SPATIAL PATTERNS OF FIRE OCCURRENCE IN THE CENTRAL APPALACHIAN MOUNTAINS AND IMPLICATIONS FOR WILDLAND FIRE MANAGEMENT

Charles W. Lafon
Department of Geography
Texas A&M University
College Station, Texas 77843-3147

Henri D. Grissino-Mayer
Department of Geography
University of Tennessee
Knoxville, Tennessee 37996-0925

Abstract: We investigated spatial variations in the incidence of anthropogenic and natural (lightning-ignited) fire in the central Appalachian Mountains of Virginia and West Virginia using a record of wildland fires that occurred on federal lands between 1970 and 2003. A consideration of spatial variability in wildland fire is important for allocating fire-suppression resources and for informing resource managers who use naturally ignited wildland fires or prescribed fires in ecological restoration efforts and fuel reduction treatments. The central Appalachian region contains three physiographic provinces with distinct climate, terrain, and vegetation characteristics. Comparing ignition density, maximum fire size, and fire cycle among the three provinces indicated that the Appalachian Plateau—the westernmost province and also the highest, coolest, and wettest of the three—was the least fire-prone environment. The Blue Ridge province along the eastern edge of the region was most fire prone. The Ridge and Valley province, which occupies the center of the region, generally was intermediate in fire characteristics, despite having the driest climate and the greatest extent of flammable pine (*Pinus* L.)–and oak (*Quercus* L.)–dominated forests. At a finer spatial scale, fire activity varied topographically in all three provinces: ignition density declined with increasing elevation, but showed weaker, less consistent relationships to aspect. Spatial variations in the importance of natural fires may be of particular interest to federal resource managers who are developing plans for permitting natural fires to burn to restore fire-associated ecosystems. The Blue Ridge appears to be a particularly favorable environment for natural ignitions. [Key words: disturbance heterogeneity, forest disturbance, lightning, Virginia, West Virginia, wildland fire use.]

INTRODUCTION

Spatial variation in the incidence of disturbance has important implications for vegetation patterns and resource management strategies (e.g., Parker et al., 2001). An important driver of disturbance heterogeneity is the synergistic association of climate and terrain (e.g., Parker and Bendix, 1996). Some portions of a landscape have greater exposure than others to damaging agents such as wind, ice, landslides, and floods. Moreover, the variations in precipitation, insolation, and moisture regimes across complex terrain exert indirect influences on spatial patterns of fire and insect outbreaks (Parker and Bendix, 1996).

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The purpose of this study is to investigate spatial patterns of fire occurrence across the central Appalachian Mountains of western Virginia and eastern West Virginia. The region contains large tracts of National Forest and National Park lands. A consideration of spatial variability in wildland fire is important for allocating fire-suppression resources on these federally managed lands. This research will also inform forest managers in their plans to use prescribed fires or naturally ignited wildland fires in ecological restoration efforts and fuel reduction treatments. Resource managers increasingly use fire to reduce fuel loads and to attempt to restore fire-associated ecosystems, such as the widespread oak (*Quercus* L.) forests and pine (*Pinus* L.) woodlands, which appear to be declining after decades of reduced fire activity (e.g., Brose et al., 2001).

The abundance of oak, pine, and other fire-associated species is thought to have been maintained in the past by extensive burning caused by lightning, Native Americans, and, later, European settlers (e.g., Pyne, 1982), although the extent of burning by Native Americans is debated (e.g., Russell, 1983; Vale, 2002). Paleoecological studies provide evidence of a long history of burning in the Appalachian region. For example, analyses of sediment pollen and charcoal indicate that fires were common during the last 3000–4000 years, and suggest that they were important for maintaining the dominance of oak, chestnut (*Castanea dentata* [Marsh.] Borkh.), and pine on the southern Appalachian landscape (Delcourt and Delcourt, 1998). Dendroecological reconstructions of fire history over the last 150–400 years in oak and pine forests of the central and southern Appalachian Mountains indicate that surface fires burned at intervals of approximately 5–15 years before declining with the advent of effective fire control in the first half of the 20th century (e.g., Harmon, 1982; Shumway et al., 2001). A survey of the southern Blue Ridge Mountains conducted by Ayres and Ashe (1905) during 1900 and 1901 illustrates the extent of burning in the decades preceding effective fire control: light surface fires occurred frequently over 80% of the region. Nonetheless, some sites within the heterogeneous Appalachian landscape burned infrequently, particularly the high-elevation forests dominated by northern hardwoods, eastern hemlock (*Tsuga canadensis* [L.] Carr.), or red spruce (*Picea rubens* Sarg.; Wade et al., 2000).

Today, prescribed burning treatments are constrained by the availability of resources and personnel, and by the number of days with suitable weather conditions. Understanding spatial patterns of wildland fires (both natural, lightning-ignited fires, and anthropogenic fires not ignited by management) can help managers prioritize the parts of the landscape in terms of where prescribed fire is most needed to augment the fire regime, and also where fire suppression efforts likely will be needed on a frequent basis. Patterns of natural fire are particularly important because of an increasing interest in lightning-ignited fires as resource-management tools and as natural hazards (e.g., Zimmerman and Bunnell, 1998; Mitchener and Parker, 2005). New wildland fire policy allows managers to develop fire-use plans designating specific areas as Wildland Fire Use (WFU) zones (Zimmerman and Bunnell, 1998). Naturally ignited fires (but not anthropogenic fires) that occur in these areas are permitted to burn to achieve resource management objectives. Identifying spatial variations in natural ignitions will inform decisions about appropriate locations to designate for WFU in the central Appalachian Mountains.

The central Appalachian region consists of three physiographic provinces (Keys et al., 1995) with distinct climatic and fuel conditions that may contribute to spatial variation in the incidence of fires. Orographic influences on precipitation could be particularly important for fire regimes. The Appalachian Plateau province in the western part of the study area and the Blue Ridge province along the eastern edge receive considerably more orographic precipitation than the Ridge and Valley province (NCDC, 2000, 2002), which lies in the rain shadow between the other two provinces (Konrad, 1994). Such regional moisture gradients can influence the occurrence of forest fires, with drier environments typically displaying greater fire activity than wetter ones (e.g., Mitchener and Parker, 2005). We hypothesize that the Ridge and Valley has greater fire activity than the other two physiographic provinces. We also expect that dry topographic positions (e.g., low elevations and south- or west-facing slopes) burn more frequently than moist sites. Such topographic patterns have been found in some other landscapes (e.g., Grissino-Mayer et al., 2004). The expected decline in fire with increasing elevation reflects that climate generally becomes wetter toward high elevations as a consequence of lower temperatures and orographically enhanced precipitation. Within a limited elevation range, however, the valleys are wetter than the ridges because of the runoff of water from high to low terrain.

This study uses a record of wildland fires that occurred on federally managed lands between 1970 and 2003, and a record of lightning activity between 1995 and 2003. All wildland fires were suppressed during the study period. The study extends previous work in which we used the wildland fire data to (1) characterize the contemporary fire regime of the entire central Appalachian region (i.e., without regard to spatial heterogeneity), and (2) explore the relation of fire to seasonal and interannual variability in climate (Lafon et al., 2005). The previous study revealed that between 1970 and 2003 most fires were small, low-intensity burns. However, as is true of most fire regimes (cf., Pyne, 1982), the fire size distribution was positively skewed because a few fires were quite large (up to 6484 ha). A handful of the largest fires accounted for most of the area burned and therefore had a disproportionate influence on the fire cycle, which is the time required for an area equivalent to the entire study area to burn (Heinselman, 1973; Johnson et al., 1990). The contemporary fire cycle appears to be much longer than in the past because of prevention and suppression practices (Lafon et al., 2005). We calculated a fire cycle of 1001 years, with anthropogenic fires making a larger contribution than natural fires to the total area burned. Anthropogenic fires had a smaller median size than natural fires, probably because they occurred in accessible sites where rapid control was possible. However, a few anthropogenic fires apparently escaped control and spread into inaccessible terrain, burning extensive areas and hence exerting a large influence on fire cycle.

This paper addresses the following specific questions about spatial patterns of wildland fire in the central Appalachian Mountains. We do not consider prescribed fires here because they are better understood and controlled by forest managers. The first question concerns the most basic measure of fire activity—the density of ignitions—and whether ignition density varies by physiographic province or topographic position (elevation or aspect). The remaining questions elaborate on the variations among the physiographic provinces by considering some other aspects of the fire regime. These last four questions do not consider elevation and aspect because the fire and lightning datasets are too sparse and/or of insufficient spatial resolution for such analyses. (1) Ignition density: (a) Does the density of natural or anthropogenic ignitions differ among the three physiographic provinces? (b) Does the density of ignitions differ topographically? (2) Natural fire and lightning: Do natural fire and lightning activity vary among the physiographic provinces? (3) Fire seasonality: Are seasonal patterns of fire occurrence similar among the three provinces? Fire seasonality is an important fire regime parameter with implications for plant mortality and recruitment (Bond and van Wilgen, 1996). (4) Fire size (areal extent): Does fire size differ among the physiographic provinces? Fire size has implications for dispersal distances of organisms colonizing the burned patch (Bond and van Wilgen, 1996), and is also an important control of the fire cycle. (5) Fire cycle: What is the length of the fire cycle for anthropogenic and natural fires in each physiographic province?

METHODS

Study Area

The study area is within 37–39° N, 78–81° W (Fig. 1). The Appalachian Plateau physiographic province in the west consists of rugged terrain formed by the dissection of gently deformed sedimentary rocks (Rodgers, 1970; Keys et al., 1995). Our study does not encompass the entire width of the Appalachian Plateau province, which slopes gradually downward toward the continental interior, but focuses on the high eastern edge (the Allegheny Mountains section) within the Monongahela National Forest. The Ridge and Valley province forms the center of the study area, where folded and faulted sedimentary rocks have been eroded into parallel mountains and valleys. Topographic relief in both provinces is generally 300–600 m. The Blue Ridge province, which forms the eastern rampart of the Appalachian Mountains, has higher relief. It is a narrow, rugged mountain range rising about 800–1000 m above the Piedmont to the east.

Our study investigates fires that occurred within Shenandoah National Park and the Monongahela, George Washington, and Jefferson National Forests (Fig. 1). Only two ranger districts of the Jefferson National Forest were used in the study because the remaining three districts extend far southwestward and are not clustered around the other federal lands. All ranger districts of the Monongahela National Forest were in the Appalachian Plateau. The ranger districts of the George Washington and Jefferson National Forests were allocated between the Ridge and Valley and the Blue Ridge, and the entire Shenandoah National Park was assigned to the Blue Ridge. Because ranger district boundaries do not follow physiographic features precisely, each province delineated here actually includes small amounts of land from the neighboring province. However, such inclusions represent < 5% of the total area of any province and therefore should have negligible influence on our results. The total area of federal land is 968,052 ha, including 370,347 ha in the Appalachian Plateau, 428,255 ha in the Ridge and Valley, and 169,450 ha in the Blue Ridge.

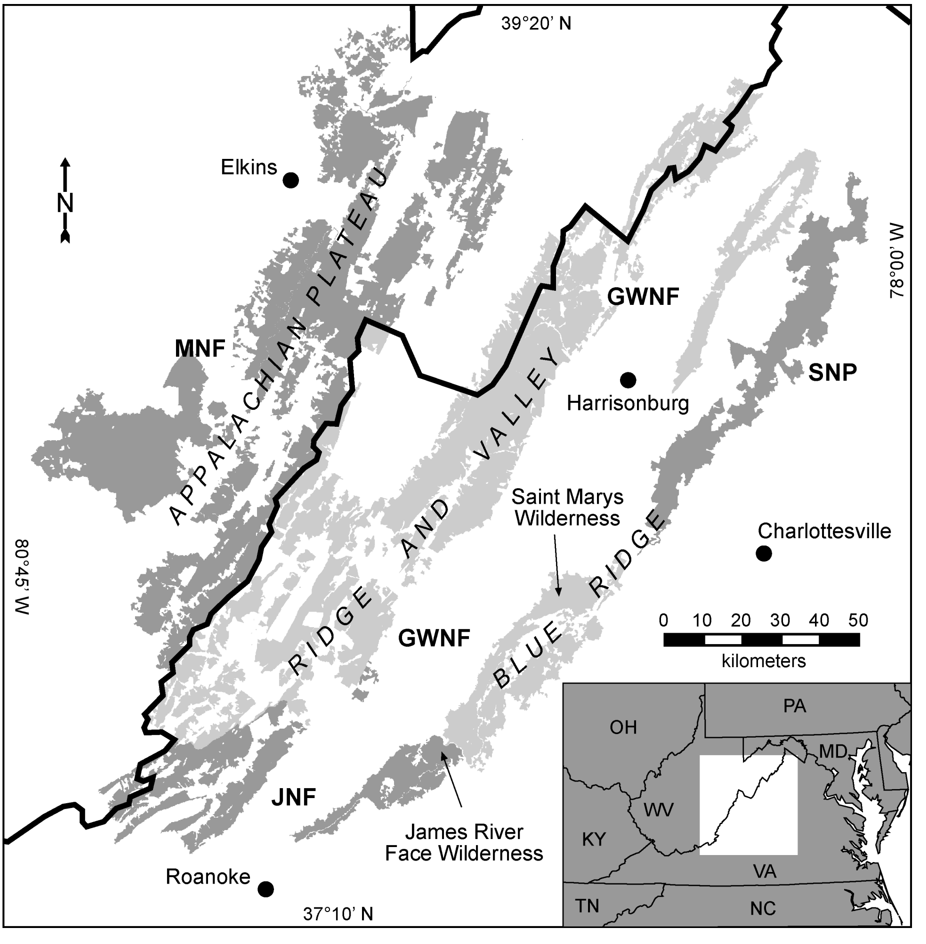

Fig. 1. Federal lands in the central Appalachian Mountains. MNF, GWNF, and JNF = Monongahela, George Washington, and Jefferson National Forests, respectively. SNP = Shenandoah National Park.

Geographic information system (GIS) data for federal ownership boundaries were obtained from the respective federal agencies.

The central Appalachian region has a humid, continental climate (Bailey, 1978) with cold winters, warm summers, and a broad warm-season peak in precipitation. Relative humidity and wind speed also vary seasonally (Lafon et al., 2005). Relative humidity is lowest from mid-winter through mid-spring. It peaks in late summer and then declines sharply during fall. Wind speed shows an opposite pattern. It is highest from mid-winter through mid-spring. It diminishes during late spring, remains low over summer, and rises during fall.

Climatic conditions vary spatially within the region. The Appalachian Plateau has higher elevations and, hence, a cooler, wetter, snowier climate than the rest of the region (NCDC, 2000, 2002). Mean annual precipitation exceeds 1270 mm over

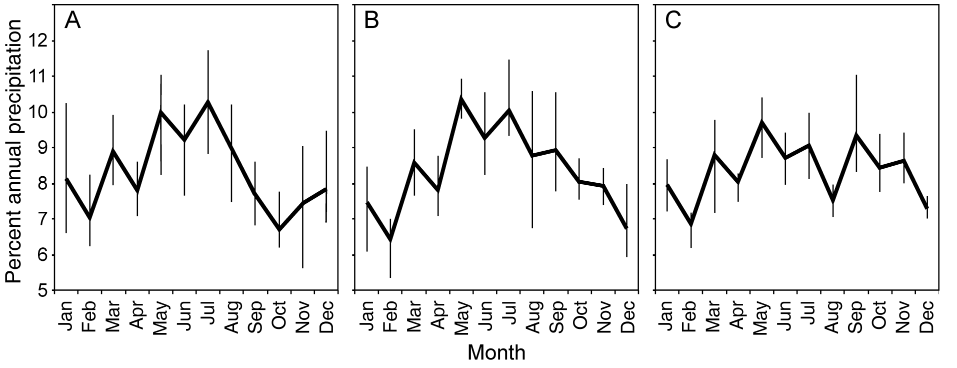

Fig. 2. Seasonal distribution of precipitation in the central Appalachian Mountains based on climate data (30-year mean) for 39 weather stations within the area covered by federal lands (NCDC, 2002). The solid line indicates the percentage of the total annual precipitation falling each month (i.e., the mean for all stations in the physiographic province), and the error bars indicate the range for all the stations. The Appalachian Plateau and the Ridge and Valley each had 17 weather stations, while the Blue Ridge had 5.

much of the plateau and also in a narrow zone along the Blue Ridge. Annual precipitation averages 900–1050 mm throughout much of the Ridge and Valley. Spatial variations also exist in precipitation seasonality (Fig. 2). The western, more continental, parts of the study area have a summer precipitation peak, while the Blue Ridge lacks the summer peak and has considerable precipitation during fall.

Hardwood-dominated forests are the prevalent land cover type. Mixed mesophytic and northern hardwoods forests predominate on the cool, moist highlands of the Appalachian Plateau, while oak forests cover most of the Ridge and Valley and the Blue Ridge (Braun, 1950). However, other forest types are scattered across the complex terrain. These include red spruce forests in high elevations, eastern hemlock stands in ravines, and pine woodlands on dry ridge tops and southwest- or west-facing slopes.

Fuel flammability differs among these vegetation types, which can be grouped into three general flammability classes reflecting differences in litter properties, resin content of the wood, and understory density (Vose and Swank, 1993; Duchesne and Hawkes, 2000; Wade et al., 2000). Specifically, pine forests are the most flammable, oak forests are moderately flammable, and the mesophytic hardwood and conifer forests (e.g., cove hardwoods, northern hardwoods, spruce, and hemlock) are least flammable. Stand inventory data obtained from the federal agencies suggest that the Ridge and Valley province has more flammable vegetation than the other provinces: 14% of the forest stands are pine-dominated, 79% are oak-dominated, and only 8% are mesophytic forests. The Blue Ridge has 9% pine, 63% oak, and 28% mesophytic forest, while the Appalachian Plateau has 2% pine, 20% oak, and 78% mesophytic forest.

Data

Data for all wildland fires occurring on federal lands between 1970 and 2003 were obtained from the National Interagency Fire Management Integrated Database

(NIFMID; USDA Forest Service, 1998), which provides fire incident details (e.g., date and ignition source) and also indicates the Ranger District in which each fire occurred. A total of 1557 anthropogenic fires and 344 natural fires was recorded between 1970 and 2003. For each fire that occurred between 1986 and 2003, NIFMID records topographic information. Specifically, the estimated point of ignition is assigned to a 305 m (1000 ft.) elevation zone and to one of eight aspect classes (USDA Forest Service, 1998). We obtained 30 m digital elevation models (DEMs) from the U.S. Geological Survey to calculate the area of the corresponding elevation and aspect zones.

We obtained lightning occurrence data for 1995–2003 from the National Lightning Detection Network (NLDN) database (Cummins et al., 1998), which records the time, location, and current for each flash detected. The data were provided by the Department of Atmospheric Sciences at Texas A&M University. ArcView GIS 3.3 (ESRI, 2002) was used to select flashes that occurred inside federal land boundaries. Detection efficiency for the NLDN is estimated at 80–90%, with approximate mean location error of 0.5 km (Cummins et al., 1998). Based on the recommendation of Cummins et al. (1998) and Orville and Huffines (2001), small positive flashes with current <10 kA were omitted because most of them probably were cloud discharges rather than cloud-to-ground strikes.

Analyses

ANOVA was employed to test for differences in ignition density among the provinces, using SPSS version 14.0 (SPSS, Inc., 2005; also used in other analyses below). We first aggregated the annual fire data into three-year periods and calculated the ignition density per triennium, expressing the calculations based on a 1000 km^2 area (Lafon et al., 2005). The triennial aggregation was useful because the low incidence of fires resulted in many years having no fire occurrences, especially on the Appalachian Plateau. Consequently, the annual fire data were not distributed normally or lognormally and could not be compared among the provinces via ANOVA. The triennial aggregation resolved this problem while retaining a relatively large number of observations (11 triennia, beginning with the triennium 1971–1973 and continuing through 2001–2003). Logarithmic transformation of the triennial fire density data yielded normally distributed data (Kolmogorov-Smirnov tests, $p > .05$) in which variance was homogeneous among the three provinces (Levene's tests, $p > .05$). Randomized block ANOVA (Zar, 1999) was used to test for differences in ignition density (log-transformed) among the provinces (the treatment, or fixed factor), using the triennium as the block (random factor) to account for synchronous, region-wide climatic forcing of fire regimes (i.e., a drought or wet spell typically would affect all three physiographic provinces simultaneously). We used Tukey multiple comparison tests (Zar, 1999) for pairwise comparisons between the provinces. Additionally, to control for the potential influence of elevational differences on patterns of fire density among the provinces, we conducted these same tests for single elevation zones over the period 1986–2003, when topographic designations were assigned to all the fires. In these analyses, the triennial aggregation yielded six observations, from 1986–1988 through 2001–2003. The elevation zones were the two with the greatest number of fires: the 458–762 m zone, with 511 of the 943 fires occurring between 1986 and 2003, and the 763–1067 m zone, with 200 fires.

Regarding topographic patterns of ignition density during the period 1986–2003, we calculated the triennial density of anthropogenic and natural fires in each elevation zone and aspect class for each physiographic province. The density calculations were based on the amount of land in each topographic category as computed from DEMs overlaid with federal land boundaries using ArcGIS 9.0 (ESRI, 2004). Non-parametric Friedman's tests and Nemenyi multiple comparison tests (Zar, 1999) were used to make the comparisons, because the fire density distributions could not be transformed to have normal distributions and homogeneous variances in all cases.

To evaluate natural fire and lightning occurrence, we used a *G*-test of correspondence with Williams' correction (Sokal and Rohlf, 1995) to determine whether the proportion of fires ignited by lightning between 1970 and 2003 was similar among the provinces. To test for differences in lightning density among the physiographic provinces from 1995 to 2003 (the period with lightning flash records), we calculated annual lightning flash density (flashes/1000 km^2) for each province and applied randomized block ANOVA; no transformation was necessary. Finally, a *G*-test was used to determine whether variations in natural fire frequency among the provinces corresponded to the pattern of lightning flashes among the provinces between 1995 and 2003.

To address seasonality of fire in the three physiographic provinces, the monthly number of fires was tallied over 1970–2003. *G*-tests were used to test whether the proportion of anthropogenic or natural fires that occurred each month was similar among the provinces.

To test for differences in fire size among the provinces for the period 1970–2003, we used Kruskal-Wallis tests and Nemenyi multiple comparison tests (Zar, 1999). To calculate the length of the fire cycle, we computed the reciprocal of the average proportion of the total land area burned annually in each province between 1970 and 2003 (Heinselman, 1973).

RESULTS

Spatial Patterns of Ignition Density

Ignition density differed among the provinces for both anthropogenic fires (ANOVA, $F_{2,20} = 63.617$, $p < .01$) and natural fires (ANOVA, $F_{2,20} = 44.332$, $p < .01$). The highest densities occurred in the Blue Ridge and the lowest densities on the Appalachian Plateau (Figs. 3A and 3B). Confining the analysis to the 458–762 m elevation zone revealed that anthropogenic fire density did not differ among the physiographic provinces (ANOVA, $F_{2,10} = 3.679$, $p > .05$; Fig. 3C), but that the density of natural fires was different (ANOVA, $F_{2,10} = 37.275$, $p < .01$; Fig. 3D). Likewise, anthropogenic fire density in the 763–1067 m zone did not differ between the Appalachian Plateau and the Ridge and Valley (ANOVA, $F_{1,5} = 5.685$, $p > .05$; Fig. 3E); the Blue Ridge was excluded from the analysis because of variance

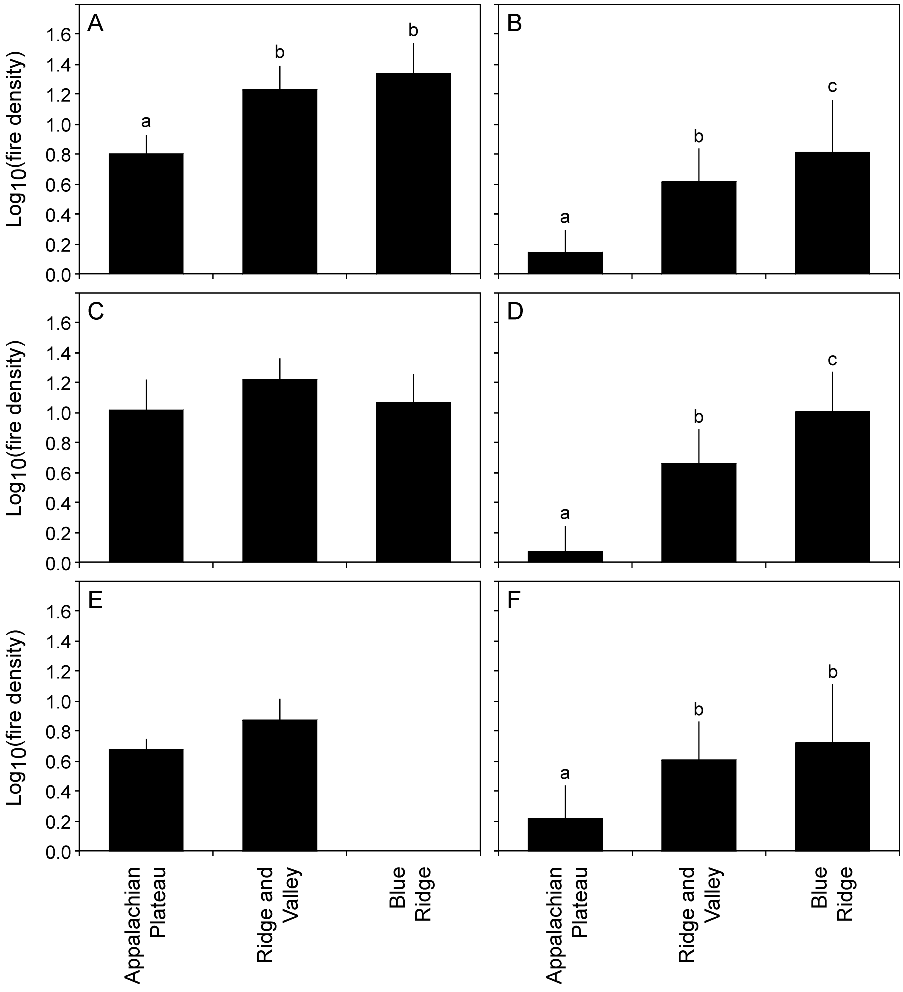

Fig. 3. Mean fire density (log-transformed) for all anthropogenic and natural fires in each physiographic province (A, B), for anthropogenic and natural fires that occurred within the 458–762 m elevation zone (C, D), and for anthropogenic and natural fires that occurred within the 763–1067 m elevation zone (E, F). Provinces labeled with different letters had significantly different ignition densities. The error bars depict standard deviation.

heterogeneity. For natural fires, the pattern in the 763–1067 m zone also was similar to that in the 458–762 m zone (ANOVA, $F_{2,10} = 6.890$, $p < .05$; Fig. 3F), except that the Tukey test did not reveal a difference between the Ridge and Valley and the Blue Ridge.

The density of anthropogenic ignitions exhibited significant elevational variations in each physiographic province (Friedman's test for the Appalachian Plateau, $\chi^2 = 16.243$, $df = 4$, $p < .01$; for the Ridge and Valley, $\chi^2 = 7.916$, $df = 4$, $p < .01$; for the Blue Ridge, $\chi^2 = 9.400$, $df = 3$, $p < .05$). Generally, fire density declined from

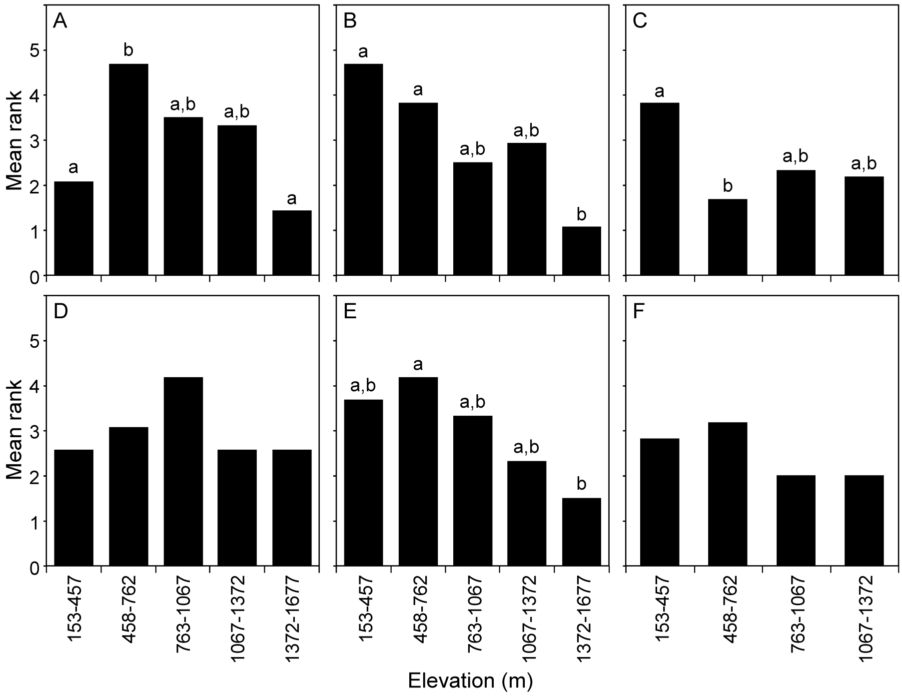

Fig. 4. Elevational patterns of anthropogenic fire (A–C) and natural fire (D–F) for the Appalachian Plateau, the Ridge and Valley, and the Blue Ridge physiographic provinces. The Friedman's test, which was used to compare ignition density among the elevation zones, is a non-parametric technique based on ranking the observations. An elevation zone with higher mean rank had a higher ignition density than a zone with lower mean rank. Elevation zones labeled with different letters had significantly different ignition densities ($p < .05$).

low to high elevations, but little fire activity occurred in the lowest elevation zone in the Appalachian Plateau (Figs. 4A–4C).

Natural ignition density differed among the elevation zones on the Appalachian Plateau (Friedman's test, $\chi^2 = 11.826$, $df = 4$, $p < .05$) and the Ridge and Valley ($\chi^2 = 12.073$, $df = 4$, $p < .05$), but not the Blue Ridge ($\chi^2 = 4.071$, $df = 3$, $p > .05$; Figs. 4D–4F). The peak in natural fire activity on the Appalachian Plateau was at moderate elevations (Fig. 4D), but Nemenyi tests did not detect differences between specific elevation zones. In the Ridge and Valley, natural ignition density declined toward higher elevations (Fig. 4E).

Aspect did not exhibit a statistically significant influence on the density of anthropogenic ignitions in any of the physiographic provinces (Friedman's test for the Appalachian Plateau, $\chi^2 = 11.960$, $df = 7$, $p > .05$; for the Ridge and Valley, $\chi^2 = 9.889$, $df = 7$, $p > .05$; for the Blue Ridge, $\chi^2 = 8.851$, $df = 7$, $p > .05$; Figs. 5A–5C). However, the pattern for natural ignitions was stronger (Friedman's test for the Appalachian Plateau, $\chi^2 = 14.797$, $df = 7$, $p < .05$; for the Ridge and Valley, $\chi^2 = 16.447$, $df = 7$, $p < .05$; for the Blue Ridge, $\chi^2 = 16.844$, $df = 7$, $p < .05$; Figs. 5D–5F). Nemenyi tests yielded significant differences only for the Blue Ridge, where the

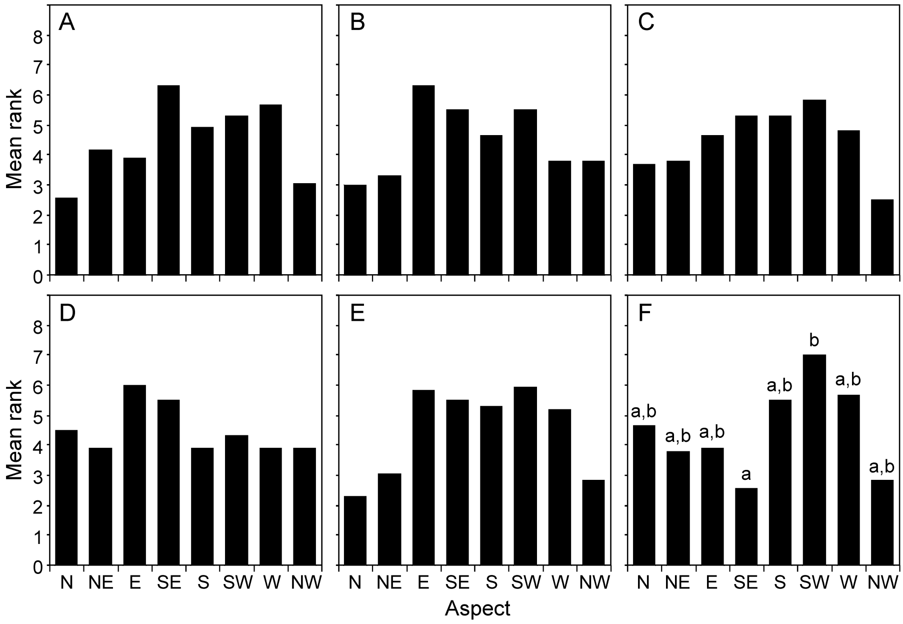

Fig. 5. Variations in the density of anthropogenic fire (A–C) and natural fire (D–F) by aspect for the Appalachian Plateau, the Ridge and Valley, and the Blue Ridge physiographic provinces. The Friedman's test, which was used to compare ignition density among the aspects, is a non-parametric technique based on ranking the observations. An aspect with higher mean rank had a higher ignition density than an aspect with lower mean rank. Aspects labeled with different letters had significantly different ignition densities ($p < .05$).

southwest-facing slopes had a significantly higher ignition density than southeast-facing slopes. In general, ignition density in the three physiographic provinces tended to peak on south-, east-, or west-facing slopes, and to decline toward north-, northeast-, or northwest-facing slopes; however, the trends were not identical among the provinces.

The Incidence of Natural Fires and Lightning in the Three Physiographic Provinces

The provinces differed in the proportion of fires caused by lightning (*G*-test, $G_{adj} = 64.621$, $df = 2$, $p < .01$). Between 1970 and 2003, natural fires comprised 7.5% of all fires on the Appalachian Plateau, 17.6% of all fires in the Ridge and Valley, and 24.3% of all fires in the Blue Ridge.

During the period 1995–2003, the mean annual density of lightning flashes was 1886 ± 725 flashes/1000 km^2 (mean ± SD) for the Appalachian Plateau, 1910 ± 559 flashes/1000 km^2 for the Ridge and Valley, and 2261 ± 665 flashes/1000 km^2 for the Blue Ridge. The lightning flash densities for the three provinces were similar (ANOVA, $F_{2,16} = 2.996$, $p > .05$). However, because of variations in natural fire activity among the provinces (cf. Fig. 3B), the number of natural fires in each province between 1995 and 2003 did not correspond to the number of lightning flashes

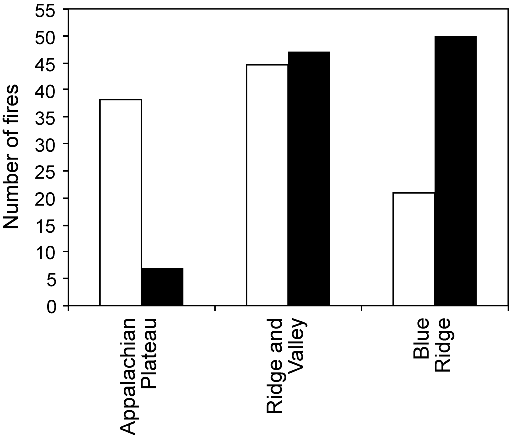

Fig. 6. Comparison of the expected number of natural fires (white bars) with the observed number (black bars) in each province, based on the number of lightning flashes.

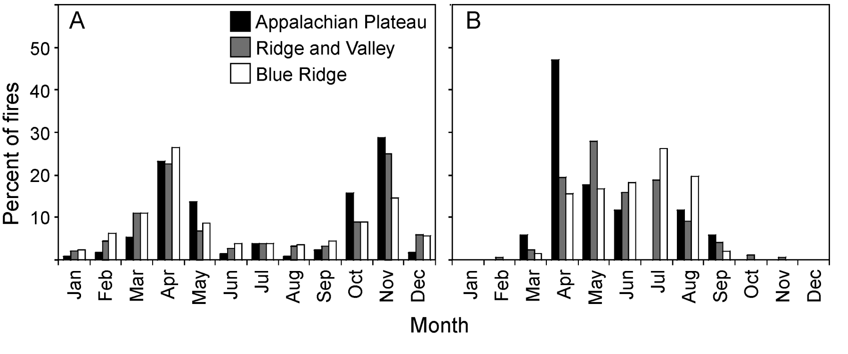

Fig. 7. Percent of anthropogenic fires (A) and natural fires (B) that occurred each month in each physiographic province.

(*G*-test, $G_{adj} = 67.188$, $df = 2$, $p < .01$; Fig. 6). The Appalachian Plateau had less fires than expected on the basis of lightning flashes, while the Blue Ridge had more than expected.

Fire Seasonality in the Three Physiographic Provinces

The frequency of anthropogenic fires had a bimodal distribution in all provinces (Fig. 7A). However, the monthly proportion of fires differed among the provinces (*G*-test, $G_{adj} = 68.534$, $df = 22$, $p < .01$). On the Appalachian Plateau, the fall burning season was more active than the spring. In contrast, the Blue Ridge had a higher proportion of fires in the spring, while the Ridge and Valley exhibited a more even distribution of fires between spring and fall. Also, the Appalachian Plateau had less fire activity during the winter and summer months than the other two provinces, where fire was not confined as strongly to the spring and fall burning seasons.

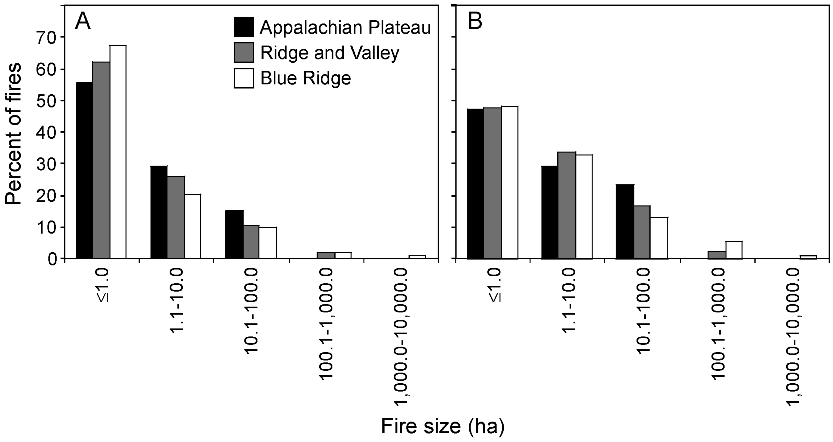

Fig. 8. Fire size distribution for anthropogenic fires (A) and natural fires (B) in each physiographic province.

Natural fires peaked during spring or summer (Fig. 7B). Again, the monthly pattern differed between the provinces (*G*-test, $G_{adj} = 14.214$, $df = 5$, $p < .05$), with the peak in fire activity occurring earlier in the year for the Ridge and Valley than for the Blue Ridge. The Appalachian Plateau was excluded from this analysis because the dataset was too sparse. Also, only the primary months of the natural fire season (April–September) were included in the analysis.

Patterns of Fire Size in the Three Physiographic Provinces

The size of most fires was small in each province, as shown by the small median fire sizes and the positively skewed fire size distributions (Table 1; Fig. 8). The size of anthropogenic fires differed among the provinces (Kruskal-Wallis test, $\chi^2 = 14.099$, $df = 2$, $p < .01$). Specifically, anthropogenic fires were smaller in the Blue Ridge than the other two provinces (Nemenyi multiple comparison tests, $p < .01$), but the size of natural fires did not differ among the provinces (Kruskal-Wallis test, $\chi^2 = 0.186$, $df = 2$, $p > .05$).

Regardless of the patterns for median fire size or the rank of fire sizes, a consideration of maximum fire size is essential because of the disproportionate influence of large fires on the fire cycle. For both anthropogenic and natural fires, the maximum fire size and the skewness of the fire size distribution were greatest in the Blue Ridge, moderate in the Ridge and Valley, and least on the Appalachian Plateau (Table 1). The importance of the largest fires for the fire regime is underscored by the small proportion of large fires that is responsible for most of the area burned. Of the 252 fires that occurred on the Appalachian Plateau between 1970 and 2003, the 13 largest fires (5.2% of the fires) accounted for half the area burned. These 13 fires ranged in size from 20 to 96 ha. In the Ridge and Valley, 9 of the 1043 fires (0.9% of fires), ranging from 223 to 1764 ha, were responsible for slightly over half (51%)

Table 1. Characteristics of Fire Size in the Three Physiographic Provinces of the Central Appalachian Mountains

Parameter	Physiographic province		
	Appalachian Plateau	Ridge and Valley	Blue Ridge
Anthropogenic fires			
Median fire size (ha)	0.8	0.4	0.4
Mean rank of fire size	844.9[a]	792.1[a]	720.7[b]
Maximum fire size (ha)	96	1,764	6,484
Skewness	4.4	13.7	14.9
Natural fires			
Median fire size (ha)	1.6	1.2	1.2
Mean rank of fire size	177.5[a]	174.1[a]	170.0[a]
Maximum fire size (ha)	57	223	1,188
Skewness	2.7	5.5	7.8

[a,b]Within a row, fire size differed significantly between a province labeled with an "a" and a province labeled with a "b" (Kruskal-Wallace test and Nemenyi multiple comparison test, $p < .05$). A province with higher mean rank had larger fires than a province with lower mean rank.
Source: Based on wildland fire data for the period 1970–2003.

Table 2. Fire Cycle (Years) for the Three Physiographic Provinces of the Central Appalachian Mountains

	Physiographic province		
	Appalachian Plateau	Ridge and Valley	Blue Ridge
Anthropogenic fires	12,216	1,472	347
Natural fires	96,637	9,461	1,560
All fires combined	10,845	1,274	284

Source: Based on wildland fire data for the period 1970–2003.

of the area burned. In the Blue Ridge, only 3 of the 606 fires (0.5% of all fires), varying between 1811 and 6488 ha, comprised over half (52%) of the total area burned.

Fire Cycle in the Three Physiographic Provinces

Anthropogenic and natural fire cycles during 1970–2003 were long on the Appalachian Plateau, moderate in the Ridge and Valley, and relatively short in the Blue Ridge (Table 2). The natural fire cycle was longer than the anthropogenic fire cycle in all three provinces during this recent period.

DISCUSSION

Spatial Patterns of Ignition Density

The relatively low density of anthropogenic ignitions on the Appalachian Plateau conforms to our initial expectations, and is consistent with the cool, moist climate and low vegetation flammability on the plateau. To a large extent, these climatic and fuel conditions are a consequence of the high elevation of the plateau landscape. Our analyses of ignition density within single elevation zones controlled for these elevational effects to expose the influences of other potential factors (e.g., population density, accessibility) that also might contribute to differences in ignition density among the provinces. However, the influences of such factors were not strong enough to detect, i.e., the density of anthropogenic ignitions did not differ significantly among provinces within single elevation zones. Therefore, it appears that the moisture and fuel conditions associated with high elevations are the primary reason for the relatively low density of anthropogenic ignitions on the Appalachian Plateau during 1970–2003.

Regarding natural ignitions, the low density on the Appalachian Plateau matched our expectations, but the high density on the Blue Ridge did not. The heterogeneity among physiographic provinces does not appear simply to reflect elevation differences, because the pattern also emerged when single elevation zones were considered. Three climatic factors have gradients across the region that may help explain the pattern of natural fire activity. The first is precipitation seasonality. The lack of a precipitation peak during summer (the peak of the natural fire season) in the Blue Ridge means that average summer precipitation is no greater for weather stations along the Blue Ridge than for many stations in the Ridge and Valley, and it is considerably less than for stations on the Appalachian Plateau (NCDC, 2002). Second, although total annual rainfall amounts are similar for the Appalachian Plateau and the Blue Ridge, the former has a regime of frequent, low-intensity precipitation events, while the latter has less frequent events that deliver heavy precipitation (Konrad, 1994; NCDC, 2000). The Ridge and Valley appears to have intermediate frequency and intensity. The infrequency of precipitation in the Blue Ridge may favor the development of relatively long dry periods and, hence, a high probability of ignition. Third, relative humidity is higher over the Appalachian Plateau than the Ridge and Valley and the Blue Ridge during the late spring/summer period when natural fires are most common (NCDC, 2000).

Topographic variations in ignition density showed patterns that generally conformed to our expectation that dry sites would experience more fires than moist sites. Fire density generally declined with increasing elevation, regardless of ignition source, but the pattern was stronger in the Ridge and Valley than elsewhere. It was also more pronounced for anthropogenic fires than natural fires. Low ignition density in the lowest elevation zone of the Appalachian Plateau may reflect low flammability along the mesic valley bottoms, difficult human access to these sites, and their limited occurrence (only 0.4 % of the total land area on the plateau). That natural ignition density did not peak at high elevations, despite the tendency for lightning to strike preferentially along ridgetops (cf. Whiteman, 2000), suggests that fuel moisture and flammability impose greater constraints on fire activity than does lightning occurrence. Additionally, many ridgetops are found at low elevations and may provide abundant sites favorable for lightning strikes (Barden and Woods, 1974).

Natural Fires and Lightning

The spatial variations in natural fire activity, despite similar lightning flash density, implies that lightning occurred during more favorable burning conditions in the eastern part of the study area than in the west. The concurrence of lightning and dry fuels is most probable when convection develops in humid air under synoptic conditions of high pressure (Nash and Johnson, 1996), a combination that apparently occurs more frequently in the Blue Ridge and the Ridge and Valley than on the Appalachian Plateau. The Blue Ridge is a particularly favorable environment for the initiation of convection (Konrad, 1994; Phillips, 2001), and it impedes penetration of unstable Atlantic air. Consequently the Appalachian Plateau and the Ridge and Valley may be less often subjected to lightning during the dry conditions that would favor burning.

Fire Seasonality

The seasonal distribution of anthropogenic fires largely reflects the suitability of fuels for burning (Lafon et al., 2005). The peaks in fire activity during spring and fall correspond with heavy fuel accumulation (especially leaf litter) and dry, windy weather. Spatial variations in the peak burning season likely reflect: (1) relatively low precipitation during fall on the Appalachian Plateau (Fig. 2A); (2) relatively high precipitation during fall on the Blue Ridge (Fig. 2C); and (3) heavy snow cover that persists longer into spring on the Appalachian Plateau than elsewhere. Conditions appear to be too snowy and/or moist on the Appalachian Plateau during winter and summer for a substantial number of fires to burn outside the peak fire seasons.

For natural fires, the springtime maximum in the Ridge and Valley, prior to the peak in lightning activity, is consistent with dry fuel conditions associated with high winds and low humidity (Lafon et al., 2005). The midsummer peak in the Blue Ridge does not correspond with such circumstances, but, surprisingly, with the lowest winds and highest humidity of the year. This midsummer burning probably reflects the favorability of the Blue Ridge for scattered thunderstorm development during otherwise rain-free periods. Another consideration is the lack of a summer rainfall maximum; in fact, August is one of the driest months in the Blue Ridge.

Fire Size

The size of anthropogenic fires was smaller in the Blue Ridge than the other provinces, but the median fire size in all three provinces was quite small, and the most important distinction among provinces was the gradient in the maximum fire size and the skewness of the fire-size distribution. As in other fire regimes (cf., Pyne, 1982), a handful of large fires is responsible for most of the area burned and is the predominant control on the fire cycle. The largest fires typically occur under hazardous burning conditions, such as drought and/or high winds, when fires can elude control (Lafon et al., 2005). The modest size of the largest fires on the Appalachian Plateau suggests that difficult fire-suppression conditions are rarely encountered, probably because of the wet climate and limited fuel flammability.

The disparity in maximum fire size between the Ridge and Valley and the Blue Ridge was not expected on the basis of climate and fuels. It may be related, at least partially, to influences of landscape structure on fire spread (cf. Turner et al., 1989). Most fire lines are constructed in bulldozer-accessible sites, especially ridgetops, and consequently the larger scale of landforms on the Blue Ridge would permit fires to spread farther before encountering fire lines, streams, or other barriers.

Fire Cycle

The differences in fire size distribution contributed to spatial variations in the fire cycle. Fire was of little consequence as a disturbance agent on the Appalachian Plateau during the study period, but it played a more important role in the other provinces. The fire cycle for the Blue Ridge is short enough that fire could be expected within the lifespan of the dominant tree species, assuming the continuation of the 1970–2003 fire regime over a long period. Therefore, fire may be common enough to exert a considerable influence on forest succession in the Blue Ridge, despite the prevention and suppression efforts that have reduced fire activity relative to historic levels. When interpreting fire cycle calculations, an important consideration is that, although fire cycle is computed on the basis of the entire area of each physiographic province, some vegetation types within these heterogeneous landscapes undoubtedly burn more frequently than others. Another consideration is that fire cycles do not remain constant over time. The long fire cycles calculated for 1970–2003 reflect the influence of fire control efforts.

CONCLUSIONS AND IMPLICATIONS

Our study indicates that in recent years the incidence of fire varied spatially over the central Appalachian region. In most respects, the Appalachian Plateau was the least fire-prone environment, and the Blue Ridge was the most fire prone. Further, low elevations tended to have greater fire activity than high elevations, but the pattern was more pronounced in the Ridge and Valley than elsewhere, and also was stronger for anthropogenic fires than natural fires. These spatial variations have implications for vegetation patterns and ecosystem management. Three considerations seem particularly important: First, at current levels, the influence of wildland fires on Appalachian ecosystems declines from east to west, and from low to high elevations. Whether similar gradients existed prior to fire suppression/prevention is an important question. Second, the east–west gradient in maximum fire size is important not only for its control on fire cycle but also for which species colonize burned sites. Third, because of its high incidence of natural fires, the Blue Ridge appears to provide the best opportunities for implementing WFU. Potential WFU areas in the Blue Ridge include Shenandoah National Park and the Saint Marys and James River Face Wildernesses on the George Washington and Jefferson National Forests (Fig. 1). Some of the extensive national forest tracts in the Ridge and Valley, but not the Appalachian Plateau, also may be appropriate for WFU. WFU alone probably cannot be relied upon to restore fire-dependent ecosystems, however, because (1) landscape fragmentation and fire suppression outside the WFU zones would impede the spread of fire into WFU areas (cf. Duncan and Schmalzer, 2004) and (2) the historic regime under which Appalachian vegetation developed likely was influenced by anthropogenic ignitions as well as natural fires.

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