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RESEARCH ARTICLE

Climatic and topographic controls on patterns of fire in the southern and central Appalachian Mountains, USA

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Abstract Climate and topography are two important controls on spatial patterns of fire disturbance in forests globally, via their influence on fuel moisture and fuel production. To assess the influences of climate and topography on fire disturbance patterns in a temperate forest region, we analyzed the mapped perimeters of fires that burned during 1930–2003 in two national parks in the eastern United States. These were Great Smoky Mountains National Park (GSMNP) in the southern Appalachian Mountains and Shenandoah National Park (SNP) in the central Appalachian Mountains. We conducted GIS analyses to assess trends in area burned under differing climatic conditions and across topographic gradients (elevation, slope position, and aspect). We developed a Classification and Regression Tree model in order to further explore the interactions between topography, climate, and fire. The results demonstrate that climate is a strong driver of both spatial and temporal patterns of wildfire. Fire was most prevalent in the drier SNP than the wetter GSMNP, and during drought years in both parks. Topography also influenced fire occurrence, with relatively dry south-facing aspects, ridges, and lower elevations burning most frequently. However, the strength of topographic trends varied according to the climatic context. Weaker topographic trends emerged in the drier SNP than GSMNP, and during low-PDSI (dry) years than high-PDSI (wet) years in both parks. The apparent influence of climate on the spatial patterning of fire suggests a more general concept, that disturbance-prone landscapes exhibit weaker fine-scale spatial patterning of disturbance than do less disturbance-prone landscapes.

Keywords Fire ecology · Forest disturbance · Climate · Topography · Fire perimeters · Spatial pattern · Great Smoky Mountains National Park · Shenandoah National Park · Classification and regression tree model

Introduction

Forest disturbance is an important source of landscape pattern and vegetation heterogeneity (Foster et al. 1998). Fire disturbance is a particularly important driver of vegetation patterns. Research on landscape-scale patterns of fire in the western U.S. have led to insights on disturbance heterogeneity and its role in the spatial arrangement of ecological communities (Turner et al. 1994; Brown et al. 1999). In the interest of linking landscape pattern with process, a central goal in landscape ecology, it is important to assess the

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underlying controls on patterns of fire, which in turn influence vegetation patterns. Climate and topography have been demonstrated as key drivers of fire disturbance patterns (Swetnam and Betancourt 1998; Taylor and Skinner 1998). However, fire does not necessarily respond consistently to these controls across space and time. Climatic and topographic controls on fire may interact with each other (Rollins et al. 2002), further complicating our understanding of the underlying processes that drive fire disturbance patterns. Additionally, the majority of research on spatial patterns of fire has been carried out in the western U.S. in dry ponderosa pine (*Pinus ponderosa*) forests or in wet subalpine and boreal forests. The mixed deciduous forests of the eastern U.S. may represent a climatic middle ground that is not well characterized by fire behavior examined in previous research. In this study, we analyzed mapped fire perimeters from two national parks in the southern and central Appalachian Mountains during the twentieth century to assess climate and topography as controls on spatial patterns of fire and whether region-scale spatial variations in climate influence the interaction between fire and topography at a finer scale.

Climate contributes to fire regimes in two primary ways, by influencing vegetation productivity and fuel accumulation and by controlling the frequency of weather conducive to fire initiation and spread (Baker 2003). Regional climate acts as a top-down control on fire, influencing fire regimes at broad spatial scales (Heyerdahl et al. 2001; Cyr et al. 2007). Regional climatic gradients have been linked to spatial variations in fire frequency, size, shape, and intensity (Parisien et al. 2006). Temporal fluctuations in climate also have been related to shifts in fire frequency and area burned, but the climatic conditions that promote fire vary by region and forest type (e.g. Swetnam and Betancourt 1998; Lafon et al. 2005; Sibold and Veblen 2006; Drever et al. 2008). In lower-elevation, dry ponderosa pine forests of western North America, for example, large fire years often occur during droughts preceded by wet years. The preceding moisture enhances the production of fine fuels that facilitate fire spread (Grissino-Mayer et al. 2004). In contrast, short windows of dry, windy weather are the main requirement for the initiation and spread of fire in mesic subalpine forests of the western U.S. (Baker 2003). These forests contain abundant fuels because of the moist conditions; therefore, anomalous antecedent wetness is not a prerequisite for extensive burning. Some previous work (Takle et al. 1994; Lafon et al. 2005) suggests a similar relationship in the humid temperate forests of the eastern U.S., where fuel productivity should be high every year but fuel moisture could restrict burning.

Topography acts as a local-scale control on many types of disturbance (e.g. Zhang et al. 1999; Boose et al. 2004; Stueve et al. 2007). Topographic variation (e.g. aspect, slope position, and elevation) influences precipitation, runoff, temperature, wind, and solar radiation, which in turn affect flammability through fuel production and moisture (Daly et al. 1994; Dubayah and Rich 1995). Spatial patterns of fire have been linked to topographic features in portions of the western U.S. (Taylor and Skinner 1998; Rollins et al. 2002; Howe and Baker 2003). However, topography appears to play a limited role in other locations (Kafka et al. 2001; Bigler et al. 2005; Schulte et al. 2005). One potential explanation for these seemingly contradictory findings is that climate modulates topographic influences on fire. For example, large, high-intensity wildfires occurring during drought conditions have been shown to exhibit weaker topographic control than small disturbances of lower intensity (Parker and Bendix 1996; Moritz 2003; Mermoz et al. 2005). A landscape in a generally more fire-prone climatic setting, therefore, might have weaker topographic patterns of fire than a landscape in a less fire-prone environment. Topographic patterns of fire also might vary temporally as climates shift over time and render a landscape more or less prone to disturbances. Here, we examine whether the topography-fire interaction changes along a regional climatic gradient and as a consequence of interannual climatic variations. We expect that in the humid eastern U.S., the driest locations and driest years are most fire-prone and that topographic patterns are less pronounced under dry conditions than under wet conditions.

Dendroecological research has demonstrated the prevalence of fire in forests of the Appalachian Mountains for the last several centuries, prior to the fire protection era during the twentieth century (Hoss et al. 2008; Aldrich et al. 2010). Additionally, charcoal records indicate the presence of fire in these forests for the past 3–4,000 years (Delcourt and Delcourt 1998; Fesenmyer and Christensen 2010). However, relatively little research has been conducted on the spatial patterns of fire in humid temperate forests (Odion et al.

2004; Weisberg 2004; Wimberly and Reilly 2007). Additional research is needed to determine how topography influences fire at different points along a climatic moisture gradient in order to further develop our general understanding of the factors that drive spatial patterns of fire.

In this paper we examine influences of climate and topography on patterns of fire using digital fire perimeter maps and climatic and terrain data from two national parks in the Appalachian Mountains of eastern North America. Digital fire perimeters were available for Great Smoky Mountains National Park (GSMNP) in the southern Appalachian Mountains and Shenandoah National Park (SNP) in the central Appalachian Mountains. Orographic influences and distance to moisture sources impose on this humid area a regional (southwest-to-northeast) precipitation gradient that results in GSMNP having a more humid climate than SNP. The hypotheses that guided our study are:

1. Climate imposes regional-scale pattern on the occurrence of fire. Therefore the relatively dry SNP should have a higher density of fires, larger fires, and a shorter fire cycle than GSMNP. Likewise, we expect that fire activity is related to temporal variations in climate, with more burning in dry years than wet years in both locations.
2. Topography imposes local-scale pattern on the occurrence of fire. We expect that fire will be most common in both study sites on dry south-facing slopes, ridgetops, and at low elevations.
3. Regional climate and local topography interact such that topographic patterns of fire are more pronounced in a less fire-prone landscape than a more fire-prone landscape. Therefore, we expect that fires are more strongly confined to dry topographic settings in the relatively wet GSMNP than in the drier SNP.
4. The fire-topography association is also influenced by temporal climatic variability. We hypothesize that topography exerts a stronger influence on fire occurrence during wet years than dry years in both national parks. Additionally, because of the moist conditions that accompany lightning, we expect that lightning-ignited fires are more strongly confined to dry topographic settings than are anthropogenic fires, which often are ignited during dry, windy weather.

Study areas

Great Smoky Mountains National Park

GSMNP contains 209,000 ha in the southern portion of the Appalachian Mountains (35°37′N, 83°31′W; Fig. 1). Located on the border between Tennessee and North Carolina, the park lies within the Unaka Range, a part of the Southern Section of the Blue Ridge Physiographic Province, and ranges in elevation from 256 to 2,025 m (Fenneman 1938). The southern Appalachian Region is classified as a humid subtropical climate with cold winters and warm summers (Lutgens and Tarbuck 2007). The greatest amount of precipitation occurs in the summer months, as revealed by climatic data for Gatlinburg, Tennessee, adjacent to the park (Fig. 2). Annual precipitation (P) at Gatlinburg exceeds potential evapotranspiration (PET, calculated using the method of Thornthwaite (1948)) by 732 mm, and P/PET = 1.82.

Climate varies significantly within the boundaries of GSMNP, as precipitation increases and temperature decreases with elevation (Shanks 1954). The vegetation is classified as Appalachian oak (*Quercus*) (Stephens et al. 1993). Oak-dominated forests cover the broad submesic to subxeric portions of the landscape. Pines (*Pinus*) occupy dry ridgetops and south-facing slopes, while mesophytic conifers and hardwoods inhabit the lower slopes, valleys, ravines, and high elevations.

Shenandoah National Park

SNP encompasses 80,000 ha in the central Appalachian Mountains (38°32′N 78°21′W; Fig. 1). The park lies within the Northern Section of the Blue Ridge Physiographic Province in Virginia and ranges in elevation from 150 to 1,234 m. SNP also has a humid subtropical climate but receives less precipitation than GSMNP (Fig. 2). At nearby Luray, Virginia, P exceeds PET by 328 mm, and P/PET = 1.32. The vegetation in SNP is classified as Appalachian oak (Stephens et al. 1993).

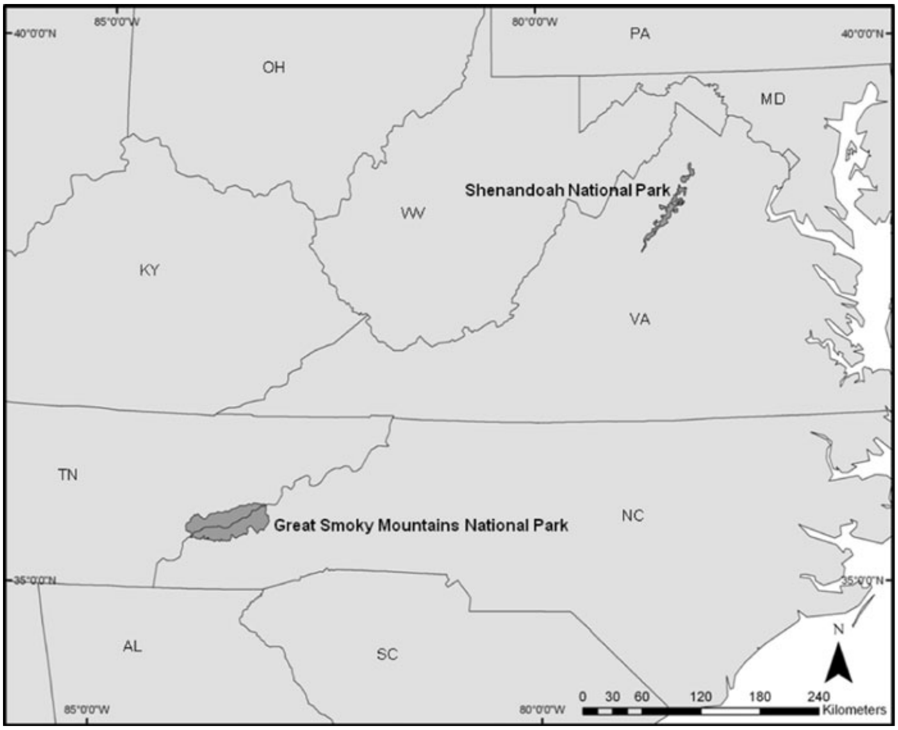

Fig. 1 Locations of Great Smoky Mountains National Park and Shenandoah National Park in the southern and central Appalachian Mountains, USA

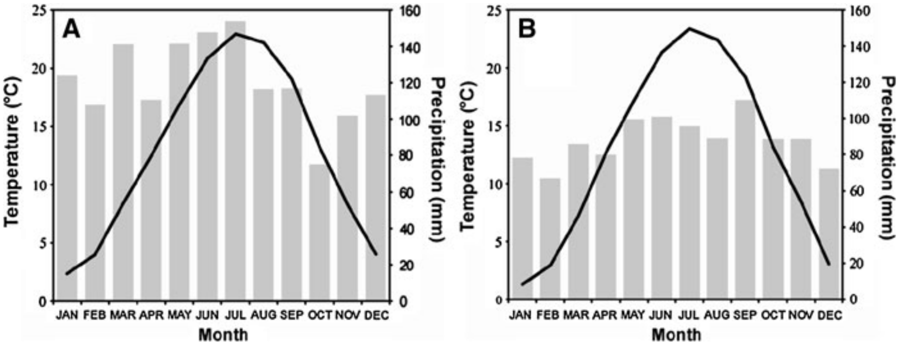

Fig. 2 Mean monthly climate average for each park NCDC (2002), based on data (1971–2000) from local climate stations **A** Gatlinburg, Tennessee (elevation 443 m, adjacent to GSMNP), and **B** Luray, Virginia (elevation 427 m, adjacent to SNP). *Bars* are precipitation and *lines* are temperature

Methods

Fire perimeter data

Following the implementation of fire suppression in the early twentieth century, the spatial extent of wildfires was mapped within the boundaries of both GSMNP and SNP. We obtained digitized fire perimeters for 1930–2003 from each national park. GSMNP records included 744 fires that burned 10,497 ha, and SNP recorded 573 fires that burned 31,610 ha. In GSMNP, anthropogenic ignitions accounted for 643 fires that burned 9,978 ha, and lightning ignited 101 fires that burned 519 ha. SNP maps did not record fire cause consistently. Resource management burns intentionally ignited by park management were excluded from analysis. The fire records did not include perimeters for small fires

(<1 ha); ignition points were recorded instead. We therefore included ignition points in calculations of the number of fires and area burned, but not in the analyses of spatial patterns of fire. Their exclusion should have little influence on the results of the spatial analyses because the small fires accounted for less than 0.5% of the total area burned in both parks. A number of the fires that occurred in SNP were not mapped, but the size of the burned area was estimated. These fires could not be used for topographic analysis, but were included in all other calculations.

For the examination of topographic patterns of fire, we limited our analysis within GSMNP to areas below 1,400 m because few fires burned above this elevation (portions of 19 fires, with a total area of 74.5 ha, <0.5% of total area burned). The exclusion of upper elevations in GSMNP also made the two study areas more similar in terms of elevation range. Finally, the digital fire maps included some fires that burned across park boundaries and some fires that occurred entirely outside of the park boundaries. Therefore we used the digitized park boundaries obtained from the National Park Service to clip the fire maps, removing any areas that burned outside the park. Digital maps of individual fires were then combined to create a map of cumulative fire occurrence since 1930 (Fig. 3).

Inherent limitations and sources of bias exist that must be considered when using historical fire perimeter records. Issues with size bias, incomplete recording, limited temporal availability, and mapping inaccuracy have been identified as potential sources of error (Morgan et al. 2001; Shapiro-Miller et al. 2007). The fire records in both parks were recorded during an era of active fire suppression, which affected the extent and spatial pattern of the fires. However, the records provide valuable information on spatial patterns of fire in this region that are not available from other sources. Previous work reveals that climatic and topographic influences on fire can be discerned even on fire-suppressed landscapes (Rollins et al. 2002; Mitchener and Parker 2005; Lafon and Grissino-Mayer 2007).

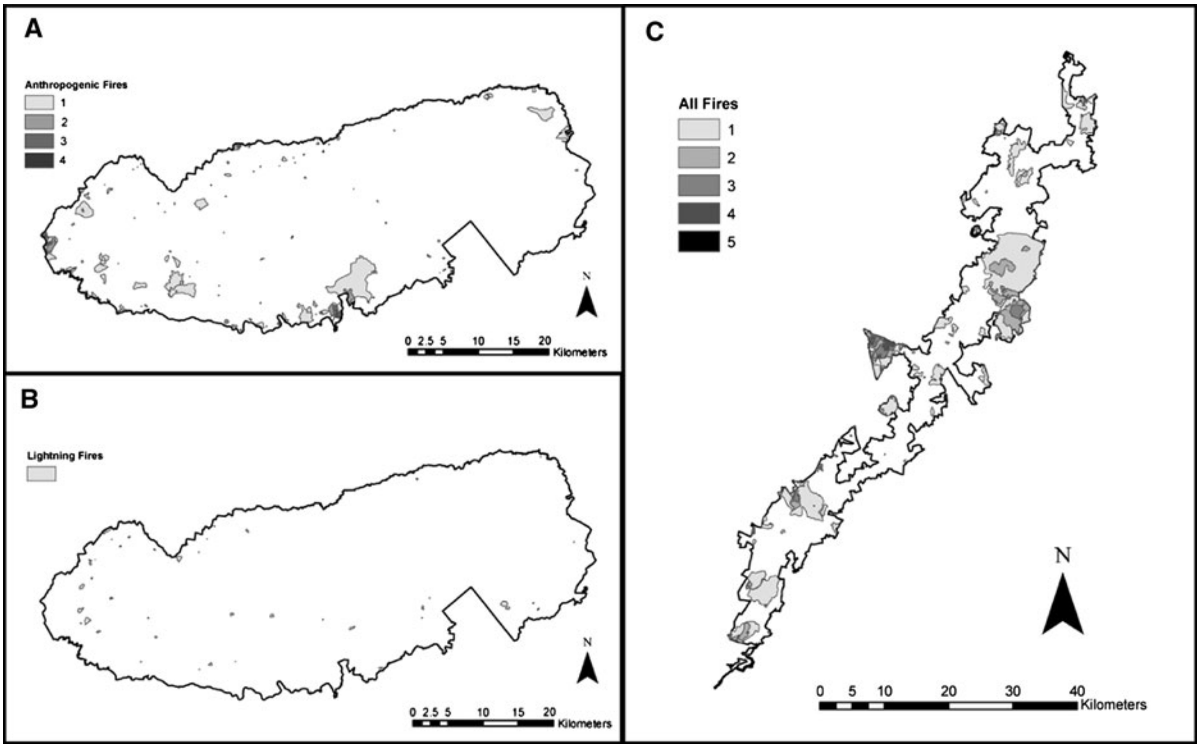

Fig. 3 Mapped fire perimeters from 1930–2003 for **A** anthropogenic fires and **B** lightning fires in Great Smoky Mountains National Park and **C** all fires in Shenandoah National Park. *Darker grey* indicates areas that burned multiple times

Climate data

As a record of temporal variations in climate, monthly Palmer Drought Severity Index (PDSI) values were used for the period of mapped fires, obtained from the National Oceanic and Atmospheric Administration National Climatic Data Center (NCDC 2002). PDSI is a soil moisture/water balance index that accounts for moisture conditions during antecedent months. It is derived from a time series of daily temperature and precipitation, and available soil water content (Palmer 1965). PDSI commonly ranges from four to negative four, with positive values indicating high moisture conditions, negative values indicating drought, and zero indicating average moisture conditions. PDSI values from Virginia Climate Division 4 were used as a record of drought in SNP, and PDSI values from Tennessee Climate Division 1 and North Carolina Climate Division 1 were averaged to provide a record of drought in GSMNP.

Topographic data

We obtained Digital Elevation Models (DEMs) at 10 m resolution for each park, including a 1 km buffer around the park boundary. We used the DEMs to derive slope aspect using the ArcGrid command "slope" (ESRI 2006). Aspect values (1–360°) were combined into eight aspect classes. Slope position classes were derived using the GIS application LANDFORM (Klingseisen et al. 2008), which classified the landscape into four categories in increasing order of topographic wetness: ridge, upper slope, lower slope, and bottom. Finally, the DEMs were used to partition the landscape into 200 m elevation classes. Each of the derived topographic layers was then clipped using the park boundaries and the upper elevation limit in GSMNP.

Data analysis procedures

Unclipped fire perimeters were used to calculate mean fire size for each park. In order to facilitate comparison between the two parks, fire perimeters were then clipped along the park boundaries and used to calculate the mean annual fire density, mean annual area burned, and fire cycle for the area within each park boundary. Mean annual fire density and mean annual area burned were corrected for park size and expressed as area burned/km^2. Fire cycle is the time required to burn an area equivalent to the area of the entire park, and is calculated as period of record × total area of park/total area burned during the period of record (Heinselman 1973). Mann–Whitney tests were used to assess differences in mean annual fire density, mean annual area burned, and mean fire size (Zar 1999). Relationships between fire and temporal variations in climate were examined by correlating the annual number of fires and area burned (log-transformed) in each park with the average PDSI for each year (calculated from monthly PDSI values). The correlations also were calculated for each of the previous 4 years to test for lagged influences of previous wet or dry years. Fire-climate correlations at a finer temporal scale (monthly area burned correlated to monthly PDSI) were not possible because many of the records provided only the year, but not the month, in which the fire burned. Monthly data likely would have yielded stronger correlations, given the bimodal (spring-fall) fire season of the Appalachian region (Lafon et al. 2005). Nonetheless, annual-level correlations should be adequate for revealing the major fire-climate relationships because wildfires in the Appalachian Highlands generally require longer periods of drought compared to adjacent regions such as the southeastern Coastal Plain (Mitchener and Parker 2005).

It is possible that different levels of anthropogenic ignition and fire spread could occur between SNP versus GSMNP because of variations in population density or land use surrounding the parks, or simply because of differences in the shape of the parks. Such differences might obscure the influence of climate. In particular, if SNP has more fires ignited near the park borders than does GSMNP, we might incorrectly attribute the fire activity at SNP to its drier climate. To estimate whether such a factor may influence our analyses, we tallied the ignitions that occurred within 500 m zones parallel to the park boundaries to compare whether the proportion of fires occurring near the boundary differed between the parks.

To examine our second hypothesis that topography is a control on patterns of fire, maps of fire occurrence were used to calculate the area burned in each elevation, aspect, and slope position class. Log-likelihood tests for goodness of fit (*G* tests) were performed to investigate the topographic patterns of fire with respect to elevation, aspect, and slope position (Rollins et al. 2002). The expected frequency was based on the number of cells in each topographic class within the park boundaries (Sokal and Rohlf 2003). Cramer's V coefficient was used as a measure to compare the strength of association for log-likelihood values (Zar 1999), with a value ≥ 0.1 indicating a relationship and a value ≥ 0.3 indicating a strong relationship.

We tested our third and fourth hypotheses concerning the interaction of climate and topography by comparing the strength of topographic trends in area burned between different regional climates (i.e., GSMNP vs. SNP) and different temporal climatic conditions. For the latter (temporal) comparison, we produced maps of fires that occurred during significant drought years and significant wet years. The 18 dry years that fell within the lowest quartile of annual PDSI values were identified for each park. All mapped fires that occurred during these years were combined into a fire map for drought years (GSMNP, $n = 152$ fires; SNP, $n = 61$ fires), and the topographic patterns were analyzed using G tests and Cramer's V. The same procedure was used to analyze topographic patterns for wet (high-PDSI) years (GSMNP, $n = 54$ fires; SNP, $n = 32$ fires). We also used the same tests to compare topographic patterns of lightning-ignited versus anthropogenic fires in GSMNP ($n = 60$ lightning fires; $n = 499$ anthropogenic fires).

We further examined the relationship of burning patterns with climate and topography through a GIS based classification and regression tree (CART) model that incorporated the topographic patterns of fire and the climatic conditions under which they occurred. A CART model is a non-parametric statistical modeling technique that provides a collection of rules displayed in the form of a binary tree (Breiman et al. 1984; Venables and Ripley 1999). The advantage of CART models is that they are straightforward to interpret with a mix of numeric and categorical data and are capable of representing non-additive behavior (Bourg et al. 2005). Moderate PDSI condition fire maps were created for each park using fires that occurred during years with PDSI values in the second and third quartile. These maps, along with the high PDSI and low PDSI maps created for the previous analysis produced a total of six burn maps (one for each PDSI condition in each park). Stratified random sampling was used to select 100 points from the burns and 100 points from the unburned sections of each of these six burn maps (total of 600 sample points per park). Values from each of the topographic layers (elevation, slope position, and aspect) were also recorded for each of the sample points.

For the CART analysis, topographic variables were treated as ordinal integers, ranked according to the presumed moisture conditions, from dry to wet. Elevation categories were (1) 0–200 m, (2) 200–400 m, (3) 400–600 m, (4) 600–800 m, (5) 800–1,000 m, (6) 1,000–1,200 m, (7) 1,200–1,400 m. Slope categories were (1) ridge, (2) upper slope, (3) lower slope, (4) bottom. Treating the aspect variable as an ordinal integer required us to reassign the cells as follows: (1) south- and southeast-facing slopes that burned most frequently were assigned the value of one, (2) southwest and east aspects, (3) northeast and west, (4) north and northwest. Climate categories were (1) points sampled from the low PDSI burn map, (2) moderate PDSI burn map, (3) high PDSI burn map. The S-PLUS 6.0 statistical package was used to perform classification tree analysis, producing a tree for each park that predicted an outcome of burned (1) or unburned (0) (Insightful Corporation 2001). A second training sample of 1,200 points was collected in the same manner as above in order to assess misclassification error and guide the pruning of the trees. Optimal recursive shrinking was performed using the training sample in order to prevent over fitting of the model. The model was pruned for parsimony in terms of the number of descriptors while maintaining a high level of accuracy.

Results

Regarding our first hypothesis that regional climate is a control on patterns of fire disturbance, SNP had a greater mean annual fire density (Mann–Whitney test, $U = 1{,}136$, $n_1 = n_2 = 72$, $P < 0.05$), mean annual area burned (Mann–Whitney test, $U = 2{,}038$, $n_1 = n_2 = 72$, $P < 0.05$), and shorter fire cycle than GSMNP (Table 1).

These differences in fire activity do not appear to result from a greater level of human ignitions along the border at SNP compared to GSMNP. The evaluation of ignition distances from park boundaries revealed that a higher percentage of ignitions in GSMNP occurred within the first 500 m of the park

Table 1 Mean (standard deviation) annual ignition density, mean annual area burned, mean fire size, and fire cycle for fire records from 1930 to 2003 in GSMNP and SNP for all fires, and for anthropogenic and lightning fires in GSMNP

	Fire density (N/1000 km^2/year)	Area burned (ha/1000 km^2/year)	Mean fire size (ha)	Fire cycle (years)
SNP All Fires	13.5 (8.3)^{a}	488. 2 (1692.3)^{c}	42.7 (309.7)	204
GSMNP All Fires	6.3 (5.2)^{a}	83.5 (422.2)^{c}	25.6 (186.2)	1197
GSMNP Anthropogenic Fires	5.5 (4.9)^{b}	79.6 (418.8)^{d}	28.3 (199.9)	1257
GSMNP Lightning Fires	0.9 (1.0)^{b}	3.9 (16.2)^{d}	8.2 (19.3)	25397

Values followed by a letter differ significantly from values followed by the *same letter* (Mann–Whitney test, $P < 0.05$)

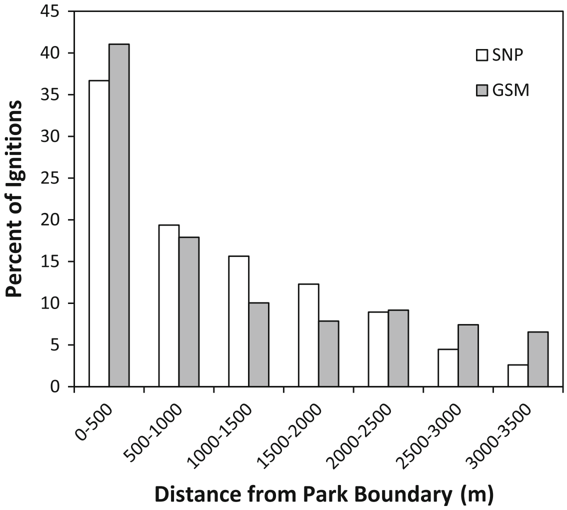

Fig. 4 Percent of ignitions occurring at different distances from the park boundaries

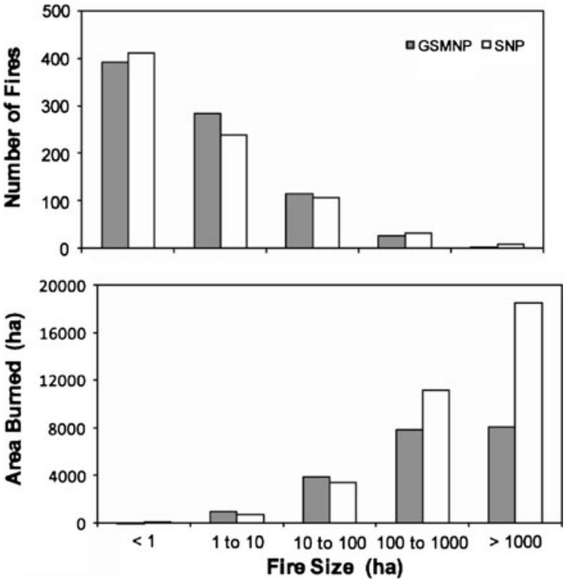

Fig. 5 Distribution of number of fires and area burned for different fire size categories in each national park

boundary and there was a more rapid decrease in ignitions within the first 2,000 m of the park boundary. The pattern suggests that increased fire activity in SNP is not the product of exterior ignitions, but a product of lower moisture conditions in the region. GSMNP had a greater concentration of burning along the border (Fig. 4); consequently for fire activity at SNP to exceed that at GSMNP it had to overcome the effect of greater human influence near the GSMNP boundary.

In both parks, small fires were numerous, but the few largest fires (>1,000 ha) accounted for the majority of area burned (GSMNP = 39%, SNP = 55%) (Fig. 5). More extensive burning occurred in dry years than wet years, as shown by the negative correlation between annual area burned and PDSI in the year of the fire (Fig. 6). Positive correlations also existed between annual area burned and PDSI of preceding years.

Evaluating our second hypothesis that fire was most common on south-facing slopes, ridgetops, and low elevations, we found that the expected pattern emerged for all fires at GSMNP (Figs. 7, 8, 9) but was strong only for elevation (Table 2, top row). At SNP, elevation showed a modest relationship with fire (Fig. 9) while aspect showed a weak tendency for burning to occur on north-facing slopes (Fig. 7). All three topographic variables were more strongly related to fire occurrence in GSMNP than SNP (Table 2), as proposed in our third hypothesis.

Our fourth hypothesis concerned temporal climatic variability and the association of fire with topography. We found that fire was more strongly related to all three topographic variables during high-PDSI (wet) years than low-PDSI (dry) years except in the case of elevation at GSMNP (Table 2; Figs. 7, 8, 9).

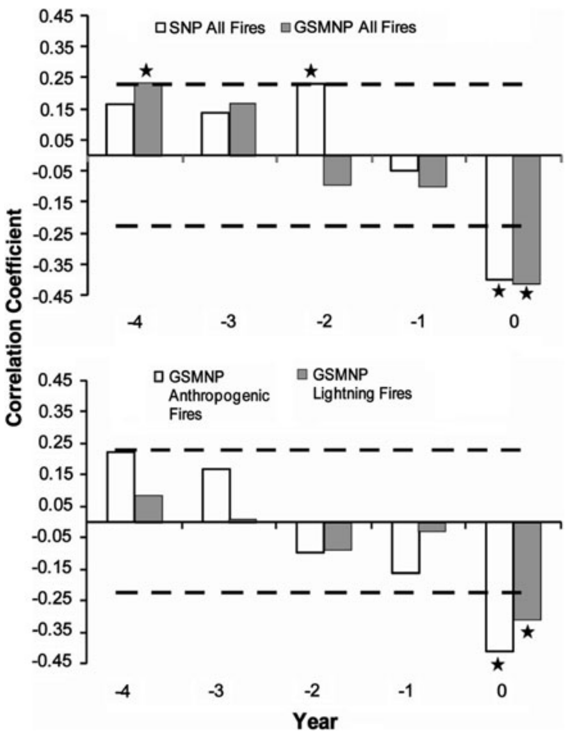

Fig. 6 Correlation of log annual area burned with average annual Palmer Drought Severity Index for actual year and previous 4 years. The *dashed lines* are confidence intervals ($P < 0.05$) and *stars* indicate years with a significant correlation

Generally, wet-year fires showed a more pronounced preference for south- or west-facing slopes, ridgetops and upper slopes, and moderate and low elevations. In dry years, burning extended more broadly over the terrain and into zones (e.g., high elevations) where fire was uncommon during wet years. Also, lightning-ignited fires at GSMNP had stronger aspect and slope position patterns, but not elevational patterns, than anthropogenic fires (Table 2; Figs. 7, 8, 9). Lightning fires accounted for smaller mean annual fire density (Mann–Whitney test, $U = 605.5$, $n_1 = n_2 = 72$, $P < 0.05$), and mean annual area burned in the park (Mann–Whitney test, $U = 961$, $n_1 = n_2 = 72$, $P < 0.05$), and exhibited a much longer fire cycle (Table 1). Both anthropogenic and lightning fires were significantly correlated with PDSI in the year of the fire, but lightning fires were less strongly correlated (Fig. 6).

The CART model identified elevation, slope position, and aspect as determinant variables (burn $\sim$ elevation + slope position + pdsi + aspect). Optimal recursive shrinking identified trees with 15 nodes and an acceptable level of misclassification error for both parks (GSMNP = 0.35, SNP = 0.36; Fig. 10). Elevation was the primary determinant of fire, with areas below 800 m (the boundary between elevation categories 4 and 5) burning in SNP. In GSMNP, areas below 1,200 m (boundary between elevation categories 6 and 7) were the most fire prone. Above 1,200 m in GSMNP fires were confined to ridges (slope position 1) during dry years. Slope position and PDSI were determining variables at lower elevation within both parks, with dry slope positions and dry aspects burning most frequently. Aspect was the least important topographic variable within the models.

Discussion

Climatic controls on spatial patterns of fire

As hypothesized, the drier SNP burned more frequently than GSMNP. The drier climatic conditions likely contributed to lower fuel moisture and consequently to greater flammability. Fuel moisture is the primary limitation on fire in the humid southeastern United States (Beckage et al. 2003; Lafon et al. 2005; Mitchener and Parker 2005). Reduced fuel moisture results in a higher susceptibility to combustion (higher fire density) and increased fire spread (larger mean fire size). Additionally, the seasonality of precipitation may amplify the effects of differences in total annual precipitation on fire. The 5 driest months in SNP are December to April, preceding or occurring in the early months of the fire season. Fuels from the previous year have had several months to cure and trees have not leafed out. Fall is the driest season in GSMNP, which follows the precipitation peak in May, June, and July. Fuels produced during the summer growing season in GSMNP have less time to dry preceding fall droughts.

Gradients in fire activity have previously been identified from west to east within the central Appalachian physiographic provinces (Lafon and Grissino-Mayer 2007). The easternmost Blue Ridge province burns more frequently than the Ridge and Valley and the Appalachian Plateau provinces to the west, apparently because of differences in seasonality and extent of dry periods. Our results suggest that a gradient of increasing fire activity also exists from

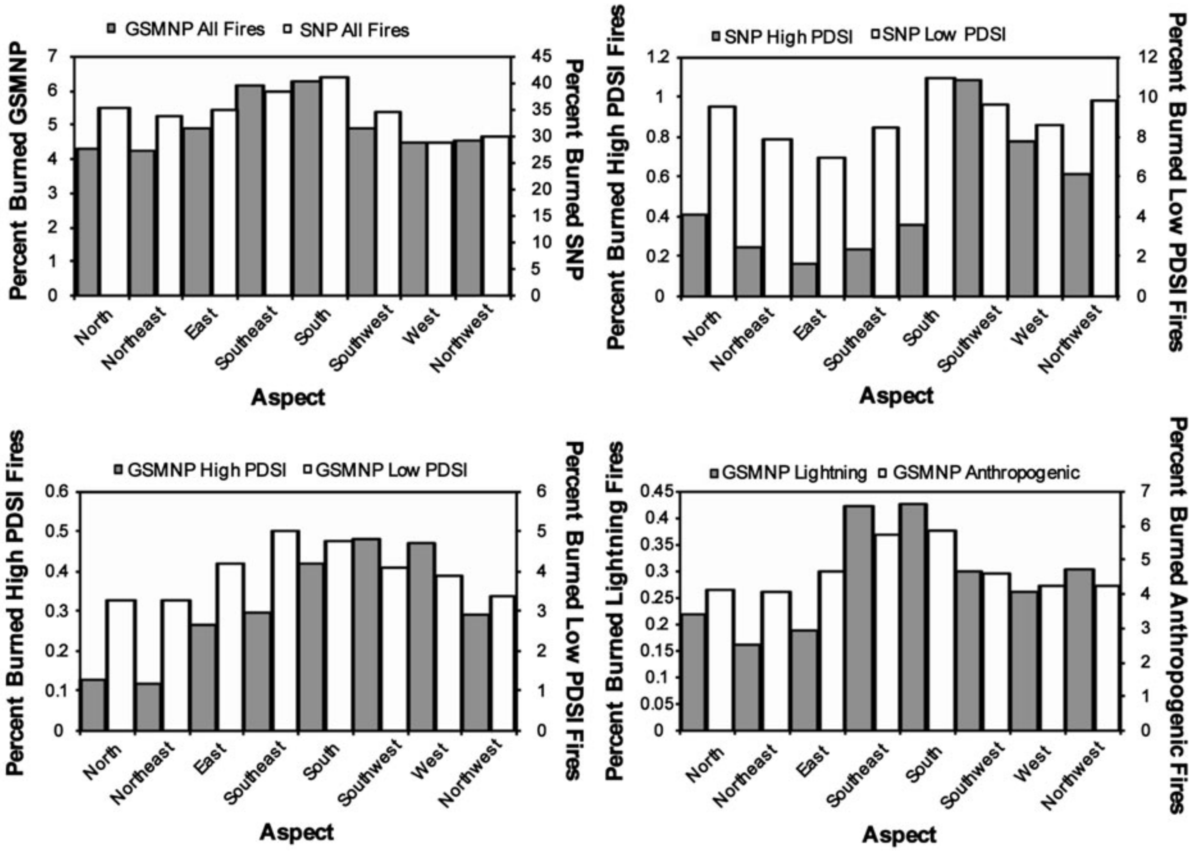

Fig. 7 Percent of total area in aspect categories that burned. Note that two *y* axes with separate scales were used for each graph

south to north along the Blue Ridge province itself. This pattern corresponds with a gradient of decreasing precipitation and varying precipitation seasonality.

Climatic controls on temporal patterns of fire

Patterns of fire activity were also influenced by temporal patterns of drought. Significant negative correlations between annual PDSI and area burned indicated that large fire years are associated with droughts. The slightly stronger correlations in GSMNP matched our expectation that burning a wetter landscape would require longer and more intense droughts. The significant positive correlations with lagged PDSI were not expected for these parks with humid climatic conditions. They may suggest that moisture in preceding years promotes fire by increasing fuel production as demonstrated in the drier forests of the southwestern U.S. (Veblen et al. 2000; Grissino-Mayer et al. 2004). In the Southwest the relationship emerges because of the dry climate, where wet years enhance the production of fine fuels that promote fire spread during subsequent dry years. Scatterplots of the lagged PDSI-area burned correlations (not shown) identified some potential outliers but did not produce an interpretable pattern. Without a longer time series of data, we can simply say that there may be an influence of prior moisture, but if so it is quite weak and does not assume the importance that it does in drier climates like the western US.

Topographic controls on spatial patterns of fire

Consistent with our second hypothesis, moisture appears to influence topographic patterns of fire, with drier elevations, slope positions and aspects burning most frequently. The patterns of area burned are particularly strong in GSMNP, where the high incidence of burning on south-facing slopes, ridges, and low elevations matches patterns found in mesic

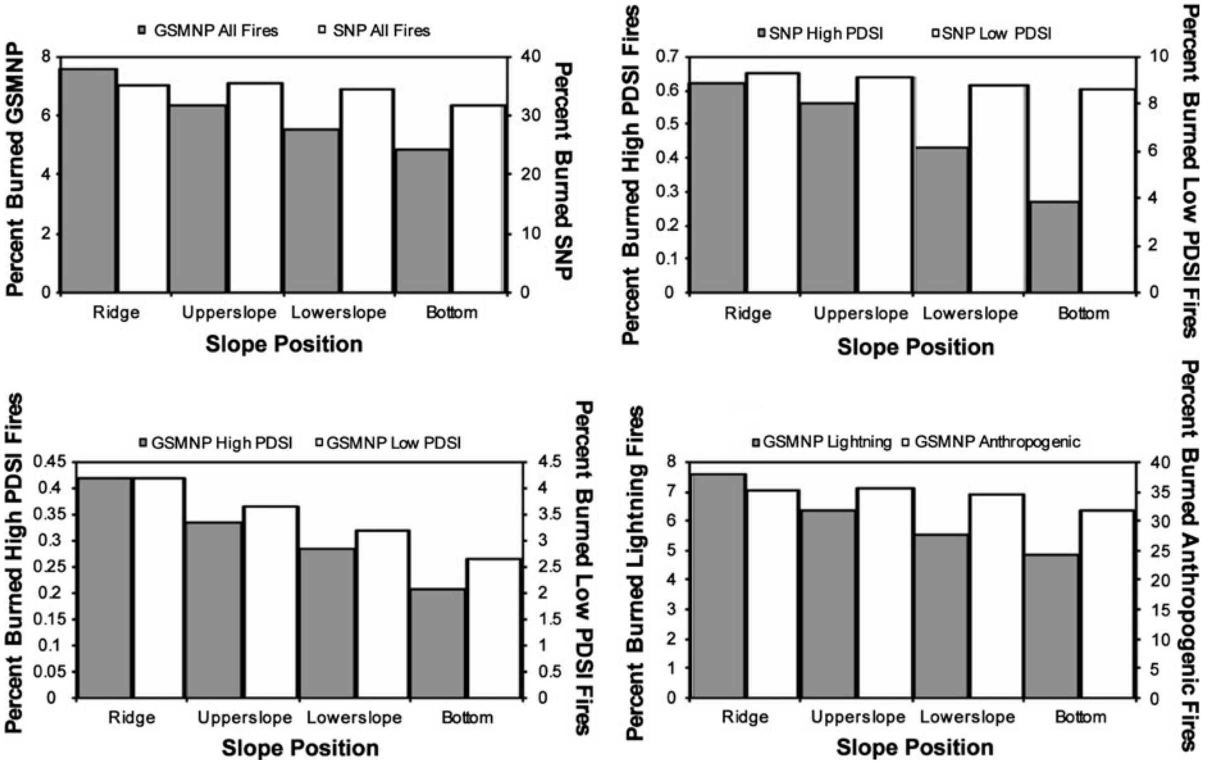

Fig. 8 Percent of total area in slope position categories that burned. Note that two *y* axes with separate scales were used for each graph

environments in the northwestern U.S. and elsewhere (Zhang et al. 1999; Rollins et al. 2002; Howe and Baker 2003). In SNP, however, these topographic patterns emerged strongly only during wet years. Apparently the relatively low precipitation in SNP results in sufficiently dry fuels across a wide range of elevations and slope positions. During the driest years in SNP, few topographic features may have high enough fuel moisture to impede the spread of fire.

The CART models enabled us to integrate the influences of climate and multiple topographic variables on the likelihood of a particular location burning. The effect of different topographic categories on model predictions was consistent between the model and the previously examined trends in area burned, with drier topographic features being most prone to fire. However, the classification tree was helpful in determining interactions between the variables. For example, the model predicted that fires would occur above 1,200 m in GSMNP only on dry ridge and upper slopes during low PDSI years. The major difference between the CART model and the results from the *G* tests of area burned was the reduced influence of aspect. This was likely a consequence of the variability in aspect patterns for burns in the different parks and under differing PDSI conditions. South and southeast aspects burned most in both parks, especially under low PDSI conditions. However, southwest and west aspects burned most frequently during high PDSI conditions. These differences in the susceptibility of certain aspects to fire under differing moisture conditions probably blurred the influence of the aspect variable and reduced its importance in the classification trees. Slope position and elevation, in contrast, maintained a consistent order of burn frequency under differing PDSI conditions in both parks. As a result, the *G* tests complemented the CART model in terms of identifying the presence of aspect patterns that likely would have been lost in the modeling assessment.

The differences in topographic patterning between GSMNP and SNP, and between wet and dry years, are consistent with our third and fourth hypotheses—broad climatic conditions interact with the topography such

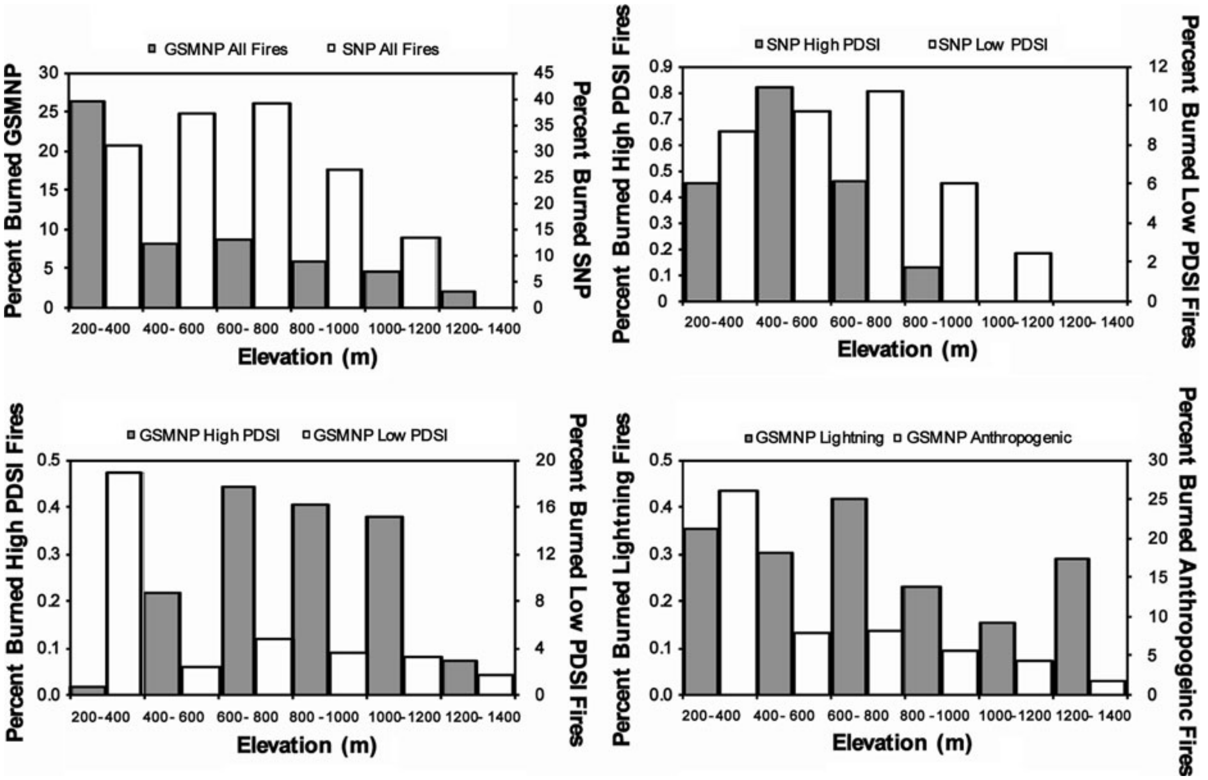

Fig. 9 Percent of total area in elevation categories that burned. Note that two *y* axes with separate scales were used for each graph

Table 2 Cramer's *V* coefficients from log-likelihood tests on distribution of area burned across different topographic classes for different fire types

	Aspect	Slope position	Elevation
GSMNP All Fires	0.15	0.15	**0.57**
SNP All Fires	0.11	0.04	0.19
GSMNP High PDSI Fires	**0.42**	0.22	**0.47**
GSMNP Low PDSI Fires	0.16	0.15	**0.62**
SNP High PDSI Fires	**0.60**	0.26	**0.54**
SNP Low PDSI Fires	0.13	0.03	0.24
GSMNP Lightning Fires	**0.32**	**0.44**	**0.33**
GSMNP Anthropogenic Fires	0.14	0.14	**0.59**

Values greater ≥0.3 (indicating strong trend) are shown in *bold*

that topography exerts less influence under dry, fire-prone conditions than under wet conditions. Regional or temporal climatic variations that reduce fuel moisture across a range of topographic positions render much of the landscape susceptible to the spread of fire. Our findings match and expand upon previous work concerning individual disturbance events, where large or high-intensity disturbances have been shown to have less topographic control than small or low-intensity disturbances (Parker and Bendix 1996; Moritz 2003; Mermoz et al. 2005; Stueve et al. 2007). The same principle appears to apply to the entire disturbance regime, i.e., disturbance-prone landscapes have weaker topographic patterns of disturbance than do less disturbance-prone landscapes.

Differences in fire disturbance patterns between the two parks likely generate different landscape patterns for fire-associated yellow pine and oak communities. Our results suggest that broader topographic patterns of fire in SNP may expand the range of fire-associated species down the moisture gradient to wetter slope positions, slope aspects, and elevations. A further understanding of this interaction between precipitation regimes, fire disturbance and vegetation is particularly important in light of possible future climate change. Predicted precipitation patterns for the southeastern U.S. are uncertain (Chen

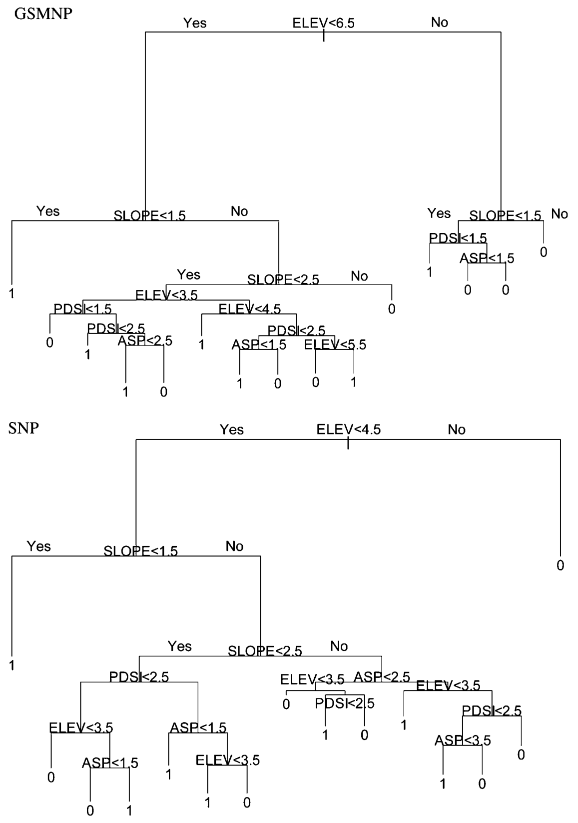

Fig. 10 Pruned classification tree model (CART) predicting fire occurence as a product of elevation, slope position, aspect, and Palmer Drought Severity Index. The classifications are burn (1) and no burn (0). Each split represents a binary division of the sample data according to the stated topographic or climatic condition. For GSMNP, the left (yes) branch following "Elev < 6.5" is interpreted as elevation categories 1 through 6, elevations less than 1,200 m. The left branch following "Slope < 1.5" is interpreted as slope category 1, ridge slope positions. The left branch following "PDSI < 1.5" is interpreted as moisture condition 1, low PDSI drought conditions. The left branch following "ASP < 1.5" is interpreted as aspect category 1, south and southeast facing slopes

et al. 2003). However, our results suggest potential changes in fire disturbance patterns and the resulting vegetation patterns in response to precipitation increases or decreases.

The differences in climatic conditions and topographic patterns of lightning fires compared to anthropogenic fires suggest that the two fire types may impart different disturbance patterns on a landscape. Our results indicate that lightning fires, occurring during wetter conditions, are more constricted to the driest aspects and slope positions. Anthropogenic fires, meanwhile, occur during drier conditions and burn across a much wider range of topographic positions. This distinction may be particularly important given the debate over the role of Native American ignitions and lightning ignitions in shaping pre-European settlement disturbance regimes in eastern North America (Petersen and Drewa 2006; Abrams and Nowacki 2008). Landscape patterns that result from a lightning fire regime probably differ substantially from the patterns caused by an anthropogenic fire regime. It is possible that patterns of contemporary anthropogenic ignitions may differ from Native American ignitions in terms of seasonality and location. However, the addition of human ignition sources, regardless of the season or location, represents an increase in the range of conditions under which fires are ignited.

Patterns of burning during dry and wet years have important implications for fire management. Prescribed fires generally are implemented during relatively moist conditions that facilitate their control. In the past, however, most burning likely occurred under drought conditions when topography imposed less control on patterns of fire. Where possible, fire managers should not consider only the typical frequency of fire and area burned in a particular landscape. They also may need to consider the typical climatic conditions and fire types (wetter vs. dry; anthropogenic vs. lightning) in order to reproduce landscape patterns that reflect historical disturbance regimes.

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