THE CONTEMPORARY FIRE REGIME OF THE CENTRAL APPALACHIAN MOUNTAINS AND ITS RELATION TO CLIMATE

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Abstract: This paper uses records of wildland fire to investigate the contemporary fire regime on federal lands in the central Appalachian Mountains of Virginia and West Virginia. During the study period (1970–2003), 1557 anthropogenic fires and 344 natural fires occurred on these lands. Most were small, low-intensity burns. However, fires of moderate to high intensity also occurred, and because of their larger sizes they were responsible for most of the area burned. Fire size also differed between natural and anthropogenic fires (median size 1.2 ha vs. 0.4 ha). A few of the anthropogenic fires were quite large, however (up to 6484 ha), whereas the largest natural fire measured only 1188 ha. Anthropogenic fires burned more area than natural fires and consequently they had a shorter fire cycle (1196 years for anthropogenic fires, 6138 years for natural fires). These fire cycles appear to be much longer than in the past, prior to fire suppression. Nonetheless, despite suppression efforts, a substantial amount of fire activity occurred during the study period when conditions were sufficiently dry. The dry conditions of spring and fall were especially favorable for burning. Moreover, on an interannual level, drought had a strong influence on the amount of fire activity. [Key words: anthropogenic fire, fire cycle, forest disturbance, lightning, natural fire, Virginia, West Virginia, wildland fire.]

INTRODUCTION

Fire exerts a strong influence on vegetation composition, structure, and distribution at local to global scales (Pyne, 1982; Whelan, 1995; Bond and van Wilgen, 1996; Bond et al., 2005). In any landscape, the general patterns of fire periodicity, seasonality, intensity, and size that emerge over time comprise the fire regime for that environment and have important consequences for vegetation development. Understanding the fire regime of an area is the basis for fire management decisions and for research concerning the ecological role of fire (Whelan, 1995). The purpose of this study is to investigate the contemporary fire regime in the central Appalachian Mountains of Virginia and West Virginia.

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Much of the vegetation in the Appalachians appears to be fire dependent. In particular, the extensive forests dominated by oak (*Quercus* L.) and pine (*Pinus* L.) are thought to require periodic burning for their long-term maintenance (Abrams, 1992, 2003; Harrod et al., 1998, 2000; Williams, 1998). Decades of fire suppression have contributed to declines in these species and to increases in stand density and fuel loads (Abrams, 1992; Williams, 1998; Harrod et al., 1998, 2000; Welch et al. 2000; Lafon and Kutac, 2003).

Resource managers increasingly use prescribed burns to restore fire-dependent ecosystems and reduce fuel accumulations in Appalachian forests, especially on the extensive lands administered by federal agencies (SAMAB, 1996; Elliott et al., 1999; Waldrop and Brose, 1999; Welch et al., 2000; Hubbard et al., 2004). Currently all wildland fires (fires not ignited by managers) on federal lands in the region are suppressed, regardless of ignition source. However, recent policy changes permit federal agencies to develop fire-use plans allowing some wildland fires to burn, as long as the fires are ignited naturally and occur in predefined areas under specific weather conditions (Zimmerman and Bunnell, 1998). Natural fires that occur outside the areas designated for wildland fire use, or during dry or windy weather conditions, would be suppressed under this policy, as would all anthropogenic wildland fires. None of the federal land management agencies in the study area have adopted such a plan, but in the future they will implement wildland fire use in some areas (Steve Croy, Forest Ecologist, George Washington and Jefferson National Forests, pers. comm., August 11, 2004, January 28, 2005; Sue Imler, Fire Program Assistant, Shenandoah National Park, pers. comm., December 8, 2004; Peter Fisher, Fire Management Officer, Monongahela National Forest, pers. comm., February 17, 2005).

The emergence of a dual role for wildland fire (i.e., natural hazard or management tool) is accompanied by an increased need to understand the regime of anthropogenic and natural fire in managed ecosystems. However, little work has been published about the past fire regime under which the vegetation of the Appalachians developed, or the contemporary regime under which it now exists. A handful of dendroecological studies provides some insights into historical fire regimes of the central and southern Appalachian Mountains (Harmon, 1982; Sutherland et al., 1995; Shumway et al., 2001; Armbrister, 2002; Shuler and McClain, 2003), and currently we are conducting further dendroecological research about past fire regimes at several sites throughout the central Appalachians. This paper complements the fire-history research by focusing on the contemporary fire regime, which has been altered by fire prevention and suppression practices. We use a 34-year record of wildland fire occurrences on federal lands to investigate the fire regime and its relation to climate in the central Appalachians.

Climate affects many aspects of a fire regime through direct and indirect controls on fuel accumulation, fuel moisture, and lightning ignitions (Kitzberger et al., 1997). A growing interest in fire regimes and the factors controlling wildland fire has stimulated research on climate-fire relationships for a number of environments (i.e., Florida [Prestemon et al., 2002], Patagonia [Kitzberger et al., 1997], Spain [Vázquez and Moreno, 1993], and western North America [Johnson et al., 1990;

Johnson and Larsen, 1991; Swetnam, 1993; Knapp, 1995; Grissino-Mayer and Swetnam, 2000; Rollins et al., 2002; Grissino-Mayer et al., 2004]). These investigations demonstrate that climate strongly influences patterns of burning, even in fire regimes dominated by anthropogenic ignitions or altered by fire suppression. Dry periods are important at the seasonal level (occurrence of fire during a dry season), the interannual level (highest fire activity during drought years), and longer periods (episodes of widespread burning during dry decades or centuries). In dry climates, fire activity often is highest when drought years follow unusually wet years, which promote the accumulation of fine fuels (Knapp, 1995; Kitzberger et al., 1997; Grissino-Mayer et al., 2004). In more humid climates, however, heavy and continuous fuel loads are present every year, and drought during the year of fire alone appears to be the climatic factor of greatest significance (Kitzberger et al., 1997). Little has been published about climate-fire relationships in the Appalachians, but given the humid environment, we do not anticipate that wet conditions are a prerequisite for high fire activity during subsequent drought.

Our paper addresses seven specific questions about the fire regime of the central Appalachians. Prescribed fires are not considered here because they are understood and controlled by resource managers. The first three questions concern attributes of the fires themselves (their intensity and size). The fourth and fifth questions address the incidence of fire on the landscape, particularly the occurrence of anthropogenic versus natural ignitions. The last two questions regard temporal patterns in the occurrence of fire. The specific questions are:

(1) What is the characteristic fire-intensity level (as indicated by recorded flame length), and what is the range of fire intensities that occur in the central Appalachians?

(2) Does fire size (areal extent) increase with increasing fire intensity?

(3) Does fire size differ between anthropogenic and natural ignitions?

(4) Which is more prevalent on the landscape—anthropogenic fire or natural fire—in terms of the annual number of fires and the area burned?

(5) What is the length of the fire cycle for anthropogenic and natural fires? The fire cycle is the time required to burn an area equivalent to the study area (Heinselman, 1973; Johnson et al., 1990).

(6) Do seasonal patterns exist in the occurrence of anthropogenic or natural fires, and, if so, does the seasonal pattern of natural fires correspond to the seasonal pattern of lightning discharges? The season of occurrence has important consequences for vegetation response, particularly plant mortality and recruitment (Whelan, 1995; Bond and van Wilgen, 1996; Dey, 2002).

(7) Are interannual variations in fire activity and fire intensity related to climatic cycles of wetness and drought?

BACKGROUND: FIRE IN THE APPALACHIANS

Fire appears to have been an important process on Appalachian landscapes for many centuries. Native Americans used fire to drive game, improve wildlife habitat, maintain open meadows, and clear underbrush, especially in proximity to their settlements (Pyne, 1982; Van Lear and Waldrop, 1989; Delcourt and Delcourt, 1997, 1998). Fires also spread into the surrounding mountains, where they promoted open forests of oak, chestnut (*Castanea dentata* [Marsh. Borkh.]), and pine. In more remote mountains, escaped campfires along travel routes likely provided an ignition source (Van Lear and Waldrop, 1989). European settlers also practiced widespread burning (Pyne, 1982). Ayres and Ashe (1905) surveyed forests of the southern Blue Ridge Mountains in 1900 and 1901 and reported that light surface fires were frequent over 80% of the region. Natural fires are thought to have been relatively unimportant in the past, and to remain unimportant today, because of the wet weather that usually accompanies lightning (Delcourt and Delcourt, 1997; Welch, 1999).

Dendroecological reconstructions of fire history suggest that over the last 150–400 years, surface fires burned at intervals of about 5–15 years, at least on dry sites, and that occasionally more intense stand-replacing fires occurred (Harmon, 1982; Sutherland et al., 1995; Shumway et al., 2001; Armbrister, 2002; Shuler and McClain, 2003). Fires appear to have been associated with drought. Sutherland et al. (1995) found that all major fires (those that scarred >50% of the trees) in two pine stands in western Virginia occurred during years with negative Palmer Drought Severity Index (PDSI), which indicates drought. Shuler and McClain (2003) obtained equivocal results for an oak stand in eastern West Virginia. They demonstrated that fall PDSI values were lower during fire years than nonfire years, but that spring PDSI values did not differ between fire years and nonfire years. (The actual season of fire was not known, because the extremely narrow rings prevented estimation of burn season from the position of the scar in the ring).

A more thorough analysis of the central Appalachian fire regime and its relation to climate is needed. Dendroecological studies provide considerable insight about historic fire regimes at a few sites in the Appalachians, but much additional, intensive sampling would be necessary to portray the historic pattern of burning at a regional scale. Determining such parameters as fire size, ignition source (lightning versus humans), or the distribution of fires by month would be difficult or impossible. The analyses we report in this paper are based on a more detailed, albeit shorter, record of fire that permits a region-level characterization of the contemporary fire regime. We use data from the National Interagency Fire Management Integrated Database (NIFMID; USDA Forest Service, 1998), which incorporates data from all the individual fire reports of federal agencies.

One study of particular relevance to our work is that by Barden and Woods (1974), who used fire records from federal lands in the southern Blue Ridge Mountains of North Carolina and Tennessee to quantify several aspects of the fire regime during the mid-20th century. Their work underscored the rarity of fire, relative to its historic frequency—only 0.3% of Great Smoky Mountains National Park burned during a 12-year period, and 2.3% of the Cherokee National Forest burned during a 10-year period. Human ignitions were responsible for most of the burning (85% of the fires in Great Smoky Mountains, 95% of the fires on the Cherokee National Forest). Anthropogenic and natural fires differed in seasonal distribution, with anthropogenic fires occurring mostly in spring and fall while natural fire activity peaked in late spring (May), prior to the summer (July–August) maximum in thunderstorm activity. Anthropogenic fires generally burned at higher intensities than

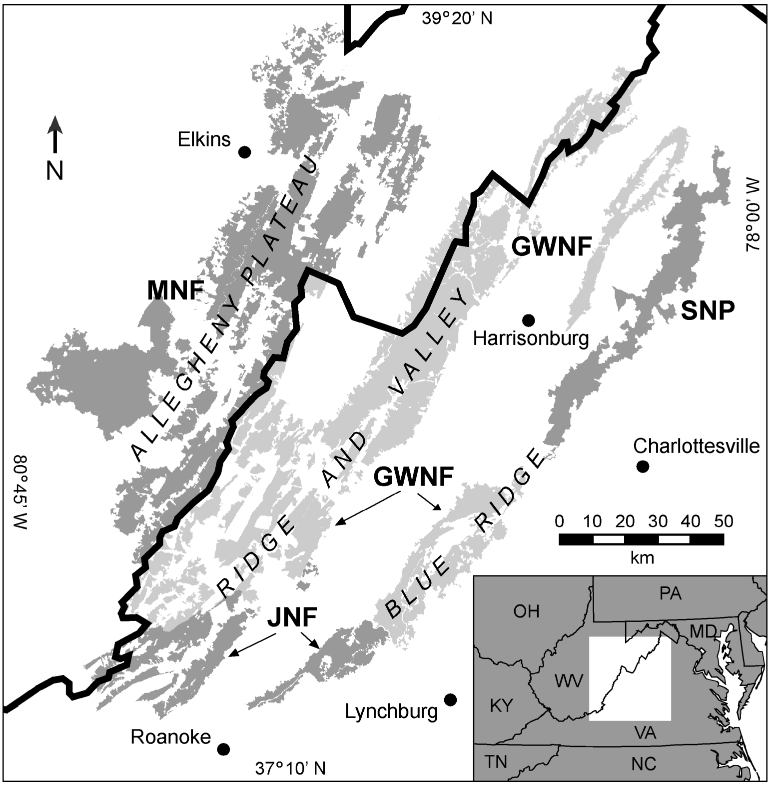

Fig. 1. Study area: federal lands in the central Appalachians. SNP = Shenandoah National Park, GWNF = George Washington National Forest, JNF = Jefferson National Forest (northern districts only), MNF = Monongahela National Forest.

natural fires, but both types of fire were similar in size. One reason for the lower intensity of natural fires is that they occurred during periods of higher rainfall and atmospheric humidity. Our study provides a similar but more detailed analysis using a longer record of fire occurrence for the drier central Appalachian region. Also, our work addresses additional questions about fire cycle, lightning activity, and climate-fire relationships.

STUDY AREA

The study area is located at approximately 37–39°N, and 78–81°W (Fig. 1). The central Appalachians comprise three physiographic provinces—the Blue Ridge along the east, the Ridge and Valley in the center, and the Allegheny Plateau along the west. Topographic relief generally is between 300 and 1000 m. Our study is concerned with fires that occurred inside the boundaries of the George Washington, Jefferson, and Monongahela National Forests, as well as Shenandoah National Park (Fig. 1). Only two of the five ranger districts in the Jefferson National Forest were included in the study because the remaining three districts stretch far to the southwest and are not

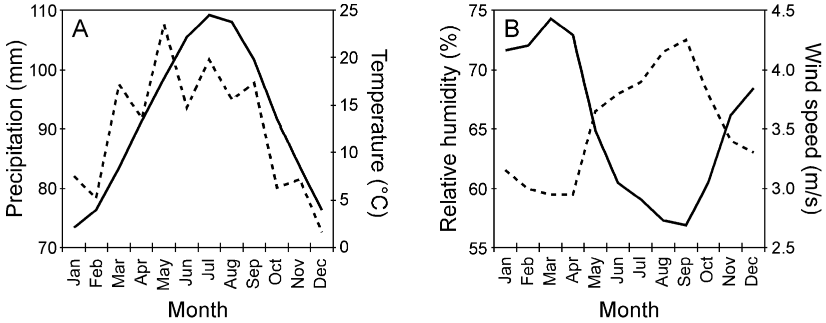

Fig. 2. Mean monthly climatic conditions for Roanoke, Virginia. (A) precipitation, indicated by dashed line, and temperature, indicated by solid line, obtained from NCDC (2002) for the period 1971–2000. (B) relative humidity, indicated by dashed line, and wind speed, indicated by solid line, obtained from NCDC (2003). Humidity data are for the period 1965–2003, and wind data are for 1949–2003.

clustered near the other federal lands. The George Washington and Jefferson National Forests are within both the Blue Ridge and Ridge and Valley provinces. The Monongahela National Forest is mostly in the Allegheny Plateau, while the Shenandoah National Park is in the Blue Ridge province. The total area of federal land in our study is 968,052 ha. Geographic Information System (GIS) data for federal ownership boundaries were obtained from the respective federal agencies.

The central Appalachians are characterized by a humid continental climate (Bailey, 1978), with pronounced seasonal temperature variability (Fig. 2A). Precipitation occurs throughout the year, but peaks during the warm season (Fig. 2A). Wind speed and relative humidity vary seasonally as well (Fig. 2B). Variability also is evident at the interannual time scale, leading to periodic droughts and wet spells that may influence fire activity. For example, annual precipitation at Roanoke, Virginia, during the period 1970–2003 (the 34-year period covered by wildland fire data) averaged 1062 mm, but varied from 638 mm during a severe drought in 2001 to 1386 mm in 2003 (NCDC, 2005).

Broadleaf deciduous trees dominate the vegetation of the central Appalachians. Oak forest is the primary vegetation type in the Blue Ridge and the Ridge and Valley, while mixed mesophytic forest predominates on the Allegheny Plateau (Braun, 1950). Because of the topographic complexity of the Appalachians, many other community types also occur. These include yellow pine woodlands on xeric ridgetops and west-facing slopes, red spruce (*Picea rubens* Sarg.) and northern hardwoods forests in the high elevations, and eastern hemlock (*Tsuga canadensis* [L.] Carr.) stands in mesic ravines (Stephenson et al., 1993; White et al., 1993).

METHODS

Data

The NIFMID database provides data on all anthropogenic and natural wildland fires that occurred on federal lands during the period 1970–2003. NIFMID includes

Table 1. Categories of Fire Intensity Reported in NIFMID during 1986–2003 for National Forest Lands[a]

Intensity level	Flame length (m)	*N*
1	0–0.6	464
2	0.7–1.2	224
3	1.3–1.8	78
4	1.9–2.4	27
5	2.5–3.7	2
6	>3.7	2

[a] Intensity data are not available for national parks. Flame length is defined as "the predominant or typical sustained average flame length observed at the head of the fire during the initial attack" (USDA Forest Service, 2003).

fires that originated on federal lands as well as those that originated elsewhere and spread onto federal lands. A total of 1557 anthropogenic fires and 344 natural fires occurred on federal lands in the study area during 1970–2003; 1475 of the anthropogenic fires and 334 of the natural fires originated on federal lands, and the remainder spread from surrounding areas onto the federal lands. For calculations of ignition density and for correlations between number of ignitions and climatic variables, we included only the fires that originated on federal lands. For analyses of area burned, we included the portion of each fire that burned on federal lands, regardless of where the fire originated.

NIFMID lists the specific human activity that caused each anthropogenic fire. Arson was the most important cause, accounting for 42% of the anthropogenic fires. Smoking and campfires were also important ignition sources, causing 13% and 11% of the fires, respectively. "Miscellaneous" causes (e.g., unknown causes, powerlines, fireworks) accounted for most of the remaining fires (21% of the total). NIFMID also reports an intensity level based on flame height for each fire that occurred on national forest during 1986–2003 (Table 1).

Data on lightning occurrence for 1995–2003 were obtained from the National Lightning Detection Network (NLDN) database, provided by the Department of Atmospheric Sciences at Texas A&M University. The NLDN consists of lightning sensors positioned throughout the contiguous United States (Cummins et al., 1998). Data on time, location, and current of each lightning flash are recorded. We used ArcView GIS 3.3 (ESRI, 2002) to select the lightning flashes that occurred within the boundaries of the federal lands in our study area.

The NLDN has operated over the entire coterminous United States since 1989. However, we chose to restrict our analyses to the period beginning in 1995, when the NLDN was upgraded to increase lightning detection efficiency and improve location error. Detection efficiency is estimated at 80–90% since 1995, and median location error is approximately 0.5 km (Cummins et al., 1998). Following the recommendation of Cummins et al. (1998) and Orville and Huffines (2001), we omitted small positive discharges with current <10 kA, as most of these probably are cloud discharges, not cloud-to-ground flashes.

Analyses

To identify the predominant intensity level for fires in the central Appalachians, we tallied the number of fires in each intensity class and also calculated the total area burned by fires in each intensity class. A Kruskal-Wallis test and a Nemenyi multiple comparison test (Zar, 1984) were used to investigate whether fire size differed by intensity level. We conducted a Mann-Whitney test to compare the size of anthropogenic versus natural fires.

To quantify the incidence of fire on the landscape, we calculated the mean annual ignition density and the mean area burned per year during 1970–2003. The calculations were expressed on the basis of a 1000 km^2 area. Paired-sample *t*-tests (Zar, 1984) were used to compare anthropogenic versus natural fires in terms of ignition density and area burned per year. The data were paired by year, and were log-transformed prior to testing. We calculated fire cycle as the reciprocal of the mean proportion of total land area burned annually (Heinselman, 1973).

To address questions of fire seasonality, we determined the average monthly distribution of anthropogenic and natural fires during 1970–2003. A goodness-of-fit *G*-test with Williams' correction (Sokal and Rohlf, 1981) was used to examine whether the monthly distribution of natural fires matched the distribution of lightning flashes between 1995 and 2003. Pronounced seasonal patterns were evident, and therefore we subdivided the fire dataset by season before proceeding with analyses of climate-fire relations. Fires were grouped into (1) spring anthropogenic fires (occurring between January and June), (2) natural fires (occurring throughout the year but mostly during April–September), and (3) fall anthropogenic fires (occurring between July and December). A *G*-test was used to compare the distribution of fires by intensity class among the three fire seasons.

With respect to climate-fire relations, we conducted a series of correlations (Zar, 1984) between climatic conditions and fire activity during each year by season. Specifically, for each of the three fire seasons, the number of fires (log-transformed), area burned (log-transformed), and proportion of fires with moderate to high intensity (levels 3–6; Table 1) were correlated with monthly values of the PDSI. To explore whether fire activity was related to moisture levels during the preceding year, the correlations were conducted for a 24-month period extending from the previous January through the current December. PDSI calculations for 1969–2003 were obtained from the National Climatic Data Center for Virginia climate division 5 and West Virginia division 4 (NCDC, 2004). These climate divisions encompass most of the federal lands in our study area. The PDSI values for the two climate divisions were averaged to represent regional moisture levels.

RESULTS

Fire Intensity and Size

Most fires were low-intensity burns—86% of all fires in the central Appalachians had intensity levels of 1 or 2 (Fig. 3). However, these low-intensity fires accounted

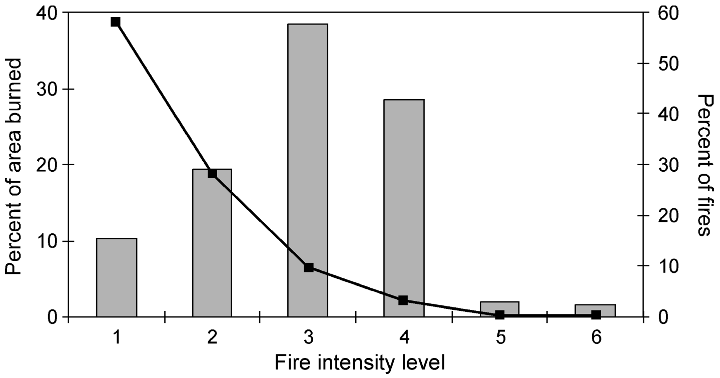

Fig. 3. Distribution of fires by intensity level (Table 1). Bars indicate the percent of total area burned by fires in each intensity level. Line indicates the percent of all fires in each intensity level.

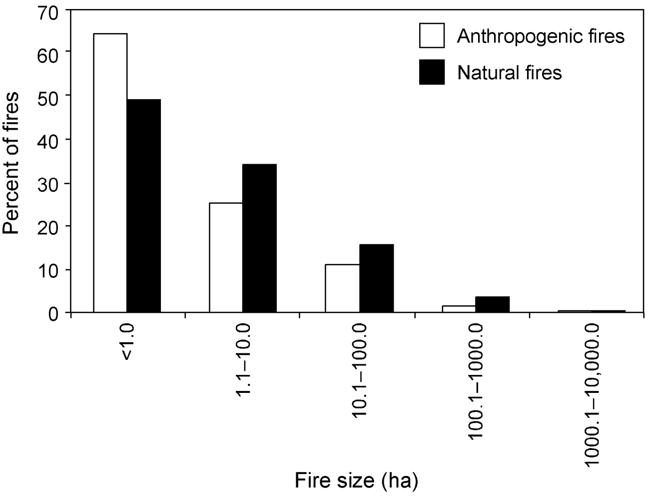

Fig. 4. Fire-size distribution for anthropogenic and natural fires in the central Appalachians.

for only 30% of the total area burned. The moderate-intensity fires in levels 3 and 4 accounted for most (67%) of the total area burned.

The moderate-intensity fires were larger than the less intense fires. The median fire sizes for intensity levels 1–4 were 0.2 ha, 1.6 ha, 6.7 ha, and 24.3 ha, respectively. Fire size differed significantly among these intensity levels (Kruskal-Wallis test, $\chi^2 = 199.830$, $df = 3$, $p < .01$; Nemenyi multiple comparison test, $p < .01$), except between levels 3 and 4 (Nemenyi test, $p > .05$). Intensity levels 5 and 6 were excluded from the significance tests because of small sample size.

Fire size also differed by ignition source. Both anthropogenic and natural fires tended to be rather small (Fig. 4), but anthropogenic fires typically were smaller (Mann-Whitney test, $U = 220{,}199.5$, $n^1 = 1557$, $n^2 = 344$, $p < .01$). The median sizes

Table 2. Mean (and Standard Deviation) Annual Ignition Density, Mean Annual Area Burned, and Fire Cycle for the Central Appalachians, Based on Wildland Fire Data for the Period 1970–2003

Category	Anthropogenic fires	Natural fires	Anthropogenic and natural combined
Ignition density (*N*/1000 km^2/yr)	4.48 (2.12)[a]	1.01 (1.06)[b]	5.50 (2.48)
Area burned (ha/1000 km^2/yr)	83.61 (167.53)[a]	16.29 (45.24)[b]	99.90 (182.63)
Fire cycle (years)	1196	6138	1001

[a,b] Values in each row that are followed by "a" differ significantly from those followed by "b" (paired sample *t*-tests, $df = 33$, $p < .01$).

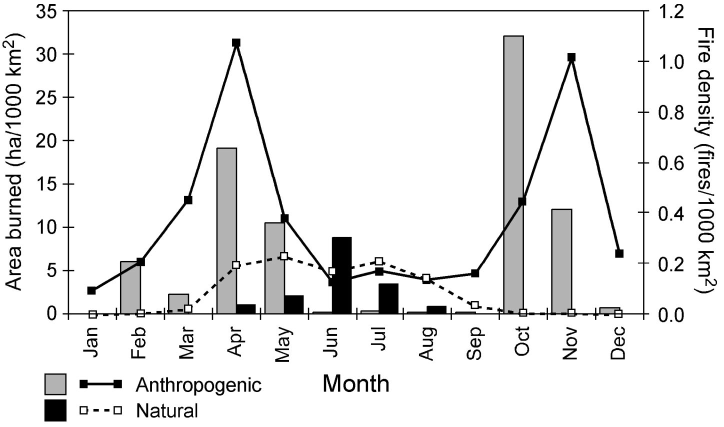

Fig. 5. Mean monthly patterns of fire activity for 1970–2003. Bars indicate mean area burned per month, and lines indicate mean density of fires per month.

for anthropogenic and natural fires were 0.4 ha and 1.2 ha, respectively. However, the size distribution for anthropogenic fires was skewed more strongly than for natural fires (skewness was 24.0 and 11.1, respectively), and a few of the anthropogenic fires were quite large. The five largest anthropogenic fires all were larger than 1500 ha (maximum 6484 ha), while the largest natural fire was only 1188 ha.

The Incidence of Fire

Humans accounted for the majority of ignitions and area burned (Table 2). Over the entire period 1970– 2003, anthropogenic fires burned a total area of 27,519 ha, while natural fires burned 5362 ha (32,881 ha total). Therefore, the fire cycle was shorter for anthropogenic fires than natural fires (Table 2).

Temporal Patterns of Fire Occurrence

Anthropogenic fires occurred predominantly in spring and fall (Fig. 5). Virtually all the natural fires occurred in spring and summer. The percentage of fires in each

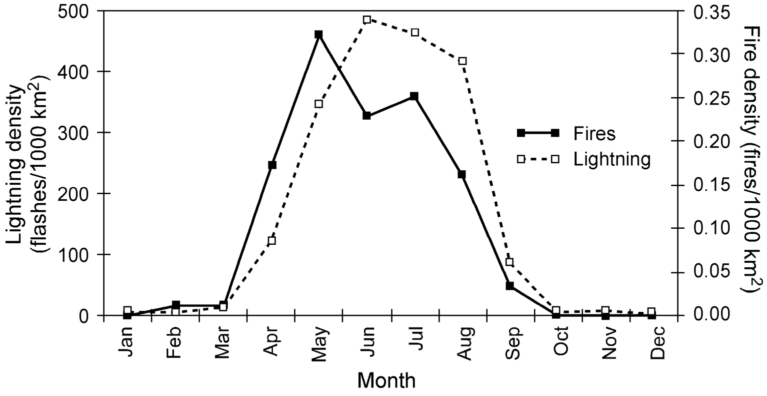

Fig. 6. Mean monthly distribution of lightning flashes and natural fires for 1995–2003.

intensity level was similar for the three fire seasons (*G*-test, $G_{adj} = 8.48$, $df = 6$, $p > .10$).

The seasonal distributions of lightning flashes and natural fires during 1995–2003 both peaked in the warm season (Fig. 6). However, the monthly pattern of fires did not match the pattern of lightning discharges (*G*-test, $G_{adj} = 17.81$, $df = 5$, $p < .01$; the test was only for the months of the natural fire season, April–September). A higher-than-expected number of fires occurred during spring, and a lower-than-expected number occurred in summer.

Fire activity also exhibited considerable interannual variation (Fig. 7). On average, 53 fires occurred per year in the central Appalachians, and 967 ha were burned annually (0.1% of total land area per year). The 5-year running means (Fig. 7) suggest that mean annual number of fires remained similar over the study period, but that an increase occurred in the average number of hectares burned annually.

The interannual variations in fire activity were related to climatic variability. Spring anthropogenic fire activity was related negatively to PDSI during winter and spring (i.e., fire activity was highest during years with a dry winter and spring; Fig. 8A). Natural fires were related to moisture conditions throughout the year, especially late spring and summer (Fig. 8B), while fall anthropogenic fire activity was related to late summer and fall moisture levels (Fig. 8C). We also found an unexpected relationship: the area burned by fall fires was related to drought during the summer of the previous year. Tests for autocorrelation in the PDSI time series revealed that significant autocorrelation did not exist between fall PDSI and the PDSI for the previous July ($p > .10$); therefore, autocorrelation does not appear to be responsible for the relationship. With respect to fire intensity, drought favored the occurrence of moderate- to high-intensity fires—the negative relationships (Fig. 8D) indicate that the percentage of moderate-to-high intensity fires increased with declines in PDSI (i.e., under drought conditions).

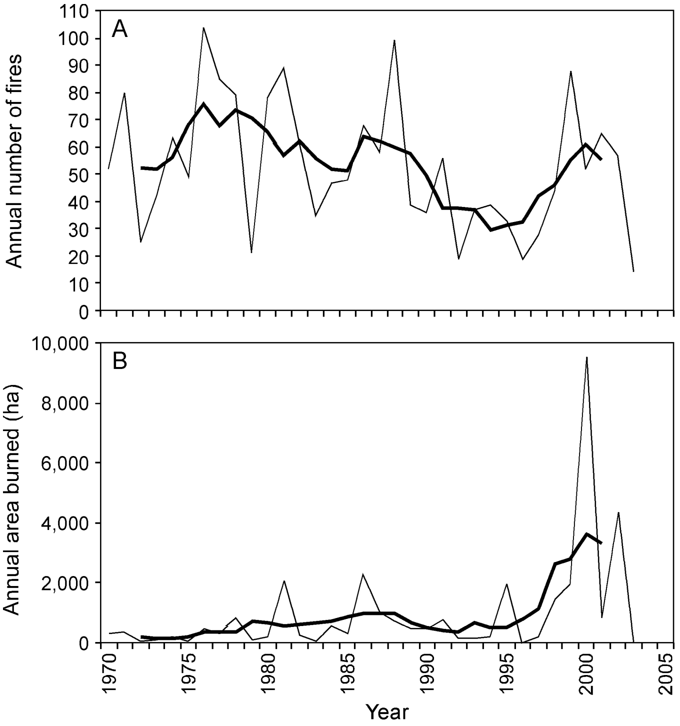

Fig. 7. (A) Total annual number of fires and (B) area burned on federal lands of the central Appalachians, 1970–2003, with five-year running averages superimposed (heavy lines).

DISCUSSION

Fire Intensity and Size

Our results portray a burning regime that is dominated, at least numerically, by small fires of low intensity (Figs. 3 and 4). Of greater consequence for vegetation, however, are the larger, moderate-intensity fires that are responsible for most of the area burned. Hence, with respect to fire as a vegetation disturbance, the fire regime is best characterized as a moderate-intensity regime. Studies of fire disturbance in Appalachian pine forests indicate that fires with flame heights characteristic of intensity levels 3 and 4 would kill most of the small-diameter trees (stem diameter <20 cm) and a few of the larger trees, resulting in an open understory with a relatively intact overstory (Waldrop and Brose, 1999; Welch et al., 2000). More severe damage can occur in hardwood stands, however, as demonstrated by the Marbleyard Fire, an intensity-level 3 burn that occurred in June 2002 and killed virtually all the overstory hardwood trees across large patches of the landscape.

The concentration of fires in the smallest size class (Fig. 4) is typical for any fire regime, as is the tendency for a small number of relatively intense fires to burn most

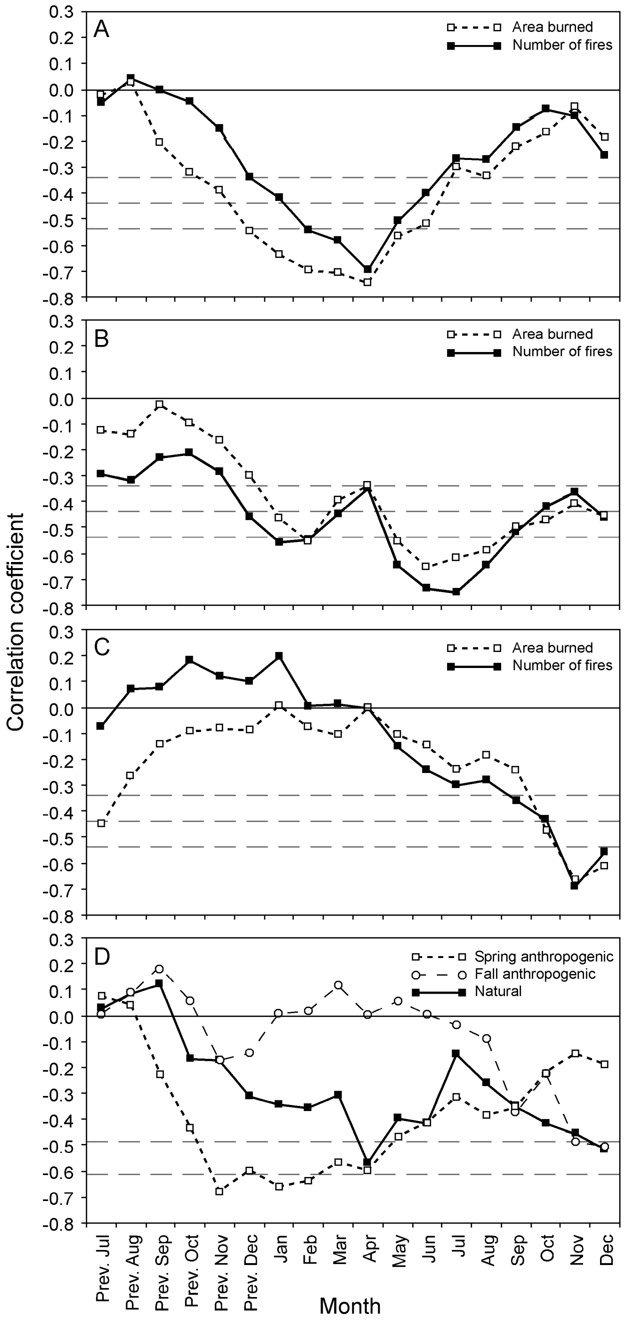

Fig. 8. Relationships between monthly PDSI and fire activity for (A) spring anthropogenic fires, (B) natural fires, and (C) fall anthropogenic fires. Panel D shows relationships between PDSI and the percent of fires in intensity classes 3–6. Relationships are shown for an 18-month period beginning in the previous July, and ending in December of the year in question. Correlations for the previous January through June were not statistically significant and therefore were not included in the graph. Horizontal dashed lines indicate critical levels of *r* for $p < .05$, $p < .01$, and (for panels A, B, and C) $p < .001$, respectively.

of the area (Fig. 3; Pyne, 1982). In fact, of the 1901 fires in our analyses, the eight largest fires were responsible for over half (51%) of the total area burned.

Comparing anthropogenic versus natural fires, the smaller median size of anthropogenic fires probably is a consequence of their occurrence in accessible locations, where they can be controlled before spreading far. Lightning fires typically occur in more remote locations where discovery is delayed and control is more difficult (Steve Croy, pers. comm., January 28, 2005). However, the large maximum size for anthropogenic fires suggests that under hazardous burning conditions (drought, high winds) these fires can elude control and spread rapidly into inaccessible terrain. Rapid fire spread would be expected for anthropogenic fires because they occur during spring and fall (Fig. 5), when weather conditions (wind speed, humidity) are especially favorable for burning (Fig. 2).

The Incidence of Fire

Our analyses revealed two general patterns of fire in the central Appalachians (Table 2). First, the contemporary fire regime is dominated by anthropogenic fires. This result is consistent with the pattern in the southern Appalachian Mountains of North Carolina and Tennessee (Barden and Woods, 1974), and probably also with the past fire regime of the Appalachians, in which burning by Native Americans and European settlers is thought to have occurred frequently (Pyne, 1982; Van Lear and Waldrop, 1989; Delcourt and Delcourt, 1997, 1998). Second, the fire cycle is long, meaning that most parts of the landscape escape burning for many years. This fire regime appears to differ considerably from the past regime under which Appalachian vegetation developed.

Temporal Patterns of Fire

Fire seasonality. The seasonal pattern of fire activity reflects the seasonal progression of weather and fuel conditions. The high incidence of fire during fall coincides with (1) the maximum annual accumulation of fine fuels (leaf litter and dead herbaceous vegetation), (2) the occurrence of relatively low precipitation, high temperatures, high winds, and low humidity (Fig. 2) that combine to dry the fine fuels rapidly, and (3) the increased penetration of sunlight and wind after the loss of foliage in October (cf. Shroeder and Buck, 1970). The paucity of lightning fires in fall reflects that lightning activity has virtually ceased before favorable burning conditions develop in October (Fig. 6). The onset of winter brings colder temperatures that inhibit drying and limit fire activity. Snow cover exists intermittently throughout the winter and also contributes to the lack of fire.

Spring witnesses a return of conditions similar to those of fall. Most of the fine fuels remain, having decomposed little under the cold conditions of winter (cf. Schlesinger, 1991). Increasing temperature and wind speed, along with low humidity (Fig. 2), help dry the surface fuels, which remain exposed to sun and wind until the development of significant new canopy foliage in middle to late April (in low to moderate elevations; later at high elevations). The increase in lightning activity during spring also enhances fire activity.

During late spring and summer, new vegetation emerges, humidity rises, and wind speed declines (Fig. 2B). These fuel and weather conditions reduce the likelihood of fire, and contribute to the low number of natural fires in summer, relative to the number of lightning flashes that occur then (Fig. 6). Another influence on lightning ignitions is the moisture status of snags (dead, standing trees), because snags are common ignition points for natural fires (Steve Croy, pers. comm., January 28, 2005). In spring, the snags are dry following several months of high winds and low humidity (Fig. 2B); consequently, the peak in natural fire activity occurs during late spring. As summer progresses, the snags gradually become moister and more difficult to ignite (Steve Croy, pers. comm., January 28, 2005; cf. Shroeder and Buck, 1970).

Natural fires have about the same intensity levels as anthropogenic fires, even though many of the natural fires occur during the relatively unfavorable burning conditions of summer. This finding contrasts with the pattern in the southern Appalachians, where natural fires were less intense than anthropogenic fires (Barden and Woods, 1974). The explanation for this difference between the central and southern Appalachians is not readily apparent, but may involve the drier climate of the central Appalachians (cf. NCDC, 2002).

The influence of natural fires on forest dynamics of the central Appalachians may be disproportionate to their frequency, because trees are more sensitive to growing-season fires than to dormant-season burns (Brose and Van Lear, 1998; Dey, 2002). Consequently, growing-season fires typically cause higher tree mortality. Moreover, sprouting capacity is lower after a summer burn, so vegetation recovery may occur more slowly or follow a different successional pathway than it would after a dormant season burn. Although anthropogenic fires occur during the summer months, the area burned is small (Fig. 5), and hence they contribute little to vegetation disturbance during the growing season.

The seasonal patterns evident in Fig. 5 may inform the interpretation of dendroecological analyses of fire history in the Appalachians. The position of a fire scar within a tree ring can be used to estimate the season of the burn (Baisan and Swetnam, 1990). A study of fire history in two Table Mountain pine (*Pinus pungens* Lamb.) stands in the Jefferson National Forest revealed that nearly all the fires that occurred from 1798 to 1944 were dormant-season burns (Sutherland et al., 1995). These fires would have occurred during either the spring or fall burn seasons and most likely were ignited by humans. One fire occurred during the latter part of the growing season, and therefore may have been ignited by lightning. Regardless of ignition source, Sutherland et al. (1995) concluded that the summer fire probably caused greater tree mortality than the dormant season burns, because, unlike the other fires, it was followed by recruitment of a new pine cohort.

Interannual variations with respect to climate. As in many other fire regimes, climate appears to exert a strong influence on interannual variations in the fire activity of the central Appalachians, including number of fires, area burned, and fire intensity. Drought clearly encourages widespread burning and high fire intensity. These patterns suggest not only that humans and lightning flashes ignite more fires during drought than wet conditions, but also that dry fuels contribute to rapid fire spread and hazardous firefighting conditions that hinder suppression. The rise in annual average area burned (Fig. 7B) appears to be a consequence primarily of drought conditions during the 1980s and 1998–2002 (NCDC, 2004). These droughts followed unusually wet conditions during 1972–1975 that stifled fire activity during the early part of the study period. Another factor that may contribute to the rising trend is an increasing shift from an aggressive suppression strategy (direct attack at the fire line) to less aggressive techniques (containment), because of concerns over fire-fighter safety and suppression costs (Steve Croy, pers. comm., January 28, 2005).

The lack of significant positive correlations between monthly PDSI and fire activity (Fig. 8A, 8B, and 8C), and monthly PDSI and percent of fires in higher-intensity classes (Fig. 8D), indicates that, unlike in arid environments, preceding wet periods are not necessary for the accumulation of fine fuels that favor high fire activity. This result is consistent with fire regimes in other humid environments (Kitzberger et al., 1997). An explanation for the negative relationship of fall fire activity to drought in July of the previous year (i.e., more than a year earlier; Fig. 8C) is not apparent. Despite this relationship, the general conclusion suggested by our results is that fire responds to drought conditions over a period of a few months.

CONCLUSIONS

Climate exerts a strong influence on the contemporary fire regime of the central Appalachians, at both seasonal and interannual time scales. Four features of the regional climate seem particularly important for controlling fire activity. First, the humid temperate conditions support high vegetation productivity and rapid fuel accumulation. Second, seasonal variations in weather conditions contribute to pronounced fire seasonality. Third, the climate is prone to periodic dry years with highly favorable burning conditions, as well as wet periods that stifle nearly all fire activity. Fourth, lightning coincides with dry conditions on a sufficiently frequent basis to ignite a number of fires during the growing season. In the past, when fire spread was less impeded by landscape fragmentation and fire suppression, natural fires likely spread over extensive areas during drought years. Natural fires may have had a much shorter cycle and a more important ecological function, especially given their occurrence during the growing season.

Another consideration is that climatic conditions vary spatially in the heterogeneous Appalachian landscape (Konrad, 1994; NCDC, 2002), probably contributing to spatial differences in fire regime characteristics. Preliminary analyses that we have conducted suggest that levels of fire activity differ among the three physiographic provinces, with the Blue Ridge being especially fire-prone and the Allegheny Plateau having limited fire activity. These spatial patterns will be investigated in a subsequent paper.

In the future, fire activity is projected to increase in many regions, including the southeastern United States, as a consequence of climate change (Bond and van Wilgen, 1996; Bachelet et al., 2001). Given that fire activity in the central Appalachians is quite sensitive to climatic variability, any changes in climate likely will lead to changes in the fire regime.

In addition to climate, human influences on the fire regime are also important. Humans ignite more fires than lightning. Moreover, their prevention and suppression efforts constrain the occurrence and spread of fire, resulting in much less burning on the contemporary landscape than appears to have occurred in the past. Prescribed burning by resource management is a recent human activity that makes a large impact on the fire regime. On the George Washington and Jefferson National Forests, for example, an average of 3156 ha, or 0.44% of total land area, was burned annually (mostly during spring) by prescribed fires during the period 1998–2003 (GWJNF 2004). The target burning level is higher (approximately 6000 ha annually) (Steve Croy, pers. comm., January 28, 2005), but is difficult to attain because weather conditions frequently do not permit implementation of the burns. Prescribed fires clearly enhance the level of fire activity in the Appalachians, but at current levels they are not sufficient to restore the fire regime of the past, except perhaps in small areas of the landscape.

Shenandoah National Park currently is drafting a fire management plan that will permit the use of natural wildland fire for resource management in certain areas (Sue Imler, pers. comm., December 8, 2004), and the George Washington and Jefferson National Forests will develop such plans during the next few years (Steve Croy, pers. comm., January 28, 2005). The Monongahela National Forest does not plan to implement fire use in the future because of concerns over the protection of fire-sensitive vegetation (especially high-elevation red spruce and northern hardwoods forests; Peter Fisher, pers. comm., February 17, 2005). Implementing wildland fire use will not restore a "natural" fire regime, because of impediments to fire spread (e.g., landscape fragmentation), and because of suppression of natural fires that occur under weather/fuel conditions that could lead to high-intensity fires that would be difficult to manage. These are precisely the conditions under which large fires and extensive burning occur (Pyne, 1982; Fig. 3, Fig. 8). Nonetheless, adopting fire use policies may lead to changes in the fire cycle and fire-size distribution, and ultimately may alter forest composition and fuel loads. One aspect of these natural fires that seems especially important is their occurrence during the growing season. By permitting these fires to burn, it may be possible to achieve ecological benefits that could not be attained through conventional prescribed burning conducted in the spring.

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