Patterns in Lightning-caused Fires at Great Smoky Mountains National Park

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ABSTRACT

Fires that burn unimpeded behave differently than suppressed or prescribed (management-ignited) fires. Studying this fire behavior increases our understanding of historic fire regimes. Wildland fire use policy allows for managing lightning-caused fires for resource benefit without suppressing them provided specific pre-defined conditions are met. Great Smoky Mountains National Park has managed ten fires under this policy from 1998 to 2006. Data from these fires and data from park fire reports for suppressed lightning-caused fires since 1940 were examined to illustrate patterns for non-anthropogenic fires. Lightning-caused fires occurred most frequently during the growing season and many persisted through numerous precipitation events. Unsuppressed fires had long durations (up to 38 days) and exhibited a wider range of fire behavior than found by previous studies for lightning-caused fires in the region. These unsuppressed fires exhibited the largest perimeter growth in periodic bursts of higher-intensity behavior; yet smoldered and crept through the majority of the active burning window. The total area burned by the ten fires managed under the wildland fire use policy from 1998 to 2006 (787 ha) has surpassed the aggregate within-park acreage of 122 suppressed lightning-caused fires over the previous 56 years (523 ha).

Keywords: fire, fire duration, fire regimes, fire suppression, Great Smoky Mountains National Park, lightning, southern Appalachians, wildland fire use

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INTRODUCTION

The identification of lightning as an important ignition source gained acceptance slowly over the last century in the United States. For instance, the idea was not widely accepted for forests in the Rocky Mountain West until the 1920s and underestimated for grasslands through the mid-1980s (Komarek 1968, Baker 2002). Eastern deciduous forests in general and the southern Appalachians in particular have not escaped this evolution of understanding. Great Smoky Mountains National Park (GSMNP) studies in the

1980s classified all burned areas, regardless of ignition source, as non-"virgin" forests; implicitly denying the role of fire as a regular forest process in park ecosystems (Pyle 1985, 1986). The 1902 U.S. Forest Service report on the southern Appalachians acknowledges only anthropogenic sources of fire with no mention of lightning-caused ignitions (Roosevelt 1902). In a 1942 letter to the Chief of Forestry for the National Park Service, the first GSMNP Superintendent, J. R. Eakin, wrote, "I am learning new things about fire here. Until a few years ago I thought lightning would not start fires" (Eakin 1942). Baker (2002) attributes the change in perception to several factors, particularly the growth of forest management practices, proliferation of trained observers, and systematic data collection.

Although it is now commonly understood that lightning causes fires in eastern deciduous systems (Komarek 1966, Barden and Woods 1973, Ruffner and Abrams 1998, Petersen and Drewa 2006), there is very little published information regarding lightning-caused fires, their behavior, and their effects in these forests. Furthermore, there have been few opportunities in these forests to observe lightning-caused fires from ignition through natural extinction. The full implementation of wildland fire use (WFU) policy at GSMNP—whereby lightning-caused fires are managed for their ecological benefits instead of being suppressed—has provided an opportunity to document characteristics of lightning-caused fires in this region and define patterns key to understanding the ecological role of non-anthropogenic fires, both historically and for the future (Arno and Fiedler 2005).

Fire's natural role as an important ecological process in the southern Appalachians is perhaps best illustrated by the decline of numerous species since the advent of fire suppression (Van Lear and Waldrop 1989, Abrams 1992, Lorimer 1993, Frost 2000). Regionally dominant oaks (*Quercus* spp.), hickories (*Carya* spp.), and pines (*Pinus* spp.) have experienced a substantial drop in recruitment since the mid-1900s. The decline of fire-dependent Table Mountain pine (*Pinus pungens*) has been well documented (Zobel 1969, Van Lear and Waldrop 1989, Williams 1998, Barden 2000, Welch and Waldrop 2001). Conversely, fire-sensitive, shade-tolerant species such as red maple (*Acer rubrum*), eastern hemlock (*Tsuga canadensis*), and black gum (*Nyssa sylvatica*) have increased across the landscape (Abrams *et al.* 1995, Russell 1997, Brose and Van Lear 1999, Harrod and White 1999, Abrams 2006). National Park Service monitoring data from plots in GSMNP support these trends (NPS 2001) (Figure 1). Fire regime changes are also corroborated by the former presence of red-cockaded woodpecker (*Picoides borealis*), in GSMNP until the early 1980s when decades of fire suppression led to the collapse of open pine habitat and woodpecker populations (Dimmick *et al.* 1980).

The purpose of this study was to augment the current knowledge base for lightning-caused fires in the southern Appalachian region with recent experience from GSMNP. The park's WFU program has provided a valuable and unparalleled opportunity to observe fires persisting without traditional suppression actions and to document their characteristics

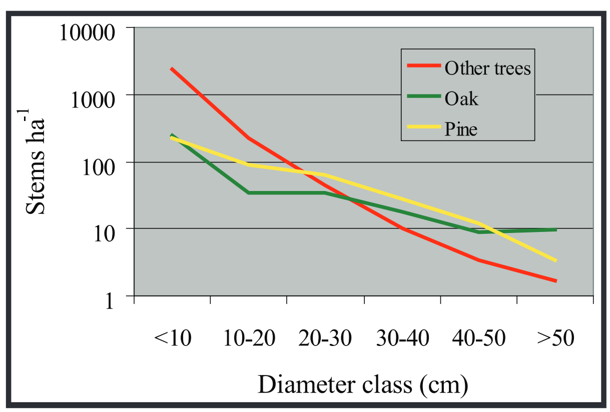

Figure 1. Frequency distribution by size class of oak, pine and other trees (e.g., red maple, black gum). Data compiled from GSMNP fire effects monitoring 0.1 ha plots, n = 57.

in a modern landscape. The park currently has the largest dataset for unsuppressed fires in the region, as the U.S. Forest Service implemented WFU fires in eastern National Forest System lands for the first time in 2006. Because the dataset from the ten fires managed thus far is too small for meaningful statistical analysis, this paper focuses on the qualitative information collected from case studies that demonstrate patterns in lightning-caused fires in the southern Appalachians. Fire monitoring and report data were analyzed to identify patterns that enhance our understanding of fire regimes in these forests.

STUDY AREA

Great Smoky Mountains National Park encompasses over 200,000 ha (519,000 ac) of forested lands in the southern Appalachians along the border of North Carolina and Tennessee. Though the park was officially established in 1934, it was first administered by the federal government in 1931 (Frome 1994). This administration included organized law enforcement, development for tourism, natural history interpretation, and suppression of all fires.

The Great Smoky Mountains are part of the Unaka range, a western extension of the Blue Ridge Province (Fenneman 1938). The park ranges in elevation from 270 m (888 ft) to 2,025 m (6,643 ft). Annual precipitation averages 147 cm (58 in) at lower elevations and 231 cm (91 in) at the highest elevations, with monthly precipitation peaking in January and August. Mean minimum temperatures reach from -5 °C to 0 °C (23 °F to 32 °F) from November through March. Mean temperatures peak in July and range from 20 °C to 30 °C (68 °F to 86 °F). Temperatures decrease with elevation, yet the lapse rate diminishes in winter months and at higher elevations (Shanks 1954). These factors combine to provide a backdrop for one of the most productive and naturally diverse parks in the country. Vegetation ranges from xeric, Table Mountain pine (*Pinus pungens*) ridgetops through oak- (*Quercus*) dominated side slopes, to biologically rich, mixed mesophytic toe slopes and coves (Whittaker 1956). The park is designated as part of an International Biosphere Reserve and a World Heritage site because it serves as an outstanding example of the eastern deciduous biome.

A wide variety of natural process (blow downs, ice storms, fire, insects, and disease) and human activities (agriculture, logging, and development) have marked the GSMNP landscape over time. The area has been long inhabited by humans, first Native Americans and later European immigrants. It remained virtually untouched by lumber interests until 1880, with full-scale logging operations beginning in the early 1900s. Over 3.54 million m^3 (1.5 billion board feet) of lumber were removed from the area that became Great Smoky Mountains National Park (Lambert 1961). However, the rugged topography made much of the park inaccessible to loggers and up to 40 % of the lands within the park boundaries are considered virgin (Stupka 1960, Pyle 1985). A strong relationship has existed between humans and fire (Pyne 1982) and fire ignitions within the park were elevated through human activities (Van Lear and Waldrop 1989, Hays 1993, Delcourt and Delcourt 1997).

The WFU policy for GSMNP has developed over several decades. The national push to return natural processes, particularly fire, throughout the National Park Service was difficult and required public education, Congressional persuasion, and managerial acceptance (Hendrickson 1973). The effort began in earnest in the early 1960s with the Leopold Report (Leopold *et al.* 1963, Sellars 1997) and is reflected in the GSMNP 1969 Resources Management Plan. In this plan, the park addressed "over protection of [the] ecosystem from natural fires" as a problem and recommended that lightning-ignited fires "run their natural course" when they posed no threat to lives or property (NPS 1969). This aspect of the 1969 plan was never implemented officially. The experimental 1976 Polecat Ridge fire, which was monitored until naturally extinguished, was described as an "unofficial switch from a strict suppression policy" (Harmon 1981). In 1979, a detailed report from Resource Management Specialist Stuart Coleman to the Park Superintendent again advocated for managing lightning fires within pre-defined boundaries to restore natural processes (Coleman 1979). However, despite these management discussions and the clearly identified need, the policy of managing lightning-caused fires for resource benefit was not formally realized until after the adoption of the park's first fire management plan in 1996.

METHODS

Fire History Data

Data for lightning-ignited fires from 1940 to 2006 were used to examine trends in area burned in GSMNP. These data were compiled from the Shared Application Computer System (SACS) database of the Department of the Interior, now the Wildland Fire Management Information (WFMI) database, which is the official fire-reporting system for the National Park Service. This database contains basic fire information including name, start date, date declared out, cause, and size. Latitude and longitude are included for records dating from 1974 to the present. These data were error-checked using published literature (Harmon 1981), original fire reports, park fire atlases, and other internal administrative documents. Any corrections made to the original dataset were confirmed with a minimum of two sources. Original fire reports were available for most of the study period and were the preferred tool for verification. Not enough information was available to verify the extant data for 1931 to 1939, therefore those years were not included in this analysis. Specific reports were missing for 1940, 1941, and 1955 to 1959. The park fire atlas, detailed tabular summary reports, annual forestry reports to the regional office, and Harmon's (1981) study for these years were used to complete and verify the final dataset. Reported area burned in this study was limited to lands inside the park's boundary. Fires that burned wholly outside the park were excluded from the analysis.

Although the first WFU fire didn't officially occur until 1998, two lightning-ignited fires in the 1970s were not suppressed in an early attempt to change park fire management policy to what is now WFU. The 1976 Polecat Ridge Fire was one of these fires (Harmon 1981). The other fire was not explicitly identified in reports but notes included in the fire report suggest it was the 1977 Polecat Ridge Fire. These two fires were not included in the suppression-era lightning fire statistics for total number of suppressed fires, size, or duration. When the area of the 1976 Polecat Ridge Fire is included in unsuppressed-lightning fire data, it is noted. The 1977 Polecat Ridge Fire was not included in the unsuppressed fire discussions due to incomplete data.

Reporting of fire size has varied during the period of this study. In the early days of park management, fire size was reported to the hundredth of an acre and single-tree fires were reported as "Neg." or negligible. More recently, fires have been documented with 0.04 ha (0.1 ac) as a minimum reporting size. For this paper, early data have been modified to meet more recent standards, rounding from hundredths to tenths and using 0.04 ha (0.1 ac) as the minimum fire size.

WFU fire monitoring has included collection of fire behavior information, perimeter growth, and onsite weather data. Through 2006, the fires managed under the park's WFU policy have received no management action that might artificially distort fire growth or behavior.

There were no burn-out operations or control lines (Cohen and Dellinger 2006).

Fire Report Narratives

Hardcopy fire reports from 1942 to the present contain narratives recorded by firefighters or the local park ranger (often the same individual) at the time of the fire, or shortly thereafter. Many of these narratives are rich with information about fire behavior, local vegetation, and fuel conditions. They often contain detailed descriptions of weather conditions, fire progression, scouting reports, and management actions. All fire reports for lightning-caused fires were read and those with detailed narratives were identified. This subset was evaluated for use as case studies. To insure that the sample fires spanned the range of management policies, at least one fire per decade from the1940s to the1980s with a duration greater than 4.5 days was selected. Fire reporting and management changes (e.g., narratives with little or no description of the vegetation; indirect fire line construction) in the 1980s made it difficult to discern fire behavior characteristics useful for case studies from this decade.

RESULTS

Lightning-caused Fire Data

Though the fire management policy allowing WFU was adopted by GSMNP in 1996, the first WFU fire did not occur until 1998. From 1998 to 2006, 10 of 16 lightning-caused fires were managed as WFU fires. These 10 fires burned a total of 787 ha (1,946 ac), which is 264 ha (652 ac) more than the total within-park area burned for the 122 suppressed lightning fires over the previous 56 yr period (Table 1). Mean duration and area burned for unsuppressed lightning fires were greater than for suppressed lightning fires (Table 2). Of the suppressed lightning fires, only the 1988 Redman Fire grew to over 40.5 ha (100 ac), however, according to the fire report, an unknown portion of the total area burned on this fire was due to fire-containment operations in conjunction with indirect line construction. The majority of suppressed lightning fires averaged between 0.1 ha (0.25 ac) and 40.5 ha (100 ac), with a median value of 2 ha (5 ac) and a mean of 5.7 ha (14.2 ac). The 10 recent unsuppressed fires are currently evenly distributed in terms of size, with four fires <0.1 ha (0.25 ac), and four at >40.5 ha (100 ac) (Table 3).

Since 1940, there were 18 years with no lightning-caused fires and nine years with five or more that burned inside the park (Figure 2) (Barden and Woods 1973, Coleman 1979, Harmon 1981). The highest number of lightning-caused fires (11) occurred in 1988. Lightning-caused fires have occurred in each month of the year except February and October (Figure 3). Ninety percent of all lightning-caused fires at GSMNP occurred during the growing season from April through August, consistent with storm-event frequency within the region (cf. Peterson and Drewa 2006). The distribution for timing of lightning-caused fire starts has shifted slightly toward spring in recent years. Of 16 total starts since 1998, April had the highest total with six recorded. Four of the 10 unsuppressed fires occurred in April (Table 3). The large unsuppressed 1976 Polecat Ridge Fire, not included in the above count, occurred in July.

Fire Behavior—Case Studies

Distinct patterns in fire behavior were apparent between suppressed and unsuppressed lightning-caused fires. Fire report narratives provided examples of fires persisting through precipitation events and becoming active after periods of dormancy. The following excerpts and synopses were selected from GSMNP fire

Table 1. Suppressed lightning fires, Great Smoky Mountains National Park, 1940-1997 The 1976 and 1977 Polecat Ridge Fires have been excluded.

Year	Number of fires	Total area burned	Mean size	Mean duration
		ha	ha	days
1940-49	27	25.4	0.9	3.1
1950-59	34	98.9	2.9	2.3
1960-69	16	56.0	3.5	4.9
1970-79	3	33.2	11.1	6.0
1980-89	27	220.1	8.2	10.0
1990-97	15	58.2	3.9	10.1
Total	122	523.4	4.3	6.6

Table 2. Lightning-caused suppressed and wildland fire use fires, Great Smoky Mountains National Park, 1998-2006. Duration for suppressed lightning-caused fires from 1998-2006 is not included because the last date of fire activity (smoke or heat) is not well documented in reports for these fires.

	Number of fires	Total area burned	Mean size	Mean duration
		ha	ha	days
Suppressed	6	15.1	2.5	*
Fire use	10	787.4	1.8	17.4

Table 3. Wildland Fire Use fires, GSMNP 1998-2006.

Fire	Start date	Duration	Size
		days	ha
Forney Creek	4/6/1998	22	149.7
Enloe Ridge	9/8/1998	3	0.0
Collins 2	4/20/1999	9	52.6
Blacksmith	8/19/1999	35	211.7
Fort Harry	3/10/2000	8	0.1
Cave Ridge	11/8/2000	6	0.0
Ekaneetlee	4/27/2001	13	2.4
Wolfpen	11/11/2001	5	1.2
Shot Beech	6/13/2004	35	0.0
Chilly Spring	4/3/2006	38	369.5

report narratives to describe the fire behavior for lightning-caused fires in the park (NPS 1940-2006). They have been organized into three groups: persistence through precipitation events, emergence from dormancy, and large unsuppressed fires.

Persistence through Precipitation Events

Three fires were selected to illustrate the persistence of fires through periods of substantial precipitation. One of these fires was a recent WFU event.

Devil's Courthouse Ridge Fire —December 1942, 0.04 ha (0.1 ac). "A large Hemlock snag was struck by lightning and was set on fire during a storm of December 1. A heavy snow storm occurred on December 3 which prevented the fire from spreading away from the snag. On December 9, Assistant Park Warden Lollis discovered the burning snag on a patrol of his district…"

Turkeypen Ridge Fire—April 1971, 32.4 ha (80 ac). "During the night of April 19th, a violent thunderstorm passed over Cades Cove. On Turkeypen Ridge, a bolt of lightning struck a large hickory tree and set it to smoldering. April 27th, in the afternoon, the top of the hickory fell, scattering fire into the dry leaves around it."

Shot Beech Fire—June 13-July 17, 2004; 0.04 ha (0.1 ac). Managed as a WFU event, this fire persisted in a single standing dead hemlock for 35 days and was not extinguished until receiving a total of approximately 16 cm (6.5 in) of rain.

Emergence from Dormancy

Three fires were chosen to illustrate how fires can become active even after they are

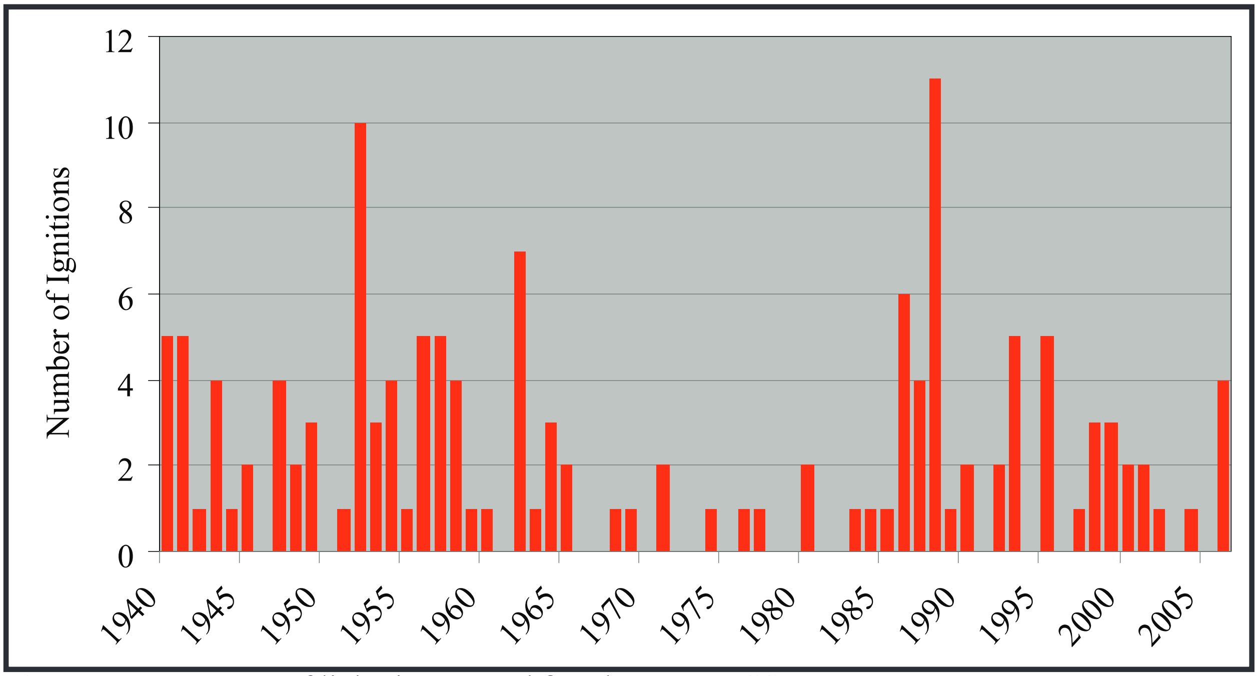

Figure 2. Frequency of lightning-caused fires by year at GSMNP, 1940-2006.

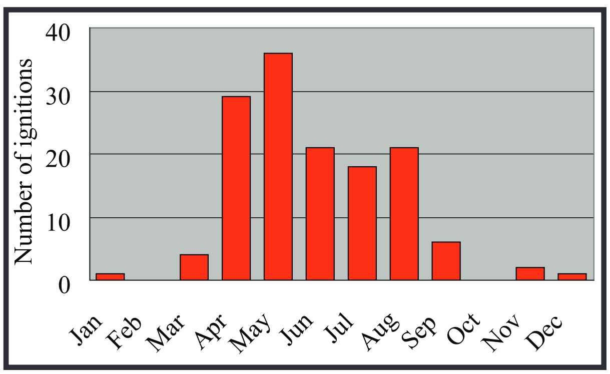

Figure 3. Frequency of lightning-caused fires by month at GSMNP, 1940-2006.

thought to be extinguished. These fires were thought to be out or were or misreported after the initial smoke report, yet re-appeared once weather, fuels, and topography aligned to permit more obvious combustion.

Tunis Ridge Fire—June 1943, 1.6 ha (4 ac). The fire began on June 8, was first reported on June 9, and, "Warden Ogle hunted for it on that day and again on June 10th; but light rains had damped it down and as no smoke was visible he did not find the fire…. Fire was corralled at 2:00 am on June 12, but kept breaking over [escaping control line] on mop up crew on that day."

Proctor Ridge Fire—May 1951, 32.8 ha (81 ac). Smoke was first reported by a lookout tower on May 18, about 3 hours after witnessing a lightning strike in the area. Firefighters searched for the fire for several hours and were unable to find anything. Other lookouts in the area were unable to observe the smoke, and it was thought that due to an afternoon rain shower, perhaps it had been a column of fog instead of smoke. At approximately 1 PM on the following afternoon, another lookout saw a column of smoke in the same general area, and with this new sighting, fire crews were able to find the fire and begin suppression actions. By the time they arrived on scene, the fire was approximately 26 ha (65 ac) and was contained later that evening. As fire crews were returning to mop-up the fire on the morning of the 20th, "a snag fell and slid down the mountainside beyond the control line" igniting a dense laurel thicket. It was several more hours before the fire was finally controlled.

Ellis Butt Fire—July 1968, 2 ha (5 ac). The fire started in a lightning-struck pine. When crews arrived it was burning in deep duff (5 cm to 10 cm). The fire was originally called controlled at 7:30 PM on July 17 at 0.6 ha (1.5 ac), but at 10:00 AM on July 18, the fire "had broken out along the line at all points except the top." Heavy rain early on July 19 helped firefighters secure the perimeter, though there were still tree stumps and standing dead trees burning in the interior of the fire.

Unsuppressed Lightning Fires >40.5 ha (100 ac)

Five of the reports for unsuppressed fires were selected for their insights about fire behavior. All of these burned for longer than a week and grew to at least 40.5 ha.

Polecat Ridge Fire—July 27 to August 18, 1976, 44.5 ha (110 ac). The 1976 Polecat Ridge fire ignited on July 27, and was reported and located on July 28. This fire was the first experimental attempt by GSMNP to implement what is now known as WFU. On discovery, the fire was approximately 1.2 ha (3 ac) on the top of the ridge in a stand dominated by pines (*Pinus pungens, P. rigida*, *P. virginiana*, and *P. echinata*). The fire smoldered and crept downslope into a pine-hardwood mix and by July 31 appeared to have been extinguished by rain. No smoke was visible on August 1. On August 2, the fire began a run that lasted through August 5, growing to its maximum size of 44.5 ha (110 ac) and stopping at a trail on the south side. The fire persisted in the interior, continuing to smolder in downed logs and standing dead trees. The fire received 1.3 cm (0.5 in) of rain from August 6 to 7 and 1.8 cm (0.7 in) of rain on August 16, and was declared out on August 18.

Forney Ridge Fire—April 6 to 27, 1998, 149.7 ha (370 ac). The first official WFU fire in the park burned in mesic, old-growth, oak-dominated communities and generally stopped upon reaching tulip poplar (*Liriodendron tulipifera)* and red maple (*Acer rubrum)* dominated communities. Fire burned predominantly through the litter layer and persisted through downed logs and stump holes. Along the west flank of the fire there were short up-slope head fires in shrub-dominated communities, with scorch heights of up to 2 m (6.6 ft) on the mountain laurel (*Kalmia latifolia*). The fire area received light rain on April 9, 1.3 cm (0.5 in) of snow on April 10, and several centimeters of rain from April 18 to 20. The majority of fire growth occurred in the first three days of the fire. By April 13, there was no growth in fire size although smoldering continued within the burn.

Collins II Fire—April 20 to 28, 1999, 52.6 ha (130 ac). The fire was discovered on April 21 and by evening had grown to approximately 12 ha (30 ac). It burned from oak-dominated ridgetop communities downslope into mesic coves, carrying through leaf litter and persisting in downed logs. It burned across moist drainages. This was largely a backing fire with little duff consumed, though higher intensities and severities were observed along ridgetops. The majority of fire growth took place from April 21 to 22, when the daily minimum relative humidity dropped to nearly 30 percent. The fire received little direct sunlight on April 23, minimum relative humidity between 40 percent and 50 percent, and light rain (reported as one millimeter at the nearest weather station) that evening. Drainages coincided with the majority of the fire perimeter. A wild boar (*Sus scrofa)* rooting site stopped fire growth along a portion of the northern fire perimeter. The fire was notable for top-killing rhododendron (*Rhododendron maximum*) and mountain laurel during the major period of fire growth. This fire took place during the height of spring wildflower season. Park fire and natural resource specialists were surprised that the fire behavior and effects were as severe as they were in light of the seasonally moist live fuels.

Blacksmith Fire—August 19 to September 22, 1999; 211.7 ha (523 ac). Part of the area of the Blacksmith fire had burned previously in 1988. Most of the Blacksmith Fire burned with a low intensity, backing fire. Small, sporadic headfire runs occurred in small patches, mostly in pine regeneration areas that resulted from the 1988 fire. Eighty-two percent of the fire growth occurred between August 29 and September 6. A series of dry cold fronts came through the unit from August 24 to 27. The relative humidity was variable throughout the duration of the fire. There were sporadic drops of relative humidity below 20 percent, but during the majority of the fire growth the relative humidity remained between 40 percent and 50 percent. Fuels were atypically dry; consumption was noted in litter, duff, and root systems.

Chilly Springs Knob Fire—April 3 to July 4, 2006; 369.5 ha (913 ac). The fire was ignited by lightning on April 3 in an oak-pine (*Quercus-Pinus*) community in the western portion of the park. The fire did not produce much smoke or exhibit noticeable growth until April 5 when fire size was estimated at about 16 ha (40 ac) by midday. By April 6, it had grown to approximately 121 ha (300 ac). The fire received 2.5 cm (1 in) of rain early in the morning of April 8. On April 10, the fire perimeter had grown to 230 ha (569 ac). There were two more major periods of fire growth and by April 18 the fire had reached its final size of 370 ha (913 ac). Fire spread to the west was impeded by roads and creeks along the southern and southeastern edges. Along the northern perimeter, the fire stopped at unreceptive fuels and a small portion was stopped where fuel continuity was disrupted by European wild boar rooting. The fire continued to smolder and creep in its interior for several weeks. The last smoke was observed on May 18 and the fire was officially declared out on July 4.

DISCUSSION

The case studies illustrate how fire behavior varies according to seasonal and weather conditions and give a broader context for interpreting the past decade of wildland fire use. While lightning-caused fires often begin during a rain event, they may persist in a live or dead tree for enough time to allow surrounding fuels to dry sufficiently for eventual fire spread. Fire may reach surface fuels in a variety of ways: through portions of the burning trunk falling to the ground, a wind that scatters embers into available fuels, or a tree that burns entirely to the ground.

Large fire growth is sporadic, occurring when forest fuel conditions align with topographic and weather conditions conducive to fire spread. For example, the major growth for the 1999 Blacksmith Fire occurred while the relative humidity remained in the 40s and included perimeter expansion spanning both day and night. Fuels had been drying for several days prior to this growth period as a cold front passed over the area. As the relative humidity rose, the fire smoldered and crept until it reached a more receptive fuel bed in terms of composition (pine needles, oak leaves, pine seedlings, and saplings) and condition (dry and combustible). This growth pattern is typical of prolonged unsuppressed fire events observed in this park and in other areas of the U.S. (Despain 1983). The majority of the fire growth occurs within a fraction of the overall fire duration. Of the five unsuppressed fire events that grew to over 40.5 ha (100 ac), the majority of fire growth occurred in just under 20 % of the total burning days. The actual start of the major growth period was highly variable, beginning on the first or second day after the lightning strike on three fires, seven days after ignition on the Polecat Ridge Fire, and 11 days after ignition on the Blacksmith Fire.

Extinguishment of unsuppressed fires occurs as a result of the sensitive relationship among fire behavior, weather, topographic features, and fuel availability. Extinguishment may also result from a variety of ecological factors, such as changes in vegetation (fuel types), weather (a rain event), or the physical environment (e.g., moist sites unfavorable to fire spread). Wet to moist coves, stream beds, drainages, and depressions formed the most common boundaries for the observed fires that were allowed to progress until "natural" extinction. Anthropogenic disruptions of fuel continuity, such as trails, roads, or historic land-use patterns, can also impede fire growth. The characteristics of these boundaries (e.g., width, fuel type, topography), again combined with weather and fuel conditions, dictate their effectiveness. For instance, a trail was effective in stopping the 1976 Polecat Ridge Fire. In contrast, an unimproved and unmaintained road did not stop the Forney Ridge Fire. Vegetation-based controls on fuel continuity and availability have also limited fire spread. Studies have suggested that leaf litter of pyrogenic species (e.g., oak) are more conducive to fire spread than the leaf litter of fire-sensitive, shade-intolerant species such as red maple (Abrams 2006). This phenomenon has been observed in the park, especially on the Forney Creek and Chilly Springs Fires.

Another interesting phenomenon has been the influence of non-native species on fire behavior, in particular the European wild boar. Boars were introduced into a North Carolina preserve near the western edge of the park as a game species in the early 1900s. They escaped their preserve and first entered the Great Smoky Mountains in the 1940s. Through their rooting for underground plant parts and buried acorns and nuts, boar extensively disturb forest floors, exposing soil that precludes fire spread. Disturbed sites have been recorded at all elevation ranges and most vegetation types (Bratton *et al.* 1982). Disturbed forest-floor patches in excess of 500 m^2 (1,235 ft^2) have been recorded (Howe and Bratton 1976). These disturbances stopped fire growth on portions of both the Collins II and Chilly Springs fires.

The effects of rooting practices of the introduced European wild boar are a unique twist on fire-floral-faunal relationships and would make a useful addition to extant studies on boar in the park (Howe and Bratton 1976, Bratton *et al.* 1982). The relationship between fire effects and boar disturbance, correlating likely rooting sites with potential fire spread, and the effects of boar on post-fire forest regeneration are some areas of potential interest. Future research in this area would be useful in planning efforts, both in terms of fire planning and prioritizing focus areas for the park's boar management program. In terms of fire regimes and fire behavior, the specific effects of rooting may not be as important as the sensitive relationship between fire spread and ambient conditions. As the case studies show, even small breaks in fuel continuity can alter fire behavior and retard fire growth.

With a larger dataset from unsuppressed lightning-caused fires, a study examining the attributes of fire barriers (e.g., aspect, slope, topography, changes in vegetation type) would be useful in identifying future prescribed burn boundaries and defining trigger points on WFU fires and wildfires. A comparison of the effectiveness of these barriers under different fuel, weather, and seasonal conditions to highlight likeliness for fire growth would also be useful in a variety of fire planning efforts. Further, understanding the effects of changing ecosystems (e.g., change to shade-tolerant species or prevalence of European wild boar) relative to fire behavior and growth would be helpful in prioritizing management efforts and defining target conditions.

A combination of weather factors, including relative humidity, wind, precipitation, and cloud cover, has been the most commonly observed determinant of fire growth or extinguishment for unsuppressed lightning-caused fires greater than 25 ha (100 ac). Three of the five large unsuppressed fires (Polecat Ridge, Forney Creek, and Collins II) had two or more precipitation events that contributed to ending the fires. In all five fires, the major periods of growth coincided with days of little to no cloud cover, which probably contributed to increased insolation, daytime heating, and drying. These growth periods also corresponded with relative humidities below 50 %, although more research is needed to discern the absolute cause-effect relationship between fire spread and relative humidity.

Instances where lightning-caused fire has crowned or spotted have not been reported previously in the region (Barden and Woods 1973, Harrod and White 1999). These GSMNP case studies provide two clear examples of high-intensity fire behavior. In portions of the Forney Ridge Fire (<20 % of the total burned area), short yet intense up-slope headfire runs occurred through patches of mountain laurel. During the main period of growth on the Blacksmith fire, an intensive uphill run consumed a stand of pine saplings that recruited from a prior fire (1988 Shop Creek).

There are wide ranges of variables that contribute to fire growth, behavior, and effects. In addition to some of the factors discussed above, there are many that may never be viably assessed. Landscape fragmentation at a large scale is one example. Regional fire history studies reflect a higher yearly average number of lightning-caused fires on the Cherokee National Forest, located at the park's southwestern boundary (Barden and Woods 1973, Cohen and Dellinger 2006). At one time, it may have been possible for fires to start in this area and progress into what is now GSMNP. Due to different management objectives and human-made barriers (e.g., Calderwood and Chilhowee Lakes), this is no longer likely to occur.

Frequency of lightning-caused fires has varied throughout the park's history (Figure 2). Changes in suppression tactics have affected fire size and duration for the period of this study. In 1962, air tankers were used in the park for the first time, enhancing wildland fire suppression efforts. In the Chestnut Ridge Fire report for that year, District Ranger Norman Roy noted, "It is estimated that [80.9 ha] 200 acres would have burned, instead of [28.9 ha] 71.52, if we had not had the aid of the air tanker." On the other hand, burnout operations—the process of securing fire perimeter by setting a back fire from a strategic location to consume available fuels—that could increase final total area burned, were not a regular part of suppression efforts up until the mid-1980s. The first mention of burnout operations on a suppressed lightning fire was in the fire report for the 1987 Slaty Fire, which covered 36.4 ha (90 ac). As noted in the results section, the only suppressed lightning fire that grew to over 40.5 ha (100 ac), the 1988 Redman Fire, had an unknown portion of the final perimeter result from burnout operations.

Discrepancies in fire reporting data contribute to uncertainty in the calculation of fire duration. The official start date is often when smoke was first reported rather than the day of lightning ignition. This could lead to an underestimation of fire duration throughout the suppression era. For this study, fire start dates taken from fire reports or summary tables were in most instances verified to reflect the date of the lightning strike using information reported by lookout tower operators. At times, especially from the mid 1980s on, it appears that fire declared-out dates were several days or weeks after fires last exhibited any activity (smoke or heat). Considering the history of fires emerging from apparent dormancy and exhibiting aggressive fire behavior several days after appearing (see case studies, above), this is a prudent policy. However, it is likely that the mean fire duration date for suppressed fires would be reduced if the correct date of the last observed smoke was consistently available. Correct ending dates would reduce the mean fire duration for the 1980s and 1990s (Table 1).

This study focused on fires originating within the park boundary and area burned within the park. When verifying extant report data against the published fire history for the park (Harmon 1981), it became evident that because of missing fire reports, it is not possible to assert that all fires used in this study started inside the park or that the area burned was wholly within it. Discrepancies between the fire history study and extant data apply to an undetermined four of 80 suppressed fires from 1940 to 1979 used in this study (Harmon 1981).

Continued study on the distribution and spread of fires in terms of weather, vegetation, the physical environment, previous natural events, and human-caused disturbances will further our knowledge of the role of fire in these forests. Specifically, research on the links between climate variables and fire growth would assist in management of lightning-caused fires and test the hypothesis that lightning-caused fires have increased in significance during periods of drought (Lafon *et al.* 2005, Peterson and Drewa 2006). Lightning-caused fires tend to occur in the growing season while prescribed fires are usually ignited in the dormant season. Data collected from the WFU program will enable the comparison of fire effects and seasonality using burn severity maps (Key and Benson 2005), GSMNP's long-term vegetative monitoring data, and data from the park's prescribed fire effects monitoring program. Fire behavior data from lightning-caused fires can be used to calibrate fire modeling software. Ultimately, any further exploration of this information would provide better understanding of historic fire regimes, fire-vegetation-site relations, and the different approaches available for comprehensive ecosystem management.

CONCLUSIONS

Though the unsuppressed-fire dataset is small, these case studies highlight several key points that begin to define the role of lightning-caused fire and fire regimes in the southern Appalachians. First, unsuppressed lightning-caused fires persist for longer periods of time and burn over larger portions of the landscape than suppressed lightning-caused fires. This is important for understanding the impacts of lightning-caused fires on eastern forests. Second, the potential for fire growth may not be directly related to weather and fuel conditions at the time of ignition. Lightning-caused fires can start during precipitation events and can persist through these wet periods, becoming active only at a later date when adjacent fuels have dried. Third, not all ignitions will result in large fires. To date, the size of unsuppressed lightning-caused fires has been evenly split between fires <0.1 ha (0.25 ac) and >40.5 ha (100 ac).

The GSMNP monitoring programs and careful collection and storage of fire data during the two fire management eras made this study possible. The park's ongoing research partnerships and long-term monitoring programs provide rich baseline ecosystem information and will enable a variety of in-depth studies in the future. The park's WFU program is unique in that all of the fires in this study had no suppression actions taken on the fire perimeter. This study not only emphasizes the benefits of such a program and data, but the importance of continuing to collect long-term, high quality fire behavior and associated data whenever possible.

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