had added up the burned area from each simulation due to the entire area of a partially

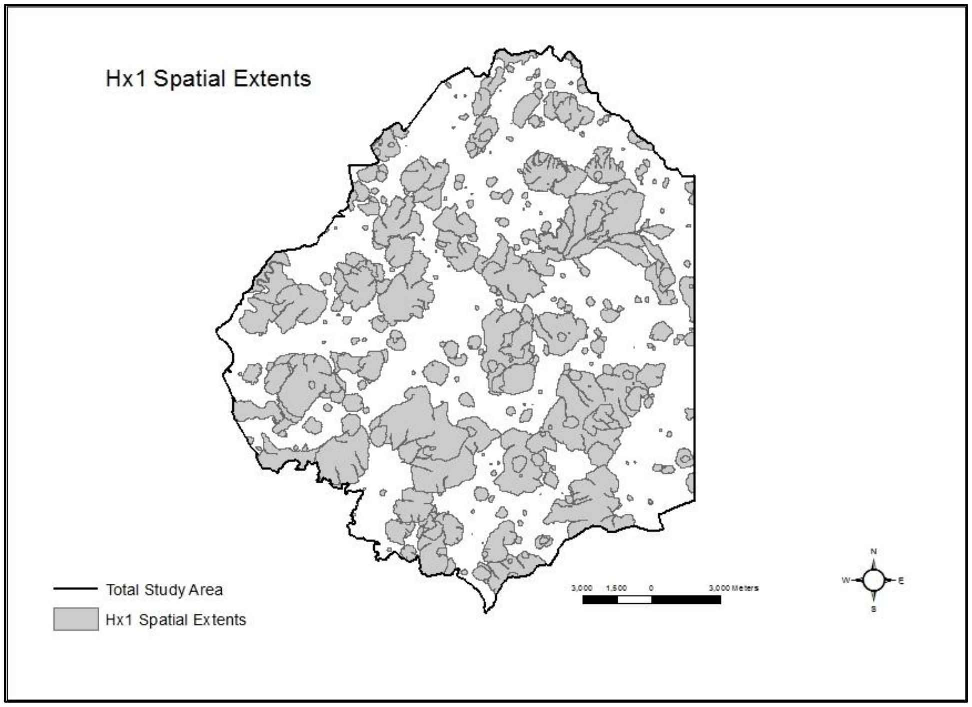

Figure 9. Fire perimeters generated on the Hx1 landscape. Grey polygons are areas burned in individual simulations. Areas could have burned in multiple simulations. Total area burned is 22,472.07 ha.

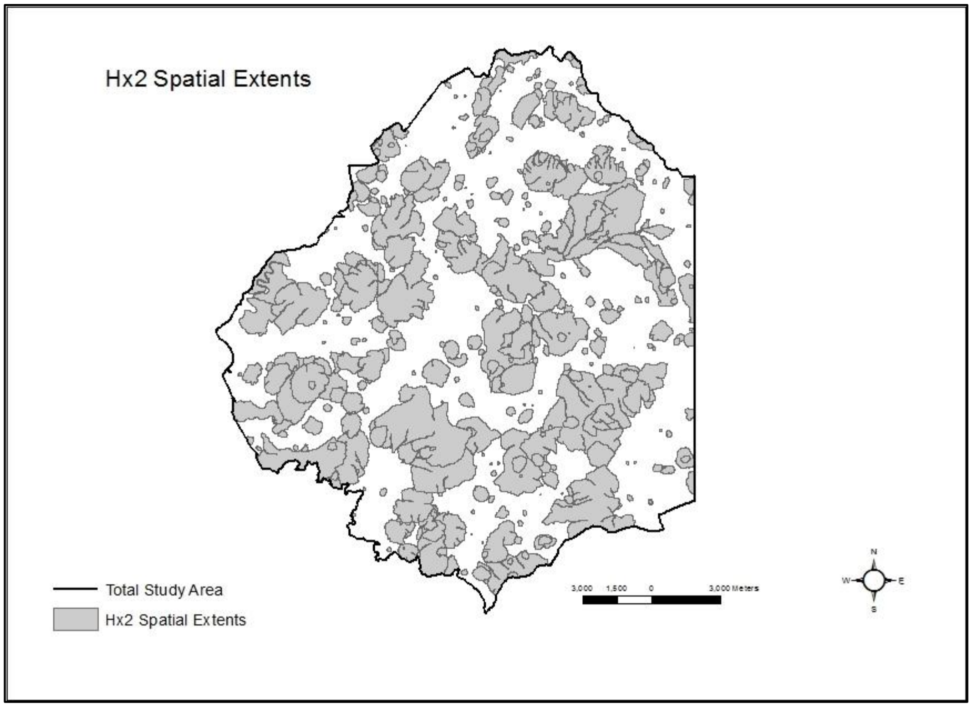

Figure 10. Fire perimeters generated on the Hx2 landscape. Grey polygons are areas burned in individual simulations. Areas could have burned in multiple simulations. Total area burned is 23,797.10 ha.

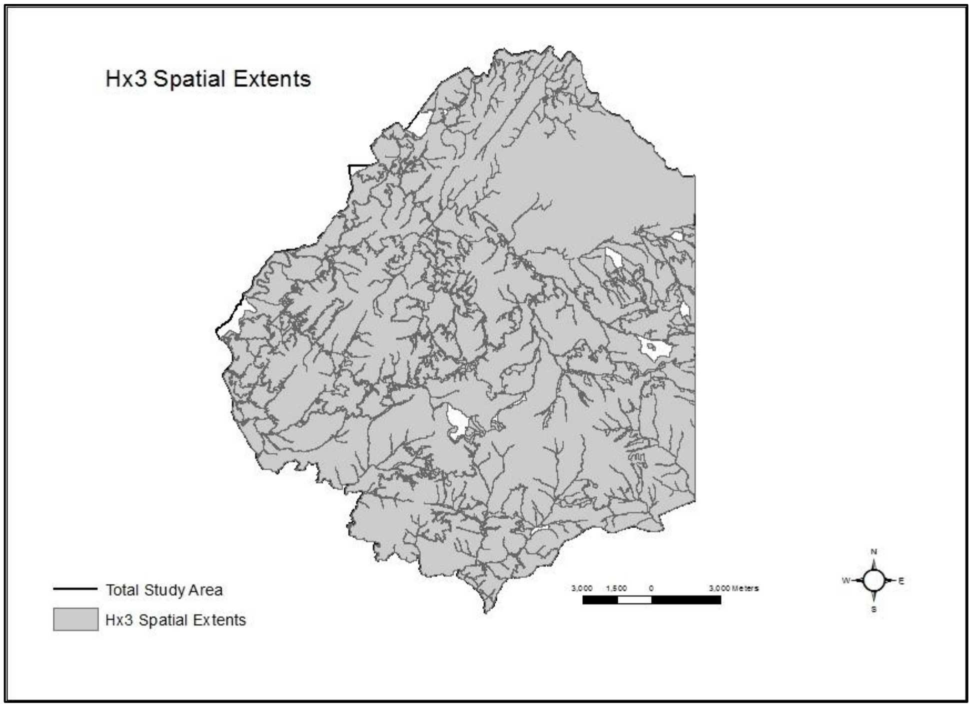

Figure 11. Fire perimeters generated on the Hx3 landscape. Grey polygons are areas burned in individual simulations. Areas could have burned in multiple simulations. Total area burned is 276,400.40 ha.

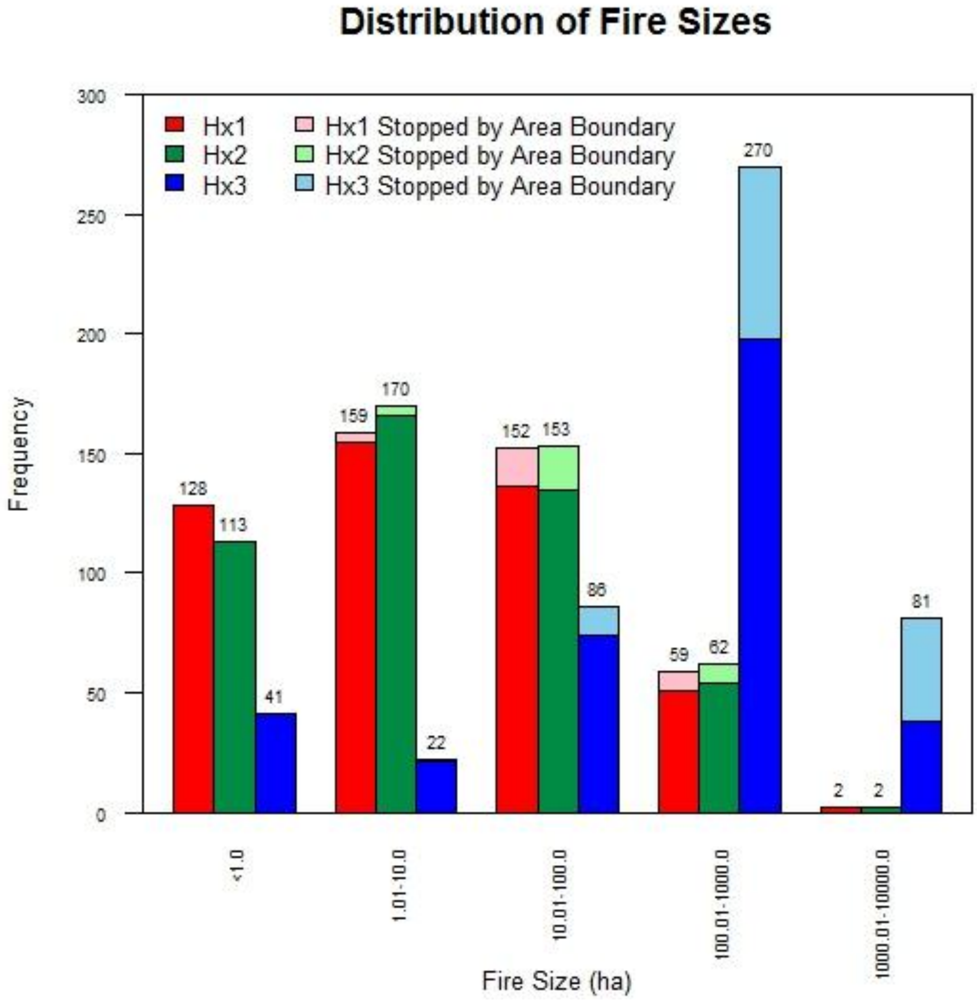

Figure 12. The fire size distribution from the Hx1, Hx2, and Hx3 landscape scenarios. Lighter colors represent simulations that were truncated by the study area boundary. The total number of simulations in each bin is listed above each column.

Table 18. Descriptive statistics of the three landscape scenarios.

Landscape	Mean (Ha)	Median (Ha)	SD	Min	Max	Mean Rank	Rank Sum	Skewness
Hx1	44.94	6.52	114.54	0.00	1275.41	1.14	571.5	5.63
Hx2	47.59	7.00	118.82	0.00	1275.01	1.95	975.5	5.47
Hx3	567.20	264.00	925.43	0.00	8125.87	2.91	1453.0	4.10

Table 19. Nemenyi post-hoc results between the three landscape scenarios.

Comparison	Difference in Mean Rank	Difference in Rank Sums	Significance
Hx1 v. Hx3	1.763	881.5	$p < 0.001$*
Hx1 v. Hx2	0.808	404.0	$p < 0.001$*
Hx2 v. Hx3	0.955	477.5	$p < 0.001$*

*Starred values are significantly different.

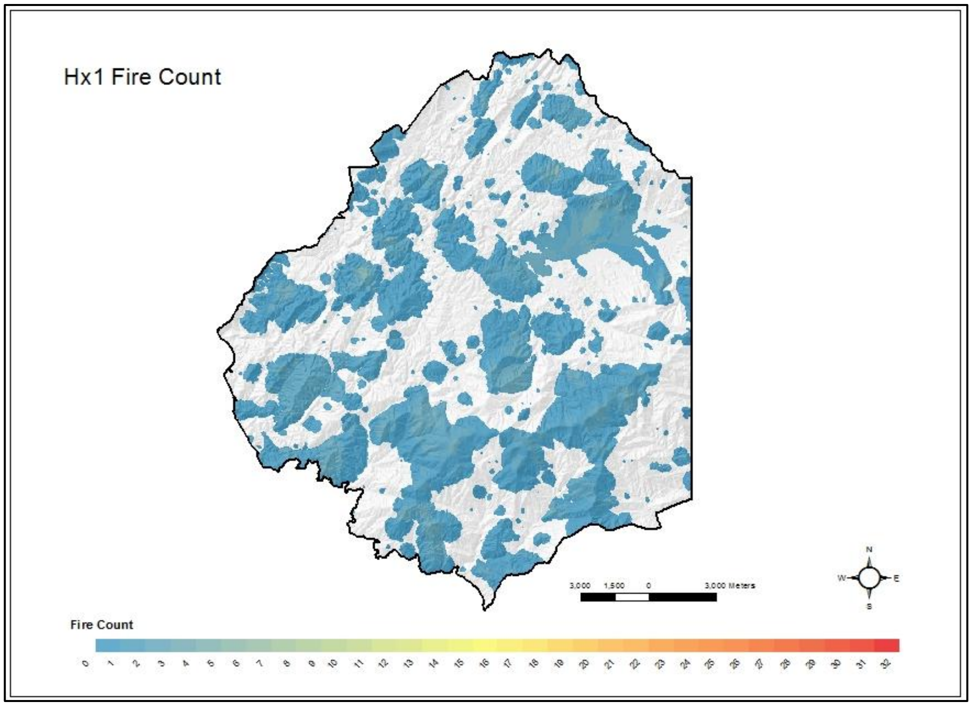

Figure 13. Count of fire occurrence for each 10 m grid cell for the Hx1 landscape. Range of counts is 0 to 6.

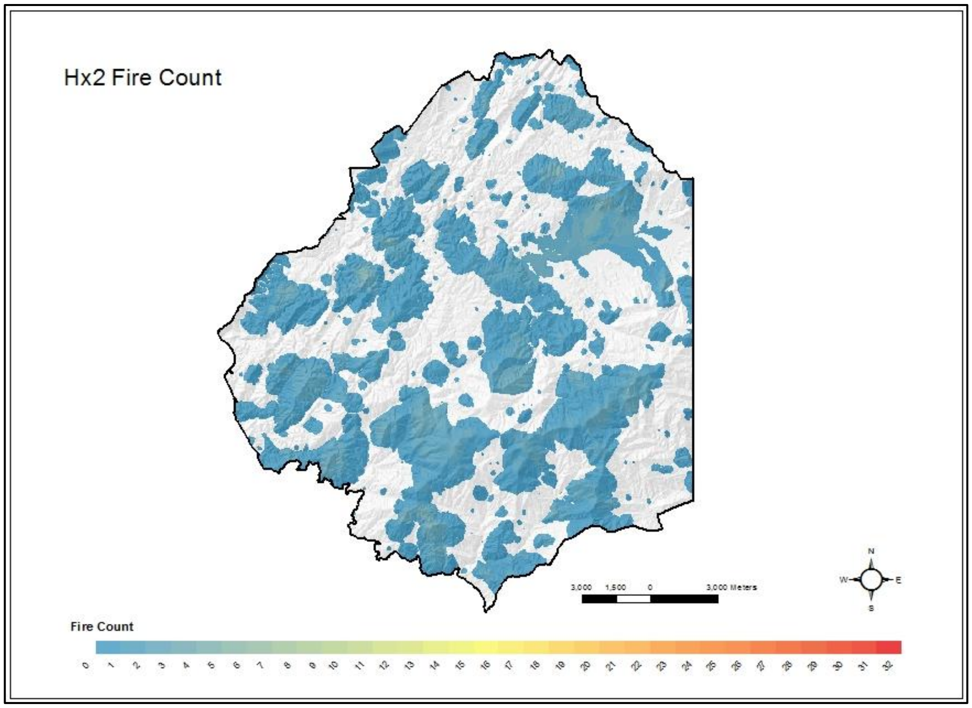

Figure 14. Count of fire occurrence for each 10 m grid cell for the Hx2 landscape. Range of counts is 0 to 6.

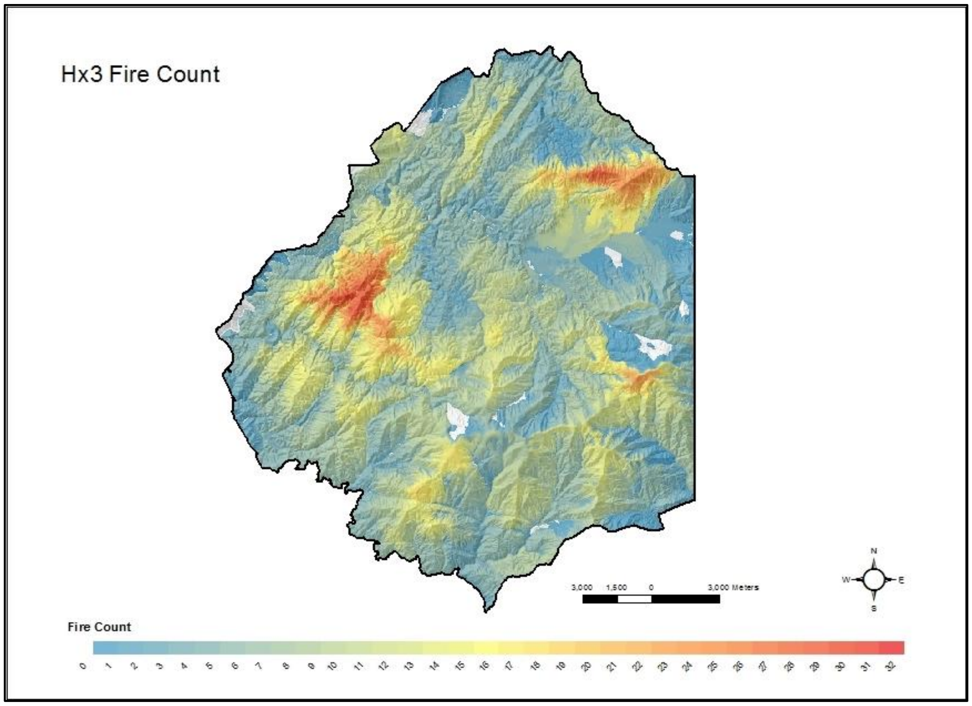

Figure 15. Count of fire occurrence for each 10 m grid cell for the Hx3 landscape. Range of counts is 0 to 32.

burned cell counting towards the total burned area for the overlays. However, this only led to a 3% increase in total burned area. Thus, it had a negligible effect on my results. I also calculated the lightning fire cycle for each cell (Fig. 16-18). A cell experiencing 32 fires in 1080 years indicates that a lightning fire burned that area on average every 34 years, whereas cells experiencing 1 fire in 1080 years indicates that a lightning fire burned that area every 1080 years.

The subset landscape was created to account for fires igniting outside the study area and burning into it. The subset landscape experienced 56.2% of Hx1 and Hx2 simulations and 74.6% of Hx3 simulations (Fig. 19-22) I calculated the number of fires and lightning fire cycle per 10m cell for the subset study area (Fig. 23-28).

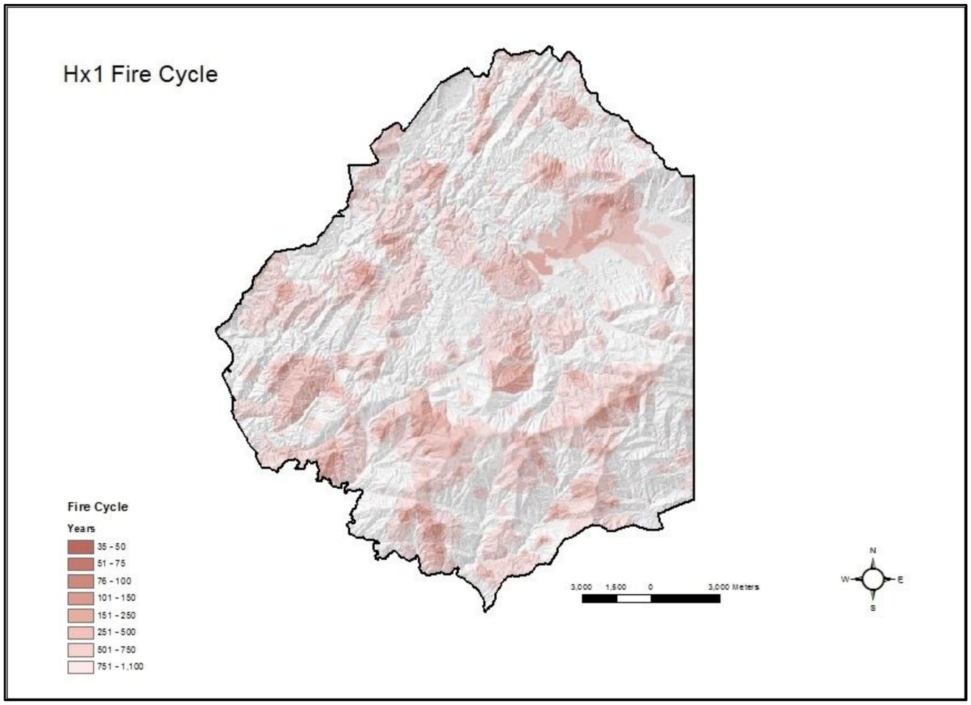

Figure 16. Fire cycle for each 10 m grid cell for the Hx1 landscape. Range of fire cycles is 34 to 1080 years.

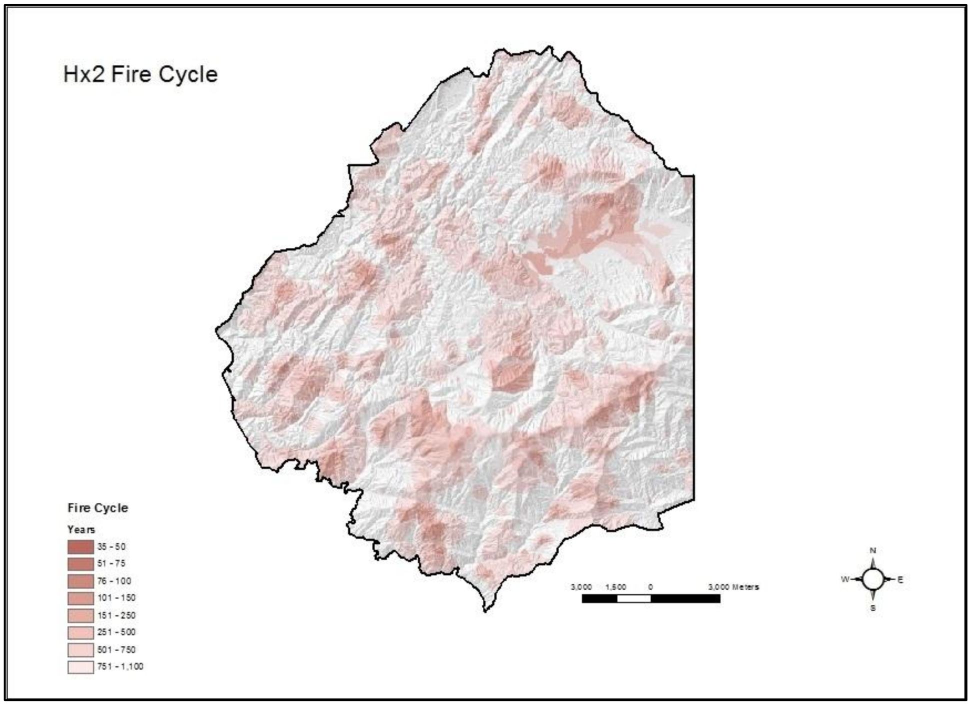

Figure 17. Fire cycle for each 10 m grid cell for the Hx2 landscape. Range of fire cycles is 34 to 1080 years.

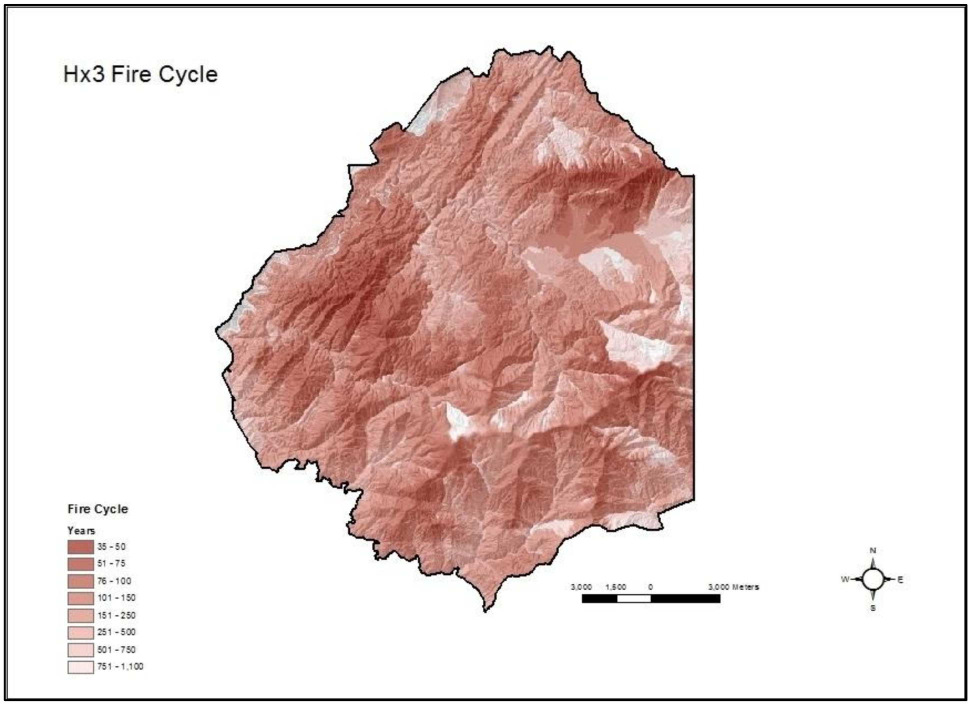

Figure 18. Fire cycle for each 10 m grid cell for the Hx3 landscape. Range of fire cycles is 34 to 1080 years.

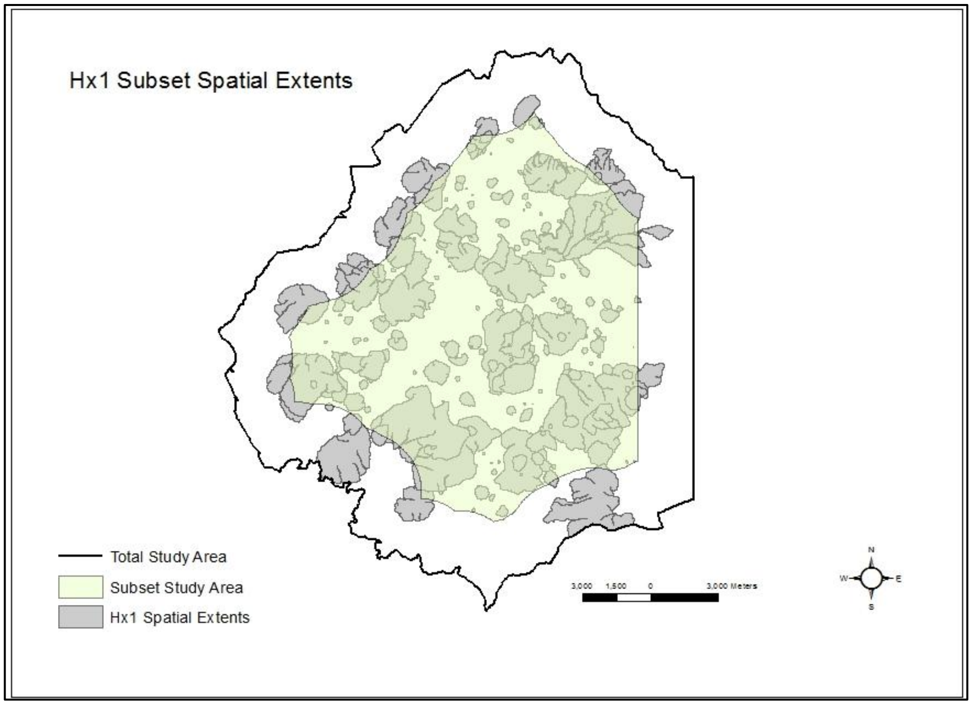

Figure 19. Fire perimeters on the Hx1 landscape that intersect the subset study area. Grey polygons are areas burned in individual simulations. Areas could have burned in multiple simulations.

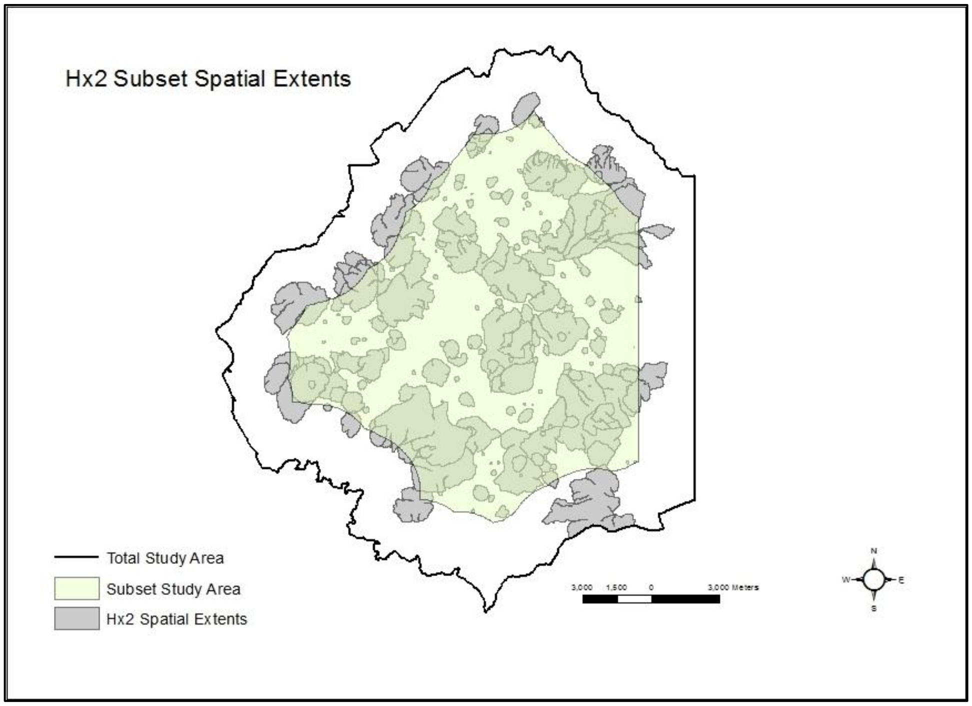

Figure 20. Fire perimeters on the Hx2 landscape that intersect the subset study area. Grey polygons are areas burned in individual simulations. Areas could have burned in multiple simulations.

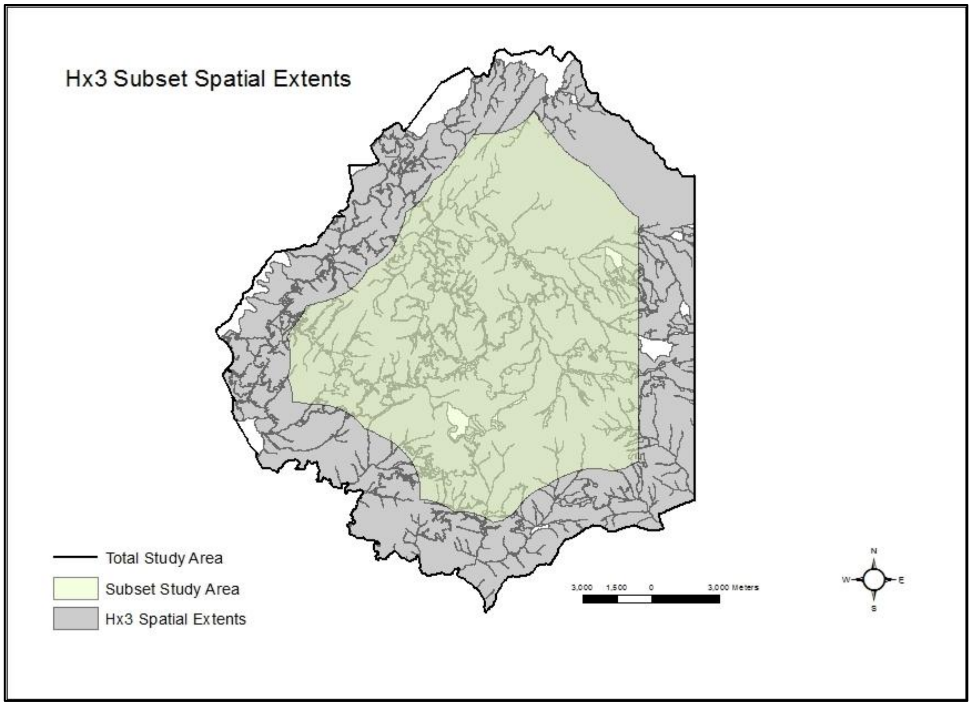

Figure 21. Fire perimeters on the Hx3 landscape that intersect the subset study area. Grey polygons are areas burned in individual simulations. Areas could have burned in multiple simulations.

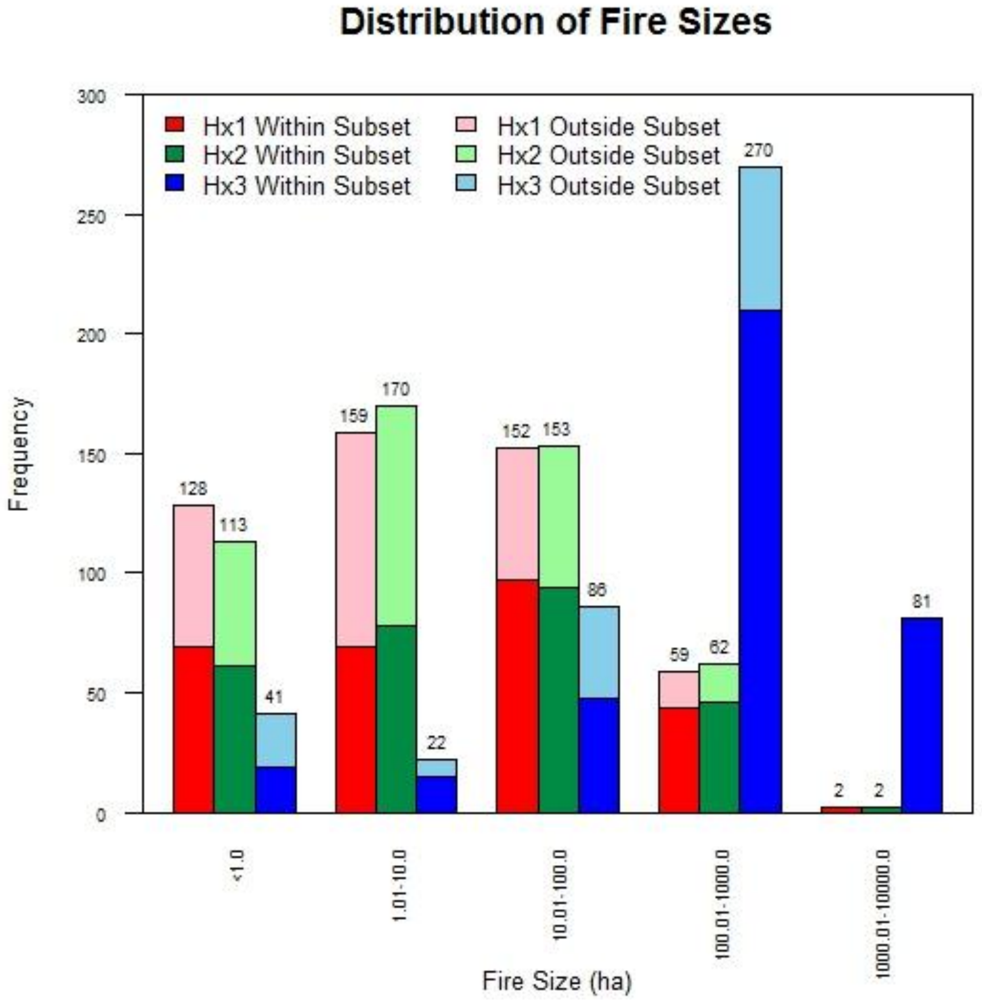

Figure 22. The fire size distribution from the Hx1, Hx2, and Hx3 landscape scenarios. Lighter colors represent simulations that are outside of the subset study area. The total number of simulations in each bin is listed above each column.

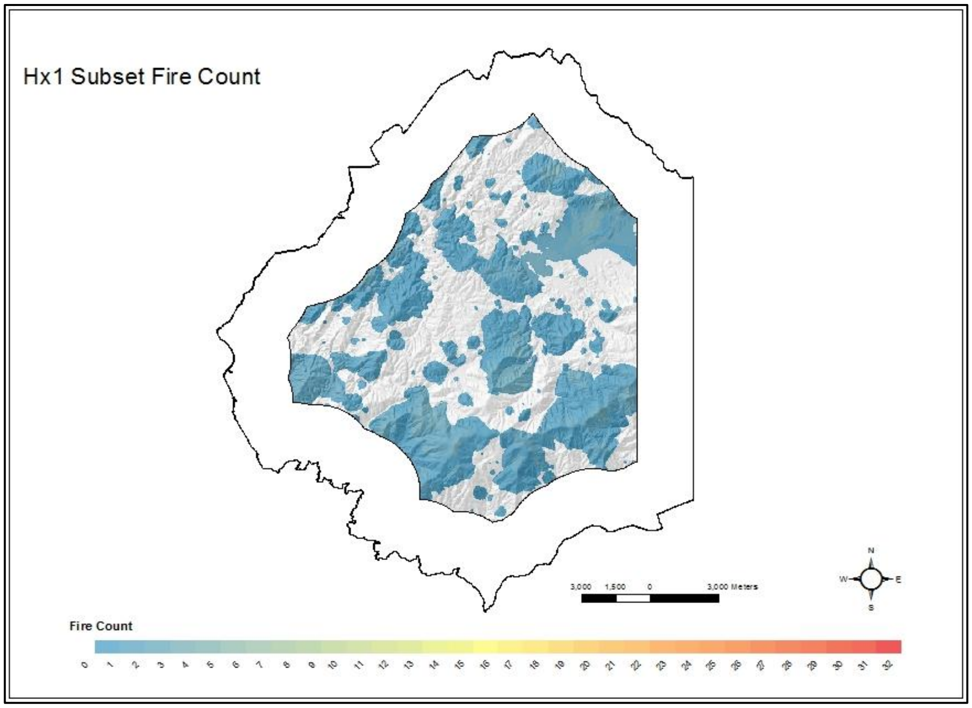

Figure 23. Count of fire occurrence for each 10 m grid cell for the subset Hx1 landscape. Range of counts is 0 to 6.

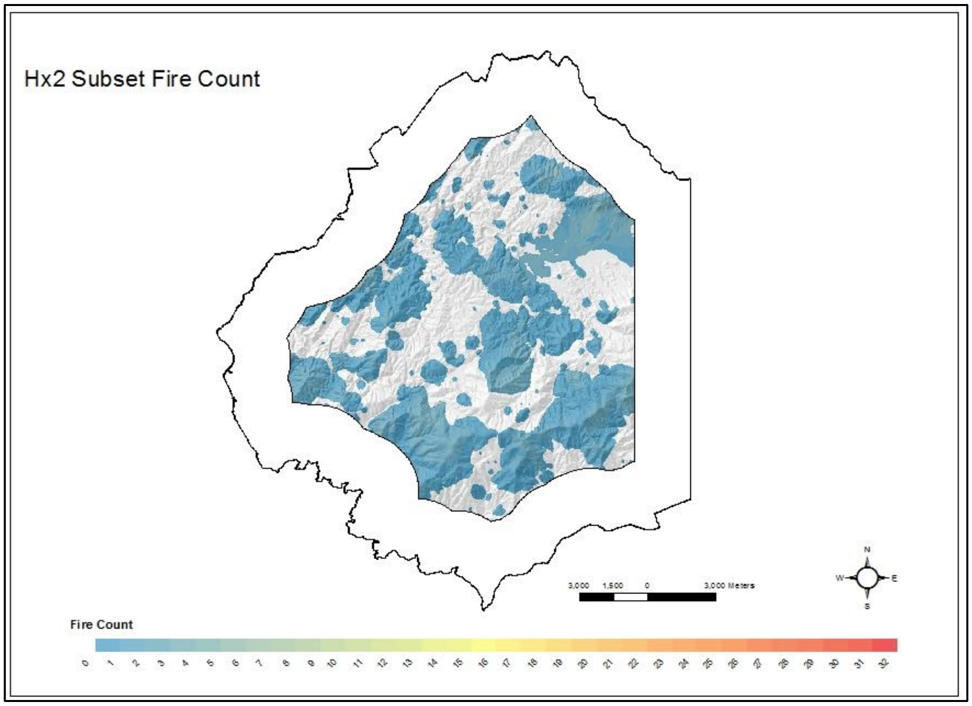

Figure 24. Count of fire occurrence for each 10 m grid cell for the subset Hx2 landscape. Range of counts is 0 to 6.

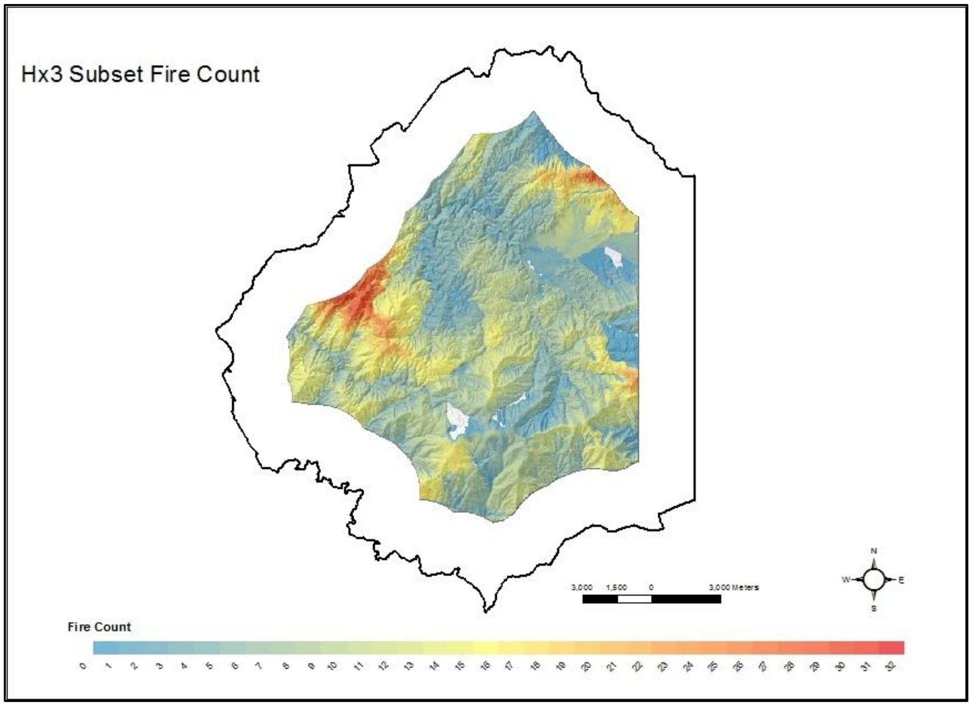

Figure 25. Count of fire occurrence for each 10 m grid cell for the subset Hx3 landscape. Range of counts is 0 to 32.

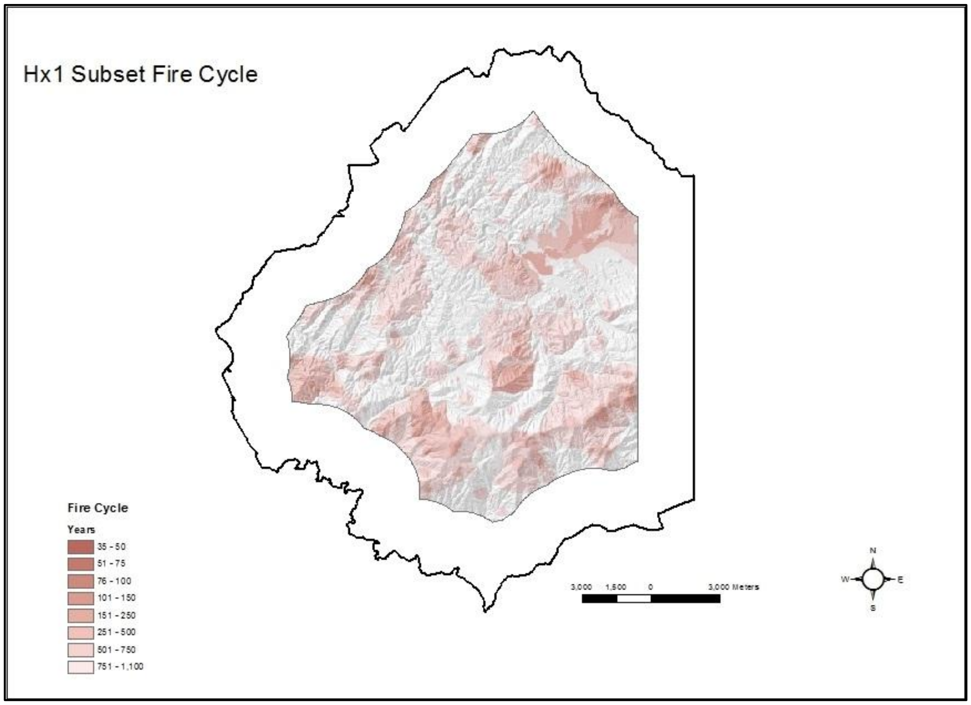

Figure 26. Fire cycle for each 10 m grid cell for the subset Hx1 landscape. Range of fire cycles is 34 to 1080 years.

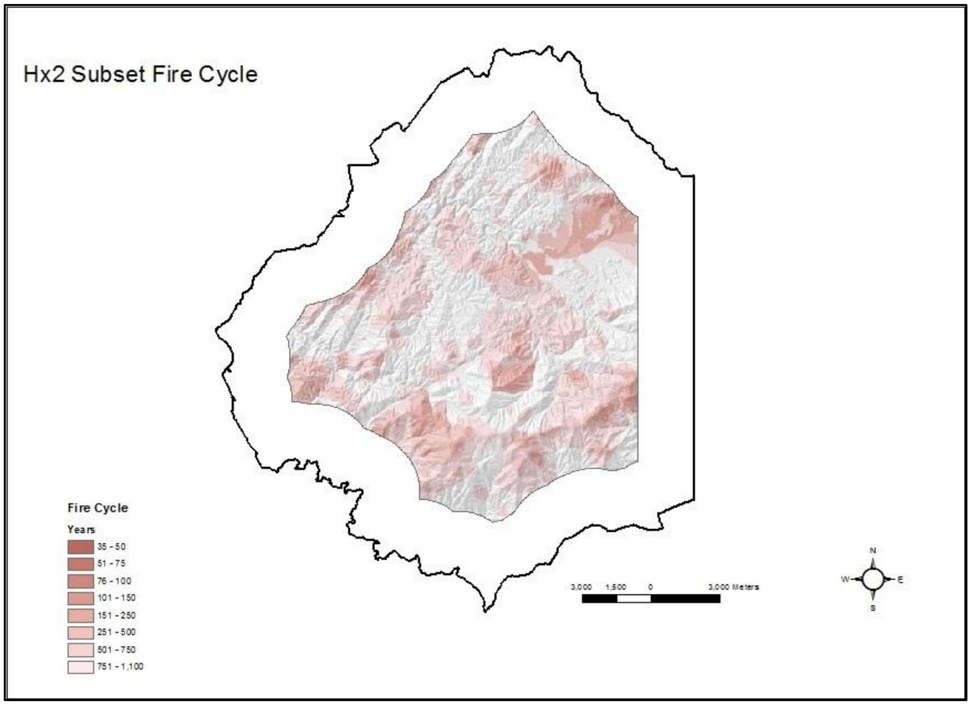

Figure 27. Fire cycle for each 10 m grid cell for the subset Hx2 landscape. Range of fire cycles is 34 to 1080 years.

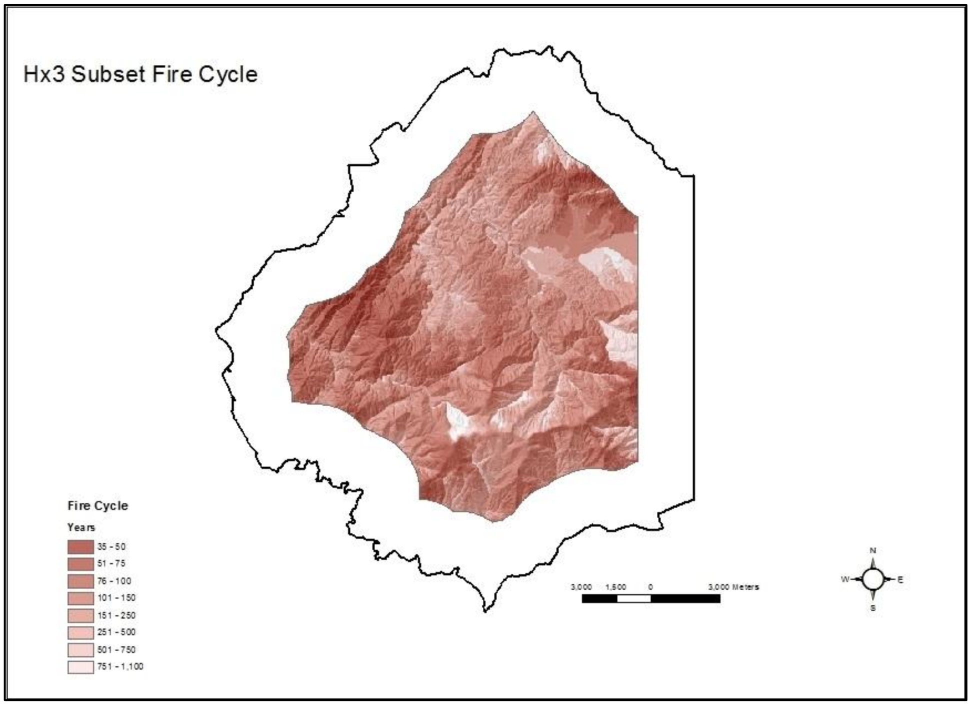

Figure 28. Fire cycle for each 10 m grid cell for the subset Hx3 landscape. Range of fire cycles is 34 to 1080 years.

Using the total area burned from the overlays, the lightning fire cycle for the entire study area, the subset study area, and the different landform classifications were between 1100 and 1900 for Hx1 and Hx2 and 100 and 150 for Hx3 (Table 20). As expected, the bottom land had the longest fire cycle for all landscapes and all topographic regions and the ridge had the shortest. I also calculated the subset fire cycle using the 1033 year time span. When using only the 478 simulations that produced fire growth, the lightning fire cycle for Hx3 showed approximately a 5 year shorter fire cycle than the 1080 year span, while the fire cycle for Hx1 and Hx2 showed approximately 65 year shorter fire cycles.

Table 20. Lightning fire cycle by landform classification

		Area Burned (ha)			Lightning Fire Cycle (Study Area/Area burned*1080 Observed years)		
	Study area (ha)	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3
Total Study Area	*34609.27*	*23246.11*	*24610.9*	*292629.65*	*1607.93*	*1518.76*	*127.73*
Ridge	9266.44	7078.45	7545.25	85002.28	1413.83	1326.36	117.74
Upper slope	11868.63	8102.97	8580.65	103243.83	1581.90	1493.84	124.15
Lower slope	7429.41	4652.43	4904.28	60891.14	1724.64	1636.07	131.77
Bottom land	6031.88	3406.28	3574.63	43422.26	1912.47	1822.41	150.03
Subset Study Area	*17875.47*	*13888.97*	*14689.3*	*168730.85*	*1389.99*	*1314.26*	*114.42*
Ridge	4876.09	4179.79	4451.53	49582.52	1259.91	1183.00	106.21
Upper slope	6076.37	4729.52	4999.90	58909.99	1387.56	1312.52	111.40
Lower slope	3801.77	2810.03	2955.27	34875.84	1461.16	1389.35	117.73
Bottom land	3121.24	2169.63	2282.61	25362.49	1553.69	1476.79	132.91

5.3 Fire size distribution

The majority of fires from Hx1 and Hx2 were small in size and a negative exponential curve was fit to their distributions (Fig. 29). Hx3 simulations consistently burned at a larger size, with the majority burning between 100 and 1000 ha, but a negative exponential curve still fit their distributions (Fig. 29). Over 70% of fires on the Hx3 landscape were larger than 100 ha, while over 80% of fires on the Hx1 and Hx2 landscapes were less than 100 ha. The majority of the area burned for Hx1, Hx2, and Hx3 were from the largest fires (Fig.30).

5.4 Ignition density

The ignition density required to maintain a 9.1 MFI for Hx1 and Hx2 ranged from 60 to 97 ignitions per year for the study area (Table 21). For the Hx3 landscape, only 5 to 8 ignitions are required. The ignition density required to maintain a 12.7 MFI for Hx1 and Hx2 ranged from 48 to 59 ignitions per year for the study area (Table 22). For the Hx3 landscape, only 4 to 5 ignitions are required. With a current ignition density of 0.46 ignitions per year for the study area, approximately 47 to 97 non-lightning ignitions would be required on the Hx1 or Hx2 landscapes to maintain the fire frequency reconstructed from fire scars. On the Hx3 landscape, 4 to 7 non-lightning ignitions would be required to maintain the observed frequency. These non-lightning ignitions would have to be anthropogenic in origin.

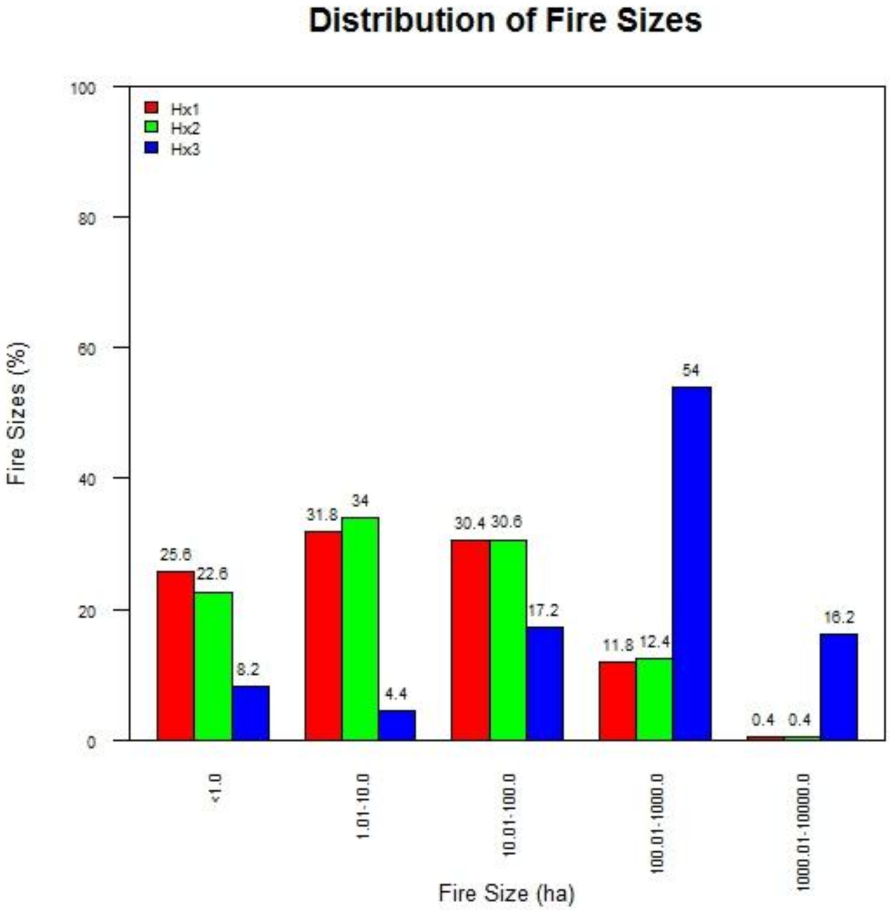

Figure 29. The fire size distribution for Hx1, Hx2, and Hx3 for different fire size categories.

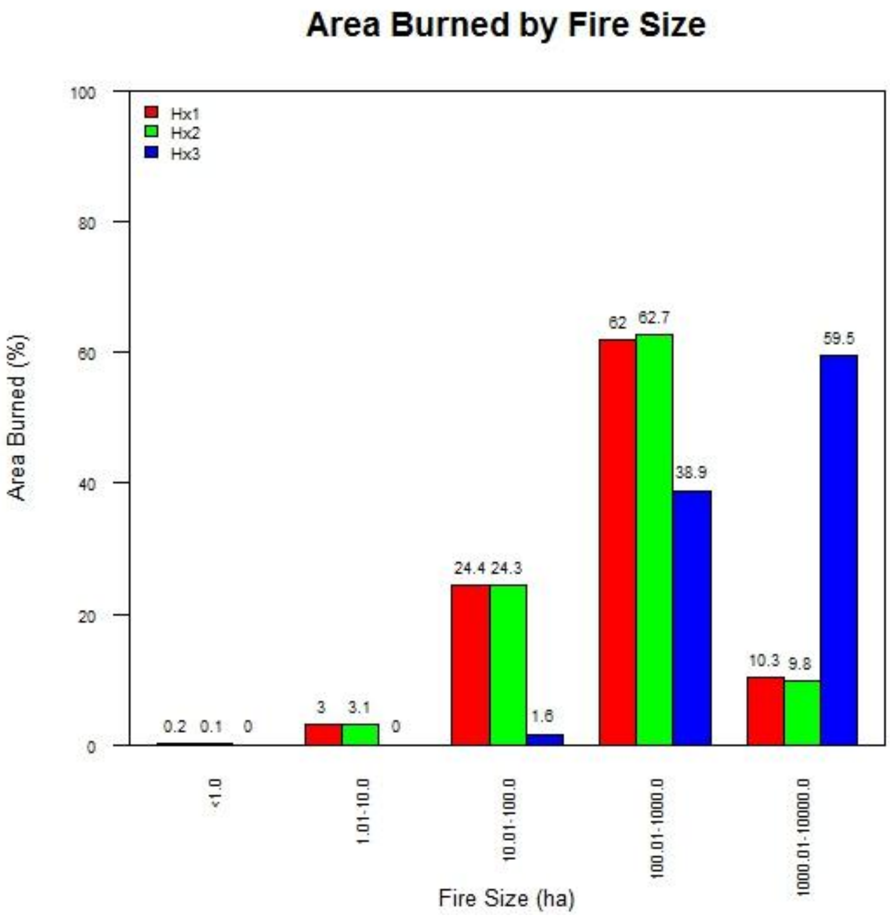

Figure 30. The percent area burned for Hx1, Hx2, and Hx3 for different fire size categories.

Table 21. Ignition density by study area and topographic region using MFI from Flatley et al. (2013)

					Mean Burned Area Per Fire (ha)			Ignition Density Required			Anthropogenic Ignition Density Required		
	Study area (ha)	MFI (years)	Current Ignition Density	Average yearly burn area (ha)	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3
Total Study Area	*34609.27*	*9.1*	*0.46*	*3803.2*	*46.48*	*49.21*	*585.12*	*81.82*	*77.29*	*6.50*	*81.36*	*76.82*	*6.04*
Ridge	9266.44	9.1	0.46	*1018.3*	14.16	15.09	170.00	*71.93*	*67.48*	*5.99*	*71.47*	*67.02*	*5.53*
Upper slope	11868.63	9.1	0.46	*1304.2*	16.21	17.16	206.49	*80.48*	*76.00*	*6.32*	*80.02*	*75.54*	*5.85*
Lower slope	7429.41	9.1	0.46	*816.4*	9.30	9.81	121.78	*87.74*	*83.24*	*6.70*	*87.28*	*82.77*	*6.24*
Bottom land	6031.88	9.1	0.46	*662.8*	6.81	7.15	86.84	*97.30*	*92.71*	*7.63*	*96.83*	*92.25*	*7.17*
Subset Study Area	*17875.47*	*9.1*	*0.46*	*1964.3*	*27.78*	*29.38*	*337.46*	*70.72*	*66.86*	*5.82*	*70.25*	*66.40*	*5.36*
Ridge	4876.09	9.1	0.46	*535.8*	8.36	8.90	99.17	*64.10*	*60.19*	*5.40*	*63.64*	*59.72*	*4.94*
Upper slope	6076.37	9.1	0.46	*667.7*	9.46	10.00	117.82	*70.59*	*66.77*	*5.67*	*70.13*	*66.31*	*5.20*
Lower slope	3801.77	9.1	0.46	*417.8*	5.62	5.91	69.75	*74.34*	*70.68*	*5.99*	*73.87*	*70.22*	*5.53*
Bottom land	3121.24	9.1	0.46	*343.0*	4.34	4.57	50.72	*79.04*	*75.13*	*6.76*	*78.58*	*74.67*	*6.30*

Table 22. Ignition density by study area using MFI from Harmon (1982)

					Mean Burned Area Per Fire (ha)			Ignition Density Required			Anthropogenic Ignition Density Required		
	Study area (ha)	MFI (years)	Current Ignition Density	Average yearly burn area (ha)	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3
Total Study Area	*34609.27*	*12.7*	*0.46*	*2725.1*	*46.48*	*49.21*	*585.12*	*58.63*	*55.38*	*4.66*	*58.17*	*54.92*	*4.19*
Subset Study Area	*17875.47*	*12.7*	*0.46*	*1407.5*	*27.78*	*29.38*	*337.46*	*50.67*	*47.91*	*4.17*	*50.21*	*47.45*	*3.71*

5.5 Percentage of pre-suppression lightning fire frequency

The percentage of lightning ignitions was under 1% for both Hx1 and Hx2 for the total study area, the subset study area and for all topographic positions when using either the 9.1 or 12.7 year MFI (Table 23 and 24). For Hx3, the percentage of lightning ignitions was between 6 and 11% for the total study area, the subset study area and for all topographic positions when using either the 9.1 or 12.7 year MFI. When using only the 478 simulations that produced fire growth, the percentage of lightning ignitions was approximately 0.03% more for Hx1 and Hx2 and 0.34% more for Hx3.

Table 23. Potential ignition source using Flatley et al. (2013)

			Lightning Fire Cycle (years)			Percentage Lightning Ignitions			Percentage Anthropogenic Ignitions		
	Study area (ha)	MFI (years)	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3
Total Study Area	*34609.27*	*9.1*	*1607.93*	*1518.76*	*127.73*	*0.57%*	*0.60%*	*7.12%*	*99.43%*	*99.40%*	*92.88%*
Ridge	9266.44	9.1	1413.83	1326.36	117.74	0.64%	0.69%	7.73%	99.36%	99.31%	92.27%
Upper slope	11868.63	9.1	1581.90	1493.84	124.15	0.58%	0.61%	7.33%	99.42%	99.39%	92.67%
Lower slope	7429.41	9.1	1724.64	1636.07	131.77	0.53%	0.56%	6.91%	99.47%	99.44%	93.09%
Bottom land	6031.88	9.1	1912.47	1822.41	150.03	0.48%	0.50%	6.07%	99.52%	99.50%	93.93%
Subset Study Area	*17875.47*	*9.1*	*1389.99*	*1314.26*	*114.42*	*0.65%*	*0.69%*	*7.95%*	*99.35%*	*99.31%*	*92.05%*
Ridge	4876.09	9.1	1259.91	1183.00	106.21	0.72%	0.77%	8.57%	99.28%	99.23%	91.43%
Upper slope	6076.37	9.1	1387.56	1312.52	111.40	0.66%	0.69%	8.17%	99.34%	99.31%	91.83%
Lower slope	3801.77	9.1	1461.16	1389.35	117.73	0.62%	0.65%	7.73%	99.38%	99.35%	92.27%
Bottom land	3121.24	9.1	1553.69	1476.79	132.91	0.59%	0.62%	6.85%	99.41%	99.38%	93.15%

Table 24. Potential ignition source using Harmon (1982)

			Lightning Fire Cycle (years)			Percentage Lightning Ignitions			Percentage Anthropogenic Ignitions		
	Study area (ha)	MFI (years)	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3	Hx1	Hx2	Hx3
Total Study Area	*34609.27*	*12.7*	*1607.93*	*1518.76*	*127.73*	*0.79%*	*0.84%*	*9.94%*	*99.21%*	*99.16%*	*90.06%*
Subset Study Area	*17875.47*	*12.7*	*1389.99*	*1314.26*	*114.42*	*0.91%*	*0.97%*	*11.10%*	*99.09%*	*99.03%*	*88.90%*

6. DISCUSSION

6.1 Hypothesis 1: Spatial extent

The smaller mean fire size from the Hx1 landscape scenario is consistent with my expectations of fire size on a landscape representing current vegetation conditions. Hx1 is the most conservative of my three landscape scenarios, assuming that the landscape prior to suppression was the same as the current landscape. Because Hx1 represents the current vegetation, its mean fire size should be similar to that seen on the current landscape. Flatley et al. (2011), in a review of 643 anthropogenic and 101 lightning ignited fires in the entire GSMNP from 1930 to 2003, found a mean fire size of 25.6 ha for all fires, 8.2 ha for lightning fires, and 28.3 ha for anthropogenic fires. Harmon (1982), in a review of anthropogenic and lightning ignited fires from 1940-1979 in approximately 9,100 ha of the westernmost GSMNP, found a mean fire size of 3.4 ha for lightning fires and 5.4 ha for anthropogenic fires. The Hx1 simulations produced a mean fire size of 44.94 ha, over 5 times what Flatley et al. (2011) found and 13 times what Harmon (1982) determined for lightning-ignited fires. However, this does not indicate that Hx1 overestimated fire spread. During the time periods for both studies, the GSMNP was practicing fire suppression. Therefore, suppression efforts limited the spread of almost all of the fires included in these studies. In addition, trails and roads, which were not included in the Hx1 scenario, potentially acted as fire breaks impeding fire spread. The 35 unsuppressed lightning fires from GSMNP from 1985 to 2008 had a mean fire size of 78.7 ha. Thirty-five is a small sample size, but this mean fire size is of the same order of magnitude of my simulations. Therefore, fire behavior on Hx1appears to be a reasonable representation of actual fire behavior. While I expected Hx2 to show more fire spread due to its open canopy conditions, its mean fire size is closer to Hx1 than Hx3. The little change between Hx1 and Hx2 when compared to Hx3 indicates that canopy opening without associated vegetation changes does not have as much effect on fire spread as canopy opening with vegetation change.

The larger mean fire size and short fire cycle on the Hx3 landscape scenario is consistent with my expectations of fire spread on a more open landscape with flammable herbaceous understories. Hx3 was the least conservative and most realistic scenario of the landscape conditions prior to suppression. Based on studies of current lightning fires in the GSMNP (Flatley et al. 2011, Harmon 1982, Cohen et al. 2007), the mean fire size of Hx3 was considerably larger. The mean fire size of Hx3 was 67 times larger than Flatley et al. (2011), 163 times larger than Harmon (1982), and 7 times larger than the 35 unsuppressed fires from 1985 to 2008. This confirms my first hypothesis that historic fire sizes predicted by fire modeling will be larger than those on the current landscape. This is in line with previous hypotheses that pre-suppression fires were larger than those on the current landscape (Harrod et al. 2000; Lafon 2010).

6.2 Lightning fire cycle

The three landscape scenarios were created to represent different vegetation conditions that could have existed prior to suppression. Hx1 and Hx2 produced significantly different fire sizes. However, the similar lightning fire cycles for the Hx1 and Hx2 scenarios indicate that lightning-ignited fires would have similar effects on both landscapes. While lightning fire cycles of 1000-2000 years are shorter than what the GSMNP has experienced during the period of fire suppression (25,000-30,000) (Harmon 1982; Flatley et al. 2011), they indicate that lightning-ignited fires would not be important shapers of the Hx1 or Hx2 landscape. On Hx1 and Hx2, lightning-ignited fires would not have been able to maintain the fire-associated species and landscape that appear to have existed prior to suppression (Wright and Baily 1982; Abrams 1992; Frost 1998; Harrod et al. 2000; Nowacki and Abrams 2008).

The lightning fire cycle for Hx3 (100-150 years) is such that the dominant tree species would have experienced at least one to two fire events within their lifespan (Lafon and Grissino-Mayer 2007). Therefore, lightning-ignited fires would be common enough and burn enough area to influence the vegetation and succession of the western GSMNP. However, the lightning fire cycle for Hx3 would still not be short enough to maintain the fire-associated species and landscape typical of the southern Appalachians throughout the entire study area or maintain the observed frequency calculated from fire scars (Harmon 1982; Flatley et al. 2013). Additional ignitions from anthropogenic sources would be required to maintain these species and landscapes.

It is apparent that active suppression by managers has changed the lightning fire cycle. The suppression-era fire cycles (25,000-30,000) (Harmon 1982; Flatley et al. 2011) indicate that lightning fires were ecologically inconsequential on the landscape during this time. By relying on suppression-era information, some researchers and managers have incorrectly concluded that lightning fires did not impact the southern

Appalachian landscape historically (Cohen and Dellinger 2006). Under current WFU policies, some lightning-ignited fires have been allowed to burn unsuppressed. Thirty-five lightning-ignited fires burned unsuppressed from 1985-2008. These fires produced a lightning fire cycle of approximately 5,300 years. While much shorter than the suppression-era fire cycle, the current unsuppressed lightning fire cycle is still thousands of years longer than the lightning fire cycle indicated by fire history reconstructions or produced by the Hx3 scenario.

6.3 Fire size distribution

Individual fires create burned-over patches on the landscape. Large fires create large patches, and small fires create small patches (Gill et al. 2003; Cui and Perera 2008). Early successional species establish on recently burned patches (DiBari 2004), transitioning to mid then later successional species as time-since-fire increases. On landscapes with shorter fire cycles, like the pre-suppression GSMNP, frequent fires maintain patches dominated by early successional species (Harrod et al. 2000; Wimberly and Reilly 2007). The frequency and distribution of fire sizes influences the patch size and age-structure of the forest (Gill et al. 2003; Cui and Perera 2008).

The same mean fire size, and consequent fire cycle, can be the result of several fire size distributions (Li et al. 1999). Therefore, a small number of large fires and many small fires, or a mixture of large, medium, and small fires can produce the same fire cycle. However, different fire size distributions will create different patterns, patch sizes, and tree age-structure on the landscape. These different patterns will influence both the ecological effects of fire and the subsequent fire behavior (Li et al. 1999).

Current literature indicates that fire sizes in the North American boreal forest, northwestern United States, Rocky Mountains, Spain, and modeled landscapes generally follow power law, negative exponential, or Pareto distributions (Malamud et al. 2005; Cui and Perera 2008). In other words, the majority of fires are small with few large fires. As the number of small fires increases and the number of large fires decreases, the slope of the distribution becomes steeper. Fire size distribution varies both spatially and temporally. The steepness of the slope is affected by regional conditions and anthropogenic actions (Cui and Perera 2008). Fire suppression is associated with an increased occurrence of small fires, leading to a steeper slope (Weber and Stocks 1998; Cui and Perera 2008). The eastern U.S. appears to have a larger ratio of small to large wildfires, or a steeper slope, than the western part of the country (Malamud et al. 2005).

On landscapes where flammable and less flammable fuels are interspersed, fire spread is hindered, resulting in few large fires and many smaller fires (Cui and Perera 2008). Currently, the southern Appalachians are consistent with this fuel configuration and fire size distribution. Current fires show a characteristic fire size distribution with many small fires and few large fires (Lafon et al. 2005; Lafon and Grissino-Mayer 2007; Flatley et al. 2011). Approximately 80% of lightning ignited fires burned under 10 ha and approximately 15% burned 10-100 ha for areas in the central Appalachians (Lafon et al. 2005; Lafon and Grissino-Mayer 2007). However, power law or negative exponential distributions have not been fit to these data to determine the steepness of their slope.

Since the majority of these fires are suppressed, they should show a steeper slope than may have existed for unsuppressed fires or prior to suppression.

Because Hx1 is representative of the current vegetation condition, it would be expected to show a similar fire size distribution to current fires. The fire size distribution for Hx1 and Hx2 are somewhat consistent with the currently observed fire size distributions on the southern Appalachians (Fig. 28). The majority of fires from Hx1 and Hx2 were small in size and a negative exponential curve was fit to their distributions. With their shorter fire cycle, the fire size distributions of Hx1 and Hx2 are consistent with Li et al (1999), who found that landscapes with longer fire cycles would have more, smaller fires than landscapes with shorter fire cycles. However, there are fewer small fires than are seen on the current landscape. This is potentially due to active suppression causing more small fires on the current landscape than was seen within the simulations (Weber and Stocks 1998; Cui and Perera 2008). Hx3 simulations consistently burned at a larger size, with the majority burning between 100 and 1000 ha, but a negative exponential curve still fit their distributions. Hx3 has what appears to be an uncommon fire size distribution, but since it fits a negative exponential curve, it is a realistic result.

A pre-suppression fire size distribution that is similar to that of Hx3 indicates that the landscape was shaped by more medium to large fires. This fire size distribution would lead to many medium to large, early successional patches that provide continuous fuel beds, leading to conditions that favored fire spread. In addition, larger fires appear to have more lasting ecological effects as smaller patches are likely in-filled more quickly than larger patches (Sousa 1984). The fire size distribution and the frequency experienced by the Hx3 landscape seems capable of maintaining the fire-associated ecosystems characteristic of the pre-suppression landscape.

An important fire regime characteristic that fire size distribution indicates is what size class of fires is burning the most area. In the GSMNP, 39% of the area burned from 1930 to 2003 was burned by the few fires larger than 1,000 ha, and approximately 80% of the area burned was burned by the approximately 10% of fires larger than 100 ha (Flatley et al. 2011). Thus, in the current GMSNP it appears that few large fires will burn most of the landscape. Hx1 and Hx2 exhibited similar patterns.

Similar to the current landscape, Hx1, and Hx2, the majority of the area burned on the Hx3 landscape was from the largest fires. However, Hx3 shows more burned area from both medium and larger fires than the current fire size distribution (Flatley et al. 2011). Therefore, Hx3 does not appear consistent with the fire size distribution seen on the current landscape. The pre-suppression fire size distribution may have resulted in more medium to large fires and did not rely only on a few large fires to burn the majority of area. There is a need for future research on the potential fire size distribution of the pre-suppression landscape to corroborate these results. With current unsuppressed fire information, the potential to detect a change in fire size distribution could inform the magnitude of fire regime change that has resulted from active fire suppression policies.

6.4 Hypothesis 2: Ignition density

As previously discussed, lightning was not the only ignition source that was affecting the landscape (Denevan 1992, Delcourt et al. 1998; Nowacki and Abrams

2008). Native Americans and European settlers used fire to manipulate the landscape (Denevan 1992; Delcourt et al. 1998; Nowacki and Abrams 2008). Assuming that lightning and anthropogenic fires produced the same mean fire size, to maintain a 9.1 MFI to a 12.7 MFI (Harmon 1982; Flatley et al. 2013), 4 to 7 ignitions a year are needed. Assuming that the pre-suppression rate of lightning ignitions is the same as the current rate of lightning ignitions (0.463), this confirms my second hypothesis that ignition density required to support the observed pre-suppression fire regime will be larger than can be accounted for by lightning ignitions alone.

6.5 Ignition source

For Licklog Ridge in the western GSMNP, Flatley et al. (2013) found that 90.6% of fires where seasonality could be determined from 1773 to pre-suppression occurred during the dormant season and 9.4% of fires occurring in the spring to summer. Since lightning ignitions are most common in the growing season and anthropogenic fires are most common in the dormant season, this could indicate that 9.4% of ignitions were caused by lightning and 90.6% were caused by human activity (Hoss et al. 2008; Lafon 2010). The percentage of lightning (6-11%) and anthropogenic (89-94%) ignitions for Hx3 agree with the seasonality from the fire history performed by Flatley et al. (2013). This lends support to the assertion that Hx3 reasonably represents the pre-suppression landscape. It also helps validate my study and is consistent with the current understanding of the importance of anthropogenic ignitions in the pre-suppression fire regime in the western GSMNP. The percentage of lighting (< 1%) and anthropogenic

(>99%) ignitions on Hx1 and Hx2 do not agree with the seasonality from Flatley et al. (2013), indicating that these are likely not accurate representations of the pre-suppression landscape.

Studies of current lightning and anthropogenic fire sizes (Harmon 1981; Harmon 1982; Lafon et al. 2005; Lafon and Grissino-Mayer 2007; Flatley et al. 2011,) generally agree that anthropogenic fires are larger than lightning fires. It is unknown whether this was the case prior to suppression since current studies include suppressed fires. In addition, the spatial pattern of anthropogenic ignitions has likely changed. Current anthropogenic ignitions are typically accidental or arson and tend to occur at lower elevations and near park boundaries (Harmon 1981). If pre-suppression lightning and anthropogenic fire sizes followed the same ratio of fire sizes as found on the current landscape, anthropogenic fires in GSMNP could be up to 2.5 times as large as lightning fires (Flatley et al. 2011; Harmon 1982). If this was the case, the mean fire size for anthropogenic ignitions would be 1385.86 ha. On the Hx3 landscape, a 1385.86 ha fire size would take only approximately 2.56 anthropogenic ignitions, in addition to lightning ignitions, per year to maintain the fire cycle for the study area. Under this scenario, 85% of ignitions would be anthropogenic and 15% of ignitions would be caused by lightning. These percentages still agree with the seasonality found by Flatley et al. (2013), i.e. that dormant season burns were far more common than growing season burns.

While lightning apparently was not the main ignition source on the pre-suppression landscape, lightning fires can have a disproportionate effect on the landscape because summer fires often cause greater mortality than dormant season fires

(Sutherland et al. 1993; Lafon et al. 2005). Their seasonality, frequency, and size show that lightning fires contributed to the structure and composition of the western GSMNP forest, with additional manipulation by Native Americans and European settlers.

6.6 Management

For over 4,000 years (Delcourt and Delcourt 1997), fire has been shaping the southern Appalachians. The frequent use of fire by Native Americans and European settlers, the extreme fires associated with logging and the Industrial Revolution in the late 19th century, and almost a century of attempted fire exclusion have determined the southern Appalachian vegetation composition and structure. The current landscape appears to be different than what existed prior to fire suppression. The dominant vegetation communities existed for thousands of years until active fire exclusion (Frost 1998; Nowacki and Abrams 2008). These communities were maintained by a combination of lightning and anthropogenic ignitions.

Today, many managers seek to restore the pre-suppression landscape with its fire-associated species. By altering the current fire cycle and fire size distribution to be more in line with those on the pre-suppression landscape, managers hope to alter the current forest composition. My study indicates that if allowed to burn, lightning fires would influence the current landscape. Under the current WFU policy, lightning ignited fires that achieve resource management objectives are allowed to burn unsuppressed (Lafon and Grissino-Mayer 2007, Cohen et al. 2007). However, lightning fires are not enough either to restore or subsequently maintain a pre-suppression landscape especially under current fuel conditions. Anthropogenic fires are also needed to effectively manage the southern Appalachian landscape. Acknowledging that the current landscape cannot be restored to exactly its pre-suppression state, the increased use of the WFU policy and prescribed burns can aid in the protection of endemic species and ultimately alter the forest composition to a more fire-associated landscape (Brose et al. 2001; Lafon et al. 2005; Lafon and Grissino-Mayer 2007). This fire-associated landscape will be more consistent with the pre-suppression vegetation conditions within GSMNP and other areas of the southern Appalachians (Brose et al. 2001; Lafon et al. 2005; Lafon and Grissino-Mayer 2007). Current WFU managed fires burn on average 75 ha/year in GSMNP (Rob Klein personal communication 2/24/2014). With current prescribed burns covering approximately 400 ha/year within the GSMNP, more fire use is needed (Rob Klein personal communication, 2/21/2014). Current management goals are to increase prescribed burning to 1200 to 2000 ha/year (Rob Klein personal communication, 2/21/2014). While the use of more fire is in line with current research and supported by studies like this one which indicate that both anthropogenic and lightning fires were important in maintaining the pre-suppression southern Appalachian landscape, burning only 1275 to 2075 ha/year does not seem sufficient to have the effects management desires.

6.7 Limitations

There are several limitations that should be addressed considering this research. Since random ignition locations were used, they are not consistent with the distribution of actual ignitions. From 1942 to 2008, there were 124 recorded lightning ignitions in GSMNP. Of those ignitions, 68% were located on ridges, 16% on upper slopes, 6% on lower slopes, and 10% on bottom lands. My random ignition locations were 27% on ridges, 35% on upper slopes, 20% on lower slopes, and 18% on bottom lands. My simulation ignitions represent a more even distribution of locations across the topographic regions, which do not appear to be consistent with actual ignition locations which favor ridges. Within my simulations upper slopes ignition locations resulted in almost double the mean fire spread than ridge, lower slope, or bottom land for Hx1 and Hx2 and one and a half times for Hx3, potentially causing an overprediction in overall fire spread (Table 25).

Table 25. Mean fire size (ha) per topographic region ignition location

	Ridge	Upper Slope	Lower Slope	Bottom Land
Hx1	34.15	67.63	33.33	29.07
Hx2	36.45	71.04	35.55	31.21
Hx3	499.83	746.53	471.30	418.81

The pre-suppression rate of lightning ignitions may have been more than the current rate if lightning was striking more flammable fuels. Thus using the current rate may underestimate the contribution of lightning ignitions in comparison to anthropogenic ignitions.

Fuel configuration could have affected the mean fire size. Multiple spatial configurations of the simulations performed on the pre-suppression landscape might have added robustness to my results. However, the random configuration of the fuels should not affect the magnitude of the results because the large number of simulations on a large study area burned many different fuel model configurations on the landscape.

My results do not appear to be affected considerably by topographic region. This was surprising since more xeric areas tend to be more flammable. The lightning fire cycle increased in length for all three landscape scenarios based on topographic wetness from ridge (driest) to upper slopes, lower slope, then bottom land (wettest). However, the difference did not seem of a magnitude that would indicate that lightning ignited fires were having different effects based on topographic region on the landscape. If this is not a realistic result, it could be due to random ignition locations or to FARSITE not being sensitive enough to the complex topography of the southern Appalachians.

6.8 Future research

Previous fire regime models incorporate mortality and regeneration of vegetation change after individual fires (Li et al. 1999; Bean and Sanderson 2008). Future research including mortality and regeneration on a pre-suppression landscape would help researchers understand more about how fire sizes are maintained. Future research investigating whether and the magnitude that compositional change would have affected fire size and fire size distribution is warranted. The Hx3 fires would leave patches of burned areas where highly flammable vegetation would establish. These patches could either act to spread throughout the entire patch from one or few ignitions (Frost 1998) or as a fire break if the ignition occurred soon after the initial fire (Cui and Perera 2008). Thus, since the simulated pre-suppression landscape had random distribution of highly flammable grass/shrub understories that carried fire at the 10m cell level, it is possible that patches that more closely resembled the burned-over areas left by fire could have affected the fire size.

Performing similar studies on different areas of the southern Appalachians could indicate the feasibility of my results, especially if conducted on areas where lightning currently has a greater effect on the landscape, such as Shenandoah National Park (Lafon and Grissino-Mayer 2007; Flatley et al. 2011). In addition, further research investigating ignition location and topographic region on fire size is warranted to either confirm or expound on my findings.

7. CONCLUSION

Previous hypotheses and research have indicated that fires were larger and that both lightning and anthropogenic ignitions were important shapers of the pre-suppression landscape. By using fire modeling, I was able to quantify potential mean fire size, fire cycle, fire size distribution, ignition density, and ignition source on the pre-suppression landscape. While further modeling studies are warranted, my results indicate that fire sizes on the pre-suppression landscape were up to an order of magnitude larger than fire sizes on the current landscape and that the pre-suppression landscape could have sustained many larger fires than are seen on the current landscape. My results also indicate that Native Americans and European settlers could have been burning up to 3500 ha/year in addition to the approximately 250 ha/year burned by lightning ignited fires. This demonstrates that lightning was active on the landscape. However, without anthropogenic ignitions, lightning would be unable to maintain the pre-suppression vegetation conditions indicated by historic accounts.

My research validates new methods that can be used in the southern Appalachians to investigate fire regime characteristics that are difficult to ascertain otherwise. My study shows that FARSITE is an appropriate tool for exploring historic fire regimes in the southern Appalachians. In addition, my research contributes to the larger body of work on the role of fire in the southern Appalachians historically. This research has important implications for both the fire history and management of GSMNP. Understanding the mean fire size, fire cycle, fire size distribution, ignition density, and ignition source that existed on the pre-suppression landscape will help researchers and managers understand the ecological processes behind the maintenance of the pre-suppression landscape, informing our understanding of the many effects of fire suppression and informing management decisions as they seek to restore fire-associated species and landscapes.

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