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Reconstructing a cultural fire regime in the Pennsylvania Anthracite Region

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ABSTRACT

Fire history reconstructions provide fire managers with valuable information regarding historical fire regime dynamics. Yet, in the Central Hardwood Forest Region (CHF), there is an absence of dendroecological studies where frequent wildfires have persisted into the twenty-first century. This study presents the first documented tree-ring reconstruction of fire history in the Pennsylvania anthracite coal-producing region. An approximately 150-year fire chronology was developed from fire-scarred pitch pine (*Pinus rigida*) and sassafras (*Sassafras albidum*) collected on Spring Mountain in Schuylkill County. Principal component analysis and *k*-means cluster analysis were used to identify four fire regime clusters based on interacting fire and non-fire parameters. Results indicate that fires occurred under a variety of moisture conditions and that a mid-twentieth century increase in fire activity on Spring Mountain was associated with the collapse of the regional anthracite industry and possibly amplified by the 1960s drought. Fires continue to burn on Spring Mountain in the twenty-first century, contrary to the dominant pattern of fire exclusion across the CHF. Future research needs are highlighted regarding historical fire regime dynamics and cultural ties to landscape burning in the Pennsylvania Anthracite Region.

Introduction

Humans have influenced fire activity for thousands of years through a variety of cultural and institutionalized land-use practices and management techniques (Bond & Keeley, 2005; Bowman et al., 2011; Coughlan & Petty, 2012). Paleoecological evidence (i.e. tree rings and lake sediments) suggests human-fire relationships have varied in intensity across space and through time, but that a marked shift from climate-modulated to predominantly human influenced fire regimes occurred with the onset of the Industrial Revolution (late eighteenth to early nineteenth centuries) (O'Connor, Garfin, Falk, & Swetnam, 2011; Pechony & Shindell, 2010). In this context, Coughlan and Petty (2013) recommend a research approach that incorporates social dimensions of fire, including individual and cultural decision-making practices that influence how a region is (or is not) impacted by anthropogenic fire. Developing methods to assess socioecological drivers of fire is, therefore, a primary objective

of twenty-first century fire ecology research, particularly where there is a history of climate-independent fire regime changes (Pausas & Keeley, 2014). The Pennsylvania Anthracite Region, with its history of economic and social instability, persistence of anthropogenic fires in the twenty-first century, and absence of fire history information, provides a unique opportunity to examine the complex relationships between humans, climate, and fire.

Estimates of historical fire frequency, extent, and seasonality are often derived from dendroecological reconstructions of fire history, which are based on the dating of fire scars that form in the annual growth rings in trees. Tree-ring reconstructions of fire are scarce, however, in the Central Hardwood Forest Region (CHF), which encompasses the oak (*Quercus* spp.)-dominated forests east of the Great Plains, south of the northern hardwood forests, and north of the southeastern pine forests (Fralish, 2003; Fralish & Franklin, 2002). Fire-scar records within this region are concentrated in the Central and Southern Appalachian Mountains, the Ozark Highlands in Missouri and northern Arkansas, and the Cumberland and Allegheny Plateaus in eastern Kentucky and southeastern Ohio, respectively (Hart & Buchanan, 2012). Within the CHF, researchers have targeted sites with long-lived pine (*Pinus* spp.) (e.g. Flatley, Lafon, Grissino-Mayer, & LaForest, 2013; Guyette, Spetich, & Stambaugh, 2006) or oak (e.g. McEwan et al., 2014; Shumway, Abrams, & Ruffner, 2001) species with fire scars that date from the beginning of the nineteenth century or earlier to the mid-twentieth century. These fire history reconstructions are used to inform fire management objectives within the CHF, providing valuable information about fire regime characteristics from pre-European settlement to the suppression era. Fire-scar records generated from these studies include management (i.e. prescribed) fires or a rare wildfire in the late twentieth century-early twenty-first century. There is an absence of fire-scar studies, however, that have targeted sites within the CHF where frequent wildfires have persisted into the twenty-first century. This research gap exists due to the fact that fire-scar records are primarily sourced from public lands or private preserves (e.g. The Nature Conservancy) where fire has been suppressed, excluded, or recently reintroduced through a prescribed burn program (Hart & Buchanan, 2012; Lafon, Naito, Grissino-Mayer, Horn, & Waldrop, 2017). Also, the length of the fire-scar record can be severely limited where early- to mid-successional forests are maintained by continuous disturbance, making these young forests less likely to provide fire history information that is useful to land managers.

In Pennsylvania, fire-scar studies are particularly scarce and have been limited to areas in which there is a near absence of fire since the second decade of the twentieth century. For instance, an approximately 400-year fire history was developed from remnant fire-scarred red pine (*Pinus resinosa* Aiton) collected at three sites on the Allegheny Plateau (Figure 1(a)) (Brose, Dey, Guyette, Marschall, & Stambaugh, 2013; Brose, Guyette, Marschall, & Stambaugh, 2015). Excluding a 2008 fire at one of the three sites, fire is absent from the tree-ring record after 1914, which coincides with the end of the logging boom and start of the fire suppression era. Approximately 100 km to the south in the Ridge and Valley physiographic province, samples were collected from living and remnant fire-scarred pitch pine (*Pinus rigida* P. Mill) at two ridgetop sites (Figure 1(a)), providing a roughly 350-year record of fire (Marschall et al., 2016). Fires were frequent before and during European settlement with fire intervals between 1 and 5 years, but only three fire years were recorded by trees during the suppression era (1915–2013), with the most recent fire in 1952. In both of these locations, human migration patterns, boom-and-bust industrialization, and forest and fire management policies were the dominant factors that determined how often and to what
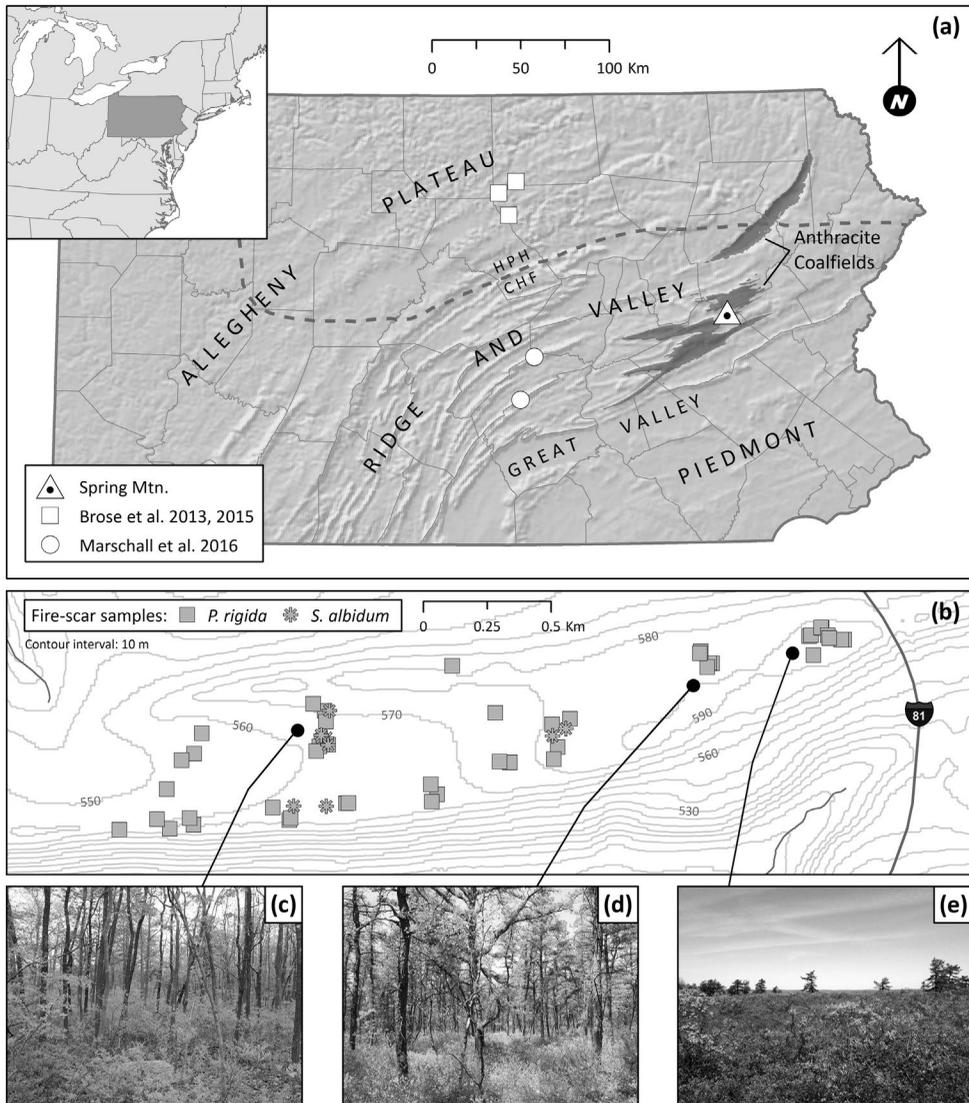
Figure 1. (a) Location of the Spring Mountain study site within the Pennsylvania Anthracite Region and nearby published fire-scar studies. The dashed line approximates the boundary between the Central Hardwood Forest Region (CHF) (Fralish, 2003; Fralish & Franklin, 2002) and the Hemlock–Pine–Northern Hardwood forest (HPH) (Braun, 1950; Nichols, 1935). (b) Locations of fire-scar samples on Spring Mountain. Photographs show: (c) an early-successional hardwood stand with remnant pitch pine (*P. rigida*), (d) a pitch pine-dominated stand, and (e) an open expanse of scrub oak (*Q. ilicifolia*) with isolated pitch pine.

extent fire occurred. Identifying and targeting sites where wildfires have persisted into the twenty-first century will complement these long, pre-suppression era fire histories and can provide a more holistic perspective on human-climate-fire relationships in Pennsylvania and the CHF in general.

In this study, I used fire-scarred pitch pine and sassafras (*Sassafras albidum* Nutt.) to reconstruct the fire history of a ridgetop barrens complex on Spring Mountain, located in the Pennsylvania Anthracite Region (Figure 1(a)). The middle and southern anthracite coalfields

are situated at the northeastern edge of the CHF in the Ridge and Valley physiographic province. These coalfields lie primarily within the Weiser Forest District, which exhibited the highest number of documented wildfires across the 20 forest districts in Pennsylvania between 1979 and 2015 (Pennsylvania Bureau of Forestry, 2015). Human population in the Anthracite Region increased rapidly in the late nineteenth to early twentieth century, fueled by large numbers of immigrants from Eastern and Southern Europe. Coal production and employment in the anthracite industry peaked in the second decade of the twentieth century, while decreasing demand, competition from other fuel sources, and continued labor struggles led to the collapse of the industry in the 1950s (Dublin & Licht, 2005). By 2010, the regional population was at a level comparable to that of the turn of the twentieth century (U.S. Census Bureau, 2010). These dynamic socioeconomic conditions, coupled with a continuous record of wildfire, provide the context in which to investigate human-climate-fire relationships.

Specifically, my goal was to assess temporal variability in fire activity on Spring Mountain as related to changes in population density, regional anthracite employment, and drought. The barrens complex on Spring Mountain was targeted because the Pennsylvania Game Commission and The Nature Conservancy have recently prioritized the restoration of ridgetop barrens in Pennsylvania that have been homogenized by fire exclusion and the gradual loss of early successional wildlife habitat (Orndorff & Coleman, 2008). Current management and restoration plans, however, are implemented without knowledge of historical fire regimes. Additionally, Spring Mountain is privately owned and has not, therefore, been subjected to formal management activities (e.g. prescribed fire). Results of this study will inform regional fire management and restoration objectives, while contributing to the growing body of literature calling for a more nuanced perspective on fire regime dynamics in the CHF and elsewhere.

Methods

Study area

Spring Mountain is located in Kline Township, Schuylkill County within the eastern middle field of the Pennsylvania anthracite coal producing region (40°53′N, 76°02′W; Figure 1(a)). Kline Township has a population of 1438 (U.S. Census Bureau, 2010) and a land area of approximately 32 km^2. Land cover is primarily forest (82%), while active or disturbed mine areas make up 5% of the total land area (U.S. Geological Survey, 2014). The regional climate is humid continental with an average annual temperature of 9.2 °C and monthly temperatures ranging from −3.7 °C in January to 21.7 °C in July (Pennsylvania Climate Division 2; National Oceanic and Atmospheric Administration [NOAA], 2015). Total annual precipitation is 119.4 cm, ranging from 7.5 cm in February to 11.8 cm in July on average (Pennsylvania Climate Division 2; NOAA, 2015).

Spring Mountain west of Interstate 81 (Figure 1(b)) is "vacant land" owned by multiple private interests and traditionally used as a hunting and recreation commons equally accessible to landowners, their lessees, and those who trespass illegally (J. Saladyga, personal communication). The ridgetop is classified as an acidic barrens complex composed of a mosaic of plant communities adapted to high winds, frequent fire, and shallow, nutrient poor soils of the Buchanan, Dakalb, and Hazleton-Clymer map units (Fike, 1999). The plant

community mosaic reflects variability in disturbance history and topo-edaphic factors such as soil depth, soil texture, and drainage (Figure 1(c)–(e)). Plant community types in the barrens mosaic include the globally imperiled and locally rare pitch pine-scrub oak (*Quercus ilicifolia* Wangenh.) woodland, pitch pine-mixed hardwood woodland, pitch pine-heath woodland, scrub oak shrubland, and low heath shrubland (Fike, 1999; NatureServe, 2014). Blackgum (*Nyssa sylvatica* Marsh.), sassafras, white oak (*Quercus alba* L.), and gray birch (*Betula populifolia* Marsh.) make up the hardwood component of the pitch pitch-mixed hardwood woodland. Blueberry (*Vaccinium* spp.), huckleberry (*Gaylussacia* spp.), and laurel species (*Kalmia latifolia* L. and *K. angustifolia* L.) dominate the heath communities (Fike, 1999).

Kline Township observational fire record

Kline Township wildfire statistics were compiled from paper and digital records to provide context for the Spring Mountain fire history reconstruction. These records are maintained by the Weiser Forest District, Pennsylvania Bureau of Forestry. District staff reported a total of 197 wildfires that burned an estimated 354 ha, or 14% of forested area, between 1961 and 2015. Fire activity (number and area burned) across the Township peaked during the early 1960s drought and again during the relatively wet mid-1970s. The majority of fires (72%) burned during the months of March, April, and May. These spring fires occurred in 45 of 55 years and accounted for 181 ha, or 51% of the total area burned. A second fire season occurs in the fall, with an additional 15% of fires burning during the months of September, October, and November. Fall fires occurred in 19 of 55 years, burning 91 ha or 26% of the total area burned. However, there were only nine fall seasons when ≥1 ha burned. Although not statistically significant, there are weak negative associations between fire activity and Palmer Drought Severity Index (PDSI) in years when ≥1 ha was burned ($n = 32$; $r = -0.26$; $p = 0.16$) and when ≥ 2 fires were reported ($n = 39$; $r = -0.20$; $p = 0.22$).

Probable cause of fire in the Kline Township record is variable, although incendiary activities were reported as the cause of 41% of all fires during the 55-year record. Accidental fires, including, for example, those caused by hunters, debris burning, and industry, accounted for the remainder. Fires resulting from lightning strikes are absent from the record, indicating that human ignitions have been the primary causes of fire. Location descriptions, hand-drawn maps, and geographic coordinates (1999–2015) in the Kline Township record indicate that 7 of the 197 wildfires occurred within the Spring Mountain study area between 1964 and 2013. These fire events were compared to the independently developed Spring Mountain tree-ring fire history.

Fire-scar sample collection and analysis

In May 2015, samples were cut with a chainsaw from 47 living and three standing dead pitch pine trees and nine living sassafras trees within the Spring Mountain study area (Figure 1(b)). Trees were selected for sampling based on the presence of visible fire-scar evidence (i.e. basal scarring or "cat face") (Arno & Sneck, 1977; Speer, 2010). Partial sections were cut from live trees at approximately 0.25–0.5 m from ground level, while full sections were cut from snags after felling. Five of the pitch pine samples were subsequently determined to be unusable due to substantial decomposition. All samples were collected between 560 and

600 m in elevation within the approximately 180-ha study area (Figure 1(b)). Pitch pine were selected for sampling without regard to tree age or number of visible scars while traversing the study area. This sampling approach was necessary in order to maximize sample size and reduce potential bias in fire interval calculations by sampling both young and old trees with different scarring potential (Guyette, Dey, & Stambaugh, 2003).

Samples were processed in the lab using standard dendrochronology methods (Orvis & Grissino-Mayer, 2002; Speer, 2010). Progressively finer grit sandpaper (40–600 grit) was used to surface each cross section until cells were clearly visible under magnification. Graphical (i.e. "skeleton") plots that highlight "marker years" with uniquely narrow ring width were constructed for each cross section (Schweingruber, Eckstein, Serre-Bachet, & Braker, 1990). All samples were then visually crossdated against a master chronology developed from the cores of eight live pitch pine with no visible evidence of basal scarring and the common marker years of three regional tree-ring chronologies (Cook, 1994a, 1994b, 1994c). If possible, season of occurrence was assigned for each fire scar based on its position in relation to annual growth rings according to the following categories: earlywood (E), latewood (L), dormant (D), or undetermined (U). Due to the high percentage of March, April, and May fires in the Kline Township record (see above), dormant season scars were considered to represent spring fires and, therefore, assigned to the calendar year in which callus tissue responded (see Figure 2).

Fire-scar data were entered in FHX2 format and analyzed in the Fire History Analysis and Exploration System (Brewer, Velásquez, Sutherland, & Falk, 2015; Grissino-Mayer, 2001).
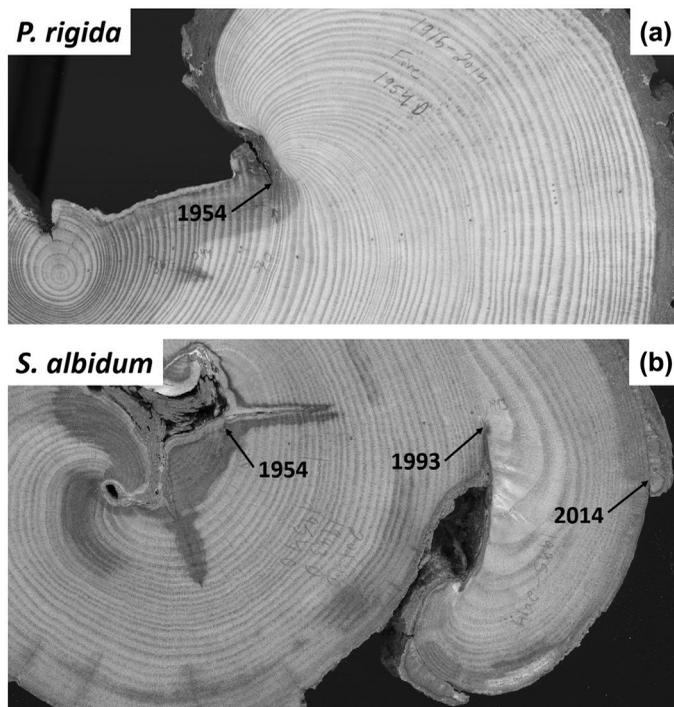

Figure 2. Examples of fire-scarred sections collected on Spring Mountain, Schuylkill County, Pennsylvania in May 2015: (a) pitch pine (*P. rigida*) and (b) sassafras (*S. albidum*).
Note: Dormant season fire-scar dates are noted for each sample.

Only distinct fire scars that were distinguishable by cambial injury and related woundwood curl were entered as such, while injuries of other possible origins (e.g. ice storm, insects) were recorded as "injury" and left out of the analysis. Statistical analysis was limited to time periods when at least three trees were included in the fire chronology (Marschall et al., 2016; Stambaugh, Marschall, & Guyette, 2014). A fire history chart and summary statistics, including composite fire intervals, were generated for both species separately. For comparison to other fire history studies, mean fire return interval (MFI), standard deviation, Weibull median fire interval (WMFI), the lower and upper exceedance intervals (LEI and UEI), and average percentage of trees scarred are reported.

Climate-fire relationships were assessed by comparing instrumental PDSI (Pennsylvania Climate Division 2; NOAA, 2015) to fire years. The instrumental PDSI record (1895–2015) was used rather than a reconstructed drought index for two reasons: (1) Tree-ring reconstructions of moisture conditions such as the North American Drought Atlas are based on tree growth-moisture relationships during the growing season. This timing is asynchronous with the regional fire season, which peaks in the spring and fall; and (2) The Spring Mountain tree-ring record is generally limited to the time span of the instrumental drought record. Superposed Epoch Analysis (SEA) was used to test for departures in instrumental PDSI during and in the 2 years preceding and following fire years in the pitch pine fire-scar record (Aldrich, Lafon, Grissino-Mayer, & DeWeese, 2014).

Decadal trends in fire activity

Fire frequency (number of fires per 10-year segment or "decade") and a 10-year moving average of the percentage of trees scarred were calculated from pitch pine fire-scar data (Guyette et al., 2006). Decadal averaging of fire parameters is useful for assessing temporal trends in fire activity, particularly when non-event (or "zero") years prevent direct comparison to continuous variables. The 10-year moving averages of three non-fire parameters were also calculated. These include percent change in regional anthracite employment (Pennsylvania Department of Environmental Protection, 2015), Schuylkill County population density (U.S. Census Bureau, 2010), and instrumental annual PDSI (Pennsylvania Climate Division 2; NOAA, 2015). Linear interpolation was used to estimate annual population density between census years prior to calculating the 10-year moving average (Guyette et al., 2006). Given the historical dominance of the anthracite coal industry in the regional economy, percent change in anthracite employment is a useful proxy of economic health when positive values indicate growth and negative values indicate decline.

Principal component analysis (PCA) and *k*-means cluster analysis were used to identify unique fire regime clusters (FRCs) using the five decadal variables described above. Using these methods, trends in the fire regime are characterized not only by fire-related parameters (e.g. frequency, extent, seasonality), but also the socioeconomic and climatic conditions under which fire does or does not occur (Conedera et al., 2009; Krebs, Pezzatti, Mazzoleni, Talbot, & Conedera, 2010). The five decadal variables were first converted into component scores, then principal components (PCs) with eigenvalues greater than 1.0 were extracted to explain model variance. This analysis was then run without PDSI to assess climate independence in decadal trends. The resulting component scores were subsequently used in a *k*-means cluster analysis to identify FRCs characterized by unique fire activity, climate, and socioeconomic conditions. The target number of clusters was set at four, which approximates

the number of major demographic and economic shifts that occurred in the Pennsylvania Anthracite Region from the late 19th to early twenty-first century (Dublin & Licht, 2005).

Results

Spring Mountain fire history

The pitch pine fire chronology spans 174 years (1841–2014), with the fire interval analysis restricted to 1854–2014 when at least three trees were present in the tree ring record (Table 1; Figure 3). During this time period, pitch pine recorded 71 fire scars, representing 44 fire years. Composite fire intervals ranged from 1 to 37 years, with a mean fire interval of 3.5 years. The lower and upper exceedance intervals (LEI and UEI, respectively) indicate that 75% of the fire intervals would be expected to fall between approximately 1 and 7 years. The percentage of trees scarred during most fire years was low (<10%), with the notable exception of 1954 (40% scarred). Scarring predominantly occurred between annual rings during the dormant season (77%), which is consistent with the early spring and late fall fire seasons represented in the Kline Township fire record.

Partial cross sections were also cut from nine fire-scarred sassafras trees to assess the use of this hardwood species in reconstructing fire history (Figure 2(b)). Fire interval analysis for sassafras was restricted to 1954–2014, when at least three trees were present in the tree-ring record (Table 1; Figure 4). Sassafras recorded 33 fire scars, representing 17 fire years when at least one tree was scarred and 4 fire years when at least three trees were scarred. The conservative fire interval estimate (≥3 trees scarred) was used in order to account for other possible scaring agents such at Nectria canker that is common in sassafras and can result in scars similar in appearance to those caused by fire. Also, there is increased risk for pathogen entry when moderate- to high-severity fires injure mature sassafras (Griggs, 1990). This provides a possible explanation for the abundance of scarring following the 1993 dormant season fire. Additional dormant season fires recorded by sassafras include 2005, 2012, and 2014 when using the conservative estimate of fire intervals.

SEA results indicate that climate conditions were not unusually dry or wet during or in the two years preceding or following fires recorded by pitch pine that overlap the instrumental

Table 1. Fire interval statistics for Spring Mountain, Schuylkill County, Pennsylvania.

Tree species	*P. rigida*	*S. albidum*[a]
Time period	1854–2014	1954–2014
Number of trees	45	9
Number of scars/injuries	71/15	33/11
Scar seasonality (E/L/D/U)	7/0/55/9	0/0/32/1
No. fire years	44	17 (4)
MFI (years)	3.5	3.8 (7.0)
Standard deviation	5.9	4.1 (5.0)
Range (years)	1–37	1–13 (2–12)
WMFI (years)	2.3	2.8 (6.4)
LEI	0.4	0.6 (2.5)
UEI	7.3	7.7 (12.0)
Mean percentage scarred	5.0	22.0 (50.0)

Note: Data are shown for pitch pine (*P. rigida*) and sassafras (*S. albidum*).
[a]Conservative (≥3 trees scarred) fire interval statistics that account for scarring agents other than fire (i.e. Nectria canker) are in parentheses. Scar seasonality: E = earlywood, L = latewood, D = dormant, U = undetermined; MFI = mean fire interval; WMFI = Weibull median fire interval; LEI/UEI = lower and upper exceedance intervals.
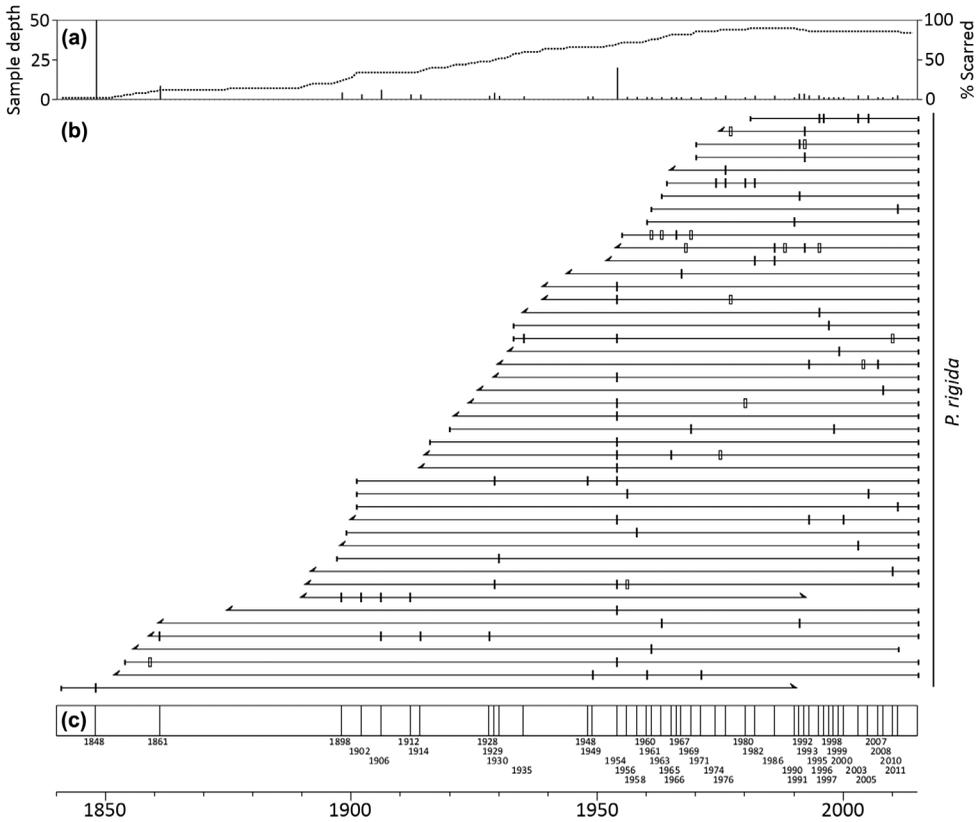
Figure 3. Fire history chart for pitch pine (*P. rigida*) collected on Spring Mountain, Schuylkill County, Pennsylvania: (a) sample depth (line) and percentage of trees scarred (bars), (b) fire history chart with each horizontal line representing one tree (*n* = 45), and (c) composite fire chronology.
Notes: In (b), solid, bold vertical lines indicate fire scars and open vertical lines indicate injuries. Pith dates and bark dates are represented by a short vertical line. Inner-ring dates are represented by a forward slash and outer-ring dates are represented by a backward slash.
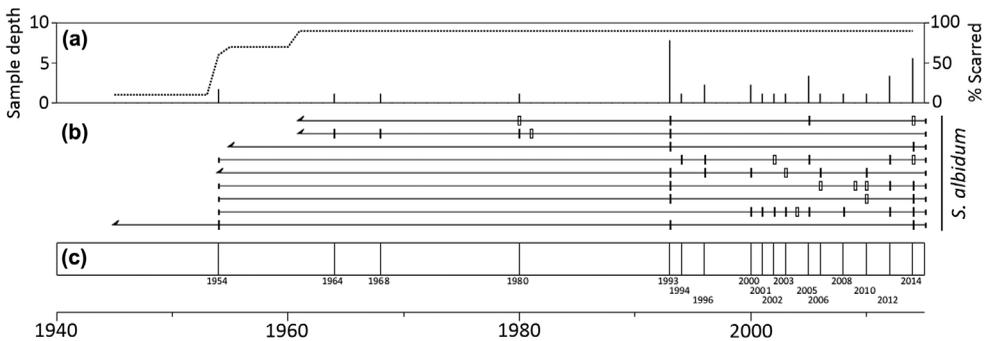

Figure 4. Fire history chart for sassafras (*S. albidum*) collected on Spring Mountain, Schuylkill County, Pennsylvania: (a) sample depth (line) and percentage of trees scarred (bars), (b) fire history chart with each horizontal line representing one tree (*n* = 9), and (c) composite fire chronology.
Notes: In (b), solid, bold vertical lines indicate fire scars and open vertical lines indicate injuries. Pith dates and bark dates are represented by a short vertical line. Inner-ring dates are represented by a forward slash.

Table 2. Fires documented within the Spring Mountain study area based on location descriptions (D), hand drawn maps (M), and geographic coordinates (G) in the Kline Township record.

Fire year	Date	Location Source	Area burned (ha)	Probable cause	No. trees scarred	Tree species scarred	PDSI
1964	12 October	D	38.9	Hunter	0[a]	–	−4.13
1968	23 October	D	1.6	Hunter	0[b]	–	−1.30
1974	25 April	D/M	0.4	Incendiary	1	*P. rigida*	1.69
1976	7 April	D/M	6.1	Incendiary	2	*P. rigida*	1.74
1993	15 May	D/M	30.4	Incendiary	8	*P. rigida/S. albidum*	0.88
2013	7 April	D/G	1.6	Incendiary	0	–	−1.10
2013	14 April	D/G	1.6	Incendiary	0	–	−1.10

Notes: Estimated fire size (hectares burned), probable cause, the number of trees and species scarred, and Palmer Drought Severity Index (PDSI) for the season of the fire are also included (averaged March/April/May or September/October/November).
Fire data source: Weiser Forest District, Pennsylvania Bureau of Forestry.
[a]One dormant season fire scar was dated to 1965, possibly representing the October 1964 fire.
[b]One dormant season fire scar was dated to 1969, possibly representing the October 1968 fire.

PDSI record (*n* = 43). These results are consistent with the absence of statistically significant fire-drought relationships in the Kline Township record. Additionally, moisture conditions during fire years when at least three pitch pine *or* three sassafras were scarred were variable. Specifically, there was a "mild drought" in 1954, 1991, 1992, and 2012 (PDSI = −1.67, −1.04, −1.60, and −1.99, respectively), moisture conditions were "near normal" in 1993 and 2014 (PDSI = 0.20 in both years), and "slightly wet" in 2005 (PDSI = 1.10) according to Palmer (1965).

Comparison of fire-scar data to the fire record

Fire-scar dates and tree locations correspond to five of the seven documented fires that burned within the Spring Mountain study area (Table 2). In two instances, dormant season fire scars in sassafras were dated to 1964 and 1968, but these scars represent either spring 1964 or fall 1963 and spring 1968 or fall 1967 fires, respectively. Instead, dormant season fire scars in pitch pine dated to 1965 and 1969 possibly represent the October 1964 and 1968 fires. Both of these fall season fires were accidentally started by a hunter when seasonal moisture conditions were below normal; "extreme drought" in the fall of 1964 (PDSI = −4.13) and "mild drought" in the fall of 1968 (PDSI = −1.30) (Palmer, 1965). The five spring season incendiary fires occurred under a wide range of seasonal moisture conditions, from "mild drought" in 2013 (PDSI = −1.10) to "incipient wet spell" in 1993 (PDSI = 0.88) and "slightly wet" in 1974 (PDSI = 1.69) and 1976 (PDSI = 1.74) (Palmer, 1965). In these incendiary cases, the individual(s) put forth effort to ignite and maintain fire, potentially overcoming any fuel moisture limitations. Finally, between 1961 and 2014, there were a total of 28 years in which pitch pine recorded fire on Spring Mountain, while Weiser Forest District staff documented only seven fires in six calendar years. This difference indicates a considerable underestimation of fire activity on Spring Mountain in the Kline Township record.

Decadal trends in fire activity

The period of analysis was limited to 107 "decades" (i.e. 10-year overlapping segments), beginning with 1895–1904, 1896–1905 and continuing to 2001–2010. This time period
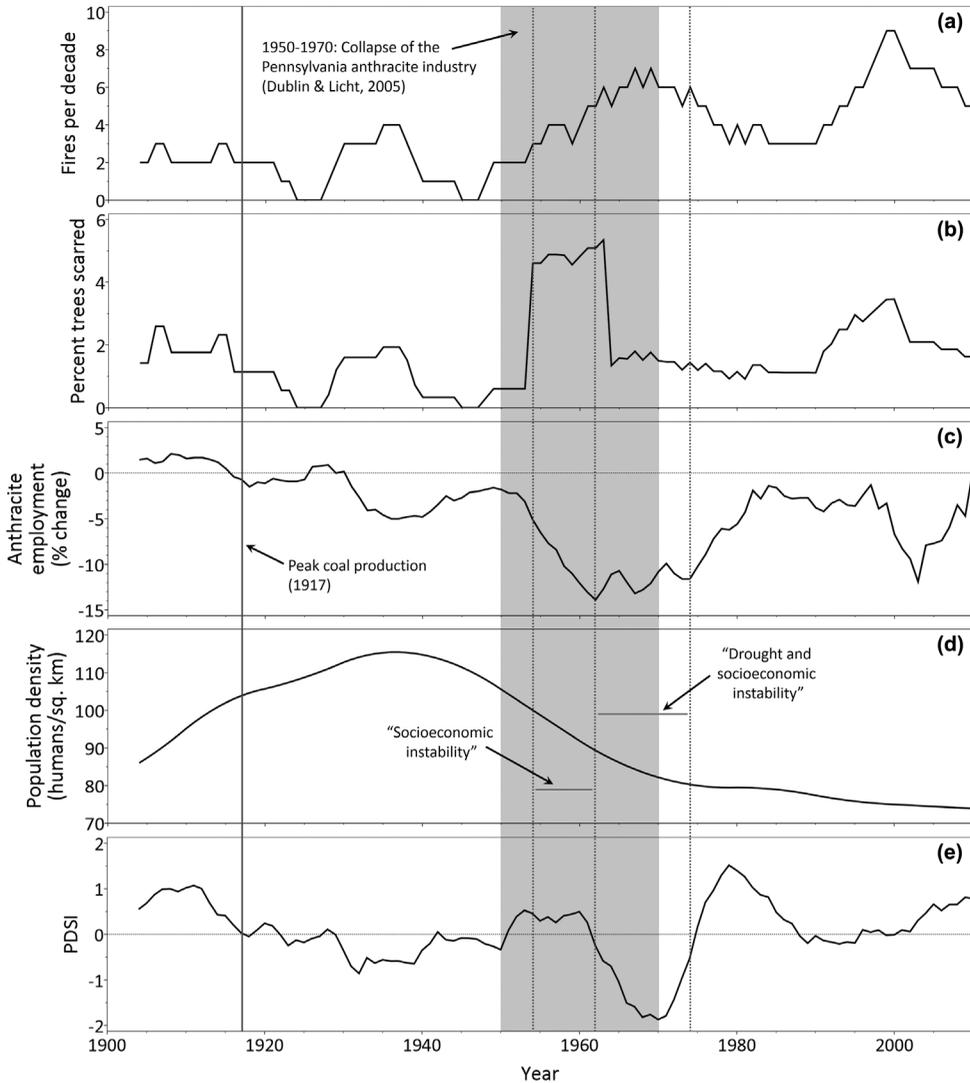
Figure 5. Decadal trends in the pitch pine (*P. rigida*) fire chronology, including (a) fire frequency (fires per decade), and (b) percentage of trees scarred, as well as (c) percent change in regional anthracite employment, (d) Schuylkill County population density, and (e) Palmer Drought Severity Index (PDSI). Notes: Each data point represents the end of one "decade" (10-year overlapping segment; *n* = 107). Selected fire regime clusters are noted for comparison to the historical collapse of the Pennsylvania anthracite industry.

was restricted by the instrumental PDSI record (1895–2015) and Schuylkill County census data (1820–2010). Decadal trends in the pitch pine fire chronology reveal a notably abrupt increase in fire activity in the 1950s/1960s and again in the 1990s, reflecting dynamic socio-economic and climatic conditions (Figure 5(a)–(e)). Fire frequency ranged from 0 to 9 with a median value of 3 fires per "decade" (*n* = 107), indicating that fires typically occurred 3 out of every 10 years between 1895 and 2010. There were notable exceptions, however, when fire frequency was well above the median during the 1960s and 1990s or decreased to zero during the 1920s and 1940s (Figure 5(a)). The percentage of trees scarred followed a similar temporal pattern, ranging from 0 to 5.3 with a median value of 1.5 (*n* = 107) (Figure 5(b)).

Table 3. Fire regime clusters determined by *k*-means cluster analysis.

	Fire regime clusters			
	Industrial decline and peak popu-lation	Pluvial and socioec-onomic stability	Socioeconomic instability	Drought and socioeconomic instability
Number of "decades"	38	28	29	12
Time period(s)	1916–1953	1904–1915 1977–1990 2009–2010	**1954–1962** 1975–1976 1991–2008	**1963–1974**
Fire frequency	2.0	3.0	5.0	6.0
Percent trees scarred	0.6	1.4	2.8	1.5
Anthracite employ-ment (% change)	−1.9	−1.5	−7.4	−11.6
Population density (humans/km^2)	110.3	79.5	76.1	83.2
PDSI	−0.12	0.84	0.26	−1.47

Notes: The number of "decades" (10-year overlapping segments) and time periods are indicated. For example, "Industrial decline and peak population" begins with the 10-year segments 1907–1916, 1908–1917 and continues to 1944–1953. Median values are shown for decadal variables: fire frequency (fires per decade), percentage of trees scarred, percent change in regional anthracite employment, Schuylkill County population density, and Palmer Drought Severity Index (PDSI). Bolded time periods are highlighted in Figure 5.

The abrupt increase in the percentage of trees scarred during the early 1950s was driven by the 1954 fire, which scarred 40% of the sampled pitch pine.

Five decadal variables were used in a PCA and *k*-means cluster analysis to identify FRCs characterized by unique trends in human-climate-fire interactions. Principal component 1 (PC1) and principal component 2 (PC2), with eigenvalues greater than 1.0, cumula-tively explain 77% of model variance. All five variables are included in PC1 (51% variance explained) and PC2 (26% variance explained). Only one principal component, explaining 63% of model variance, was extracted when the PCA was run without PDSI, suggesting that climate-independence in the fire regime was not complete. This method was useful for reducing a relatively complex set of five collinear variables to two uncorrelated "components". However, serial autocorrelation in the decadal time series data make it difficult to assess statistical significance in these models.

Principal component scores (PC1 and PC2) were subsequently used in *k*-means cluster analysis to identify four FRCs (Table 3; Figure 6): (1) Industrial decline and peak population (1916–1953), (2) Pluvial and socioeconomic stability (1904–1915; 1977–1990; 2009–2010), (3) Socioeconomic instability (1954–1962; 1975–1976; 1991–2008), and (4) Drought and socioeconomic instability (1963–1974).

The first FRC, "Industrial decline and peak population" (1916–1953), was characterized primarily by increasing or high population density, but also by a steady and/or marked decline in anthracite employment (i.e. the Great Depression) and "near normal" (Palmer, 1965) moisture conditions (Table 3; Figure 5(c)–(e)). Median values for fire frequency and percentage of trees scarred were below the respective median values for the entire time series. The second FRC, "Pluvial and socioeconomic stability" (1904–1915; 1977–1990; 2009–2010), was characterized by generally wet conditions (an "incipient wet spell"; Palmer, 1965), during which changes in anthracite employment were relatively slow or minimal and population density was low (Table 3; Figure 5(c)–(e)). Median values for fire frequency and percentage of trees scarred were equivalent and nearly equivalent to the respective median values for the entire time series. The third FRC, "Socioeconomic instability" (1954–1962;
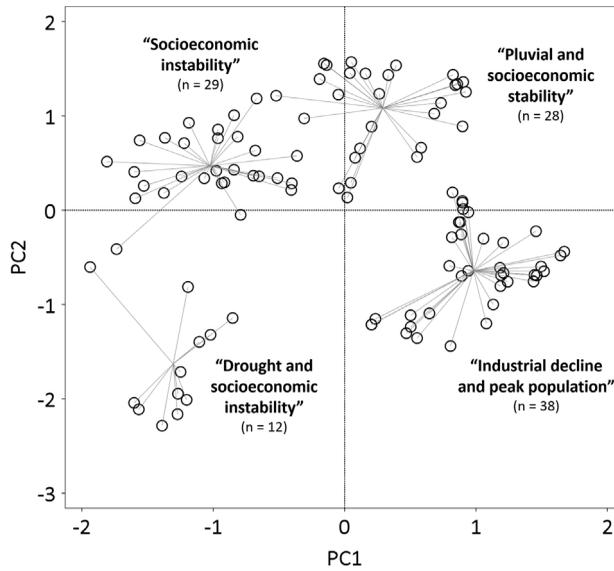
Figure 6. Principal component (PC) scores for decadal variables used in *k*-means cluster analysis: fire frequency (fires per decade), percentage of trees scarred, percent change in regional anthracite employment, Schuylkill County population density, and Palmer Drought Severity Index (PDSI).
Notes: Each (○) represents one "decade" (10-year overlapping segment; *n* = 107). Line intersections indicate the centroid of each fire regime cluster.

1975–1976; 1991–2008), featured abrupt changes in socioeconomic conditions, as well as rapid decline in anthracite employment, declining or low population density, and "near normal" (Palmer, 1965) moisture conditions (Table 3; Figure 5(c)–(e)). Median values for fire frequency and percentage of trees scarred were nearly double the respective median values for the entire time series. The 1960s drought was the distinguishing feature of the fourth FRC, "Drought and socioeconomic instability" (1963–1974), during which there were steady declines in anthracite employment and population density, and "mild drought" (Palmer, 1965) conditions (Table 3; Figure 5(c)–(e)). Median values for fire frequency and percentage of trees scarred were double and equivalent to the respective median values for the entire time series.

Discussion

The late nineteenth century to twenty-first century fire regime on Spring Mountain is distinctly anthropogenic, driven primarily by accidental or incendiary ignitions, but characterized by unique "fire regime clusters" (FRCs) defined by complex interactions between ecological, socioeconomic, and climatic factors. The methods used in this study differ from those of previous dendroecological studies that have described temporal variation in fire regime characteristics (e.g. Stambaugh et al., 2014; Taylor & Scholl, 2012). Those studies provided valuable information to fire managers by placing fire parameters (e.g. frequency, extent, seasonality) in the context of known historical land-use eras or cultural periods. Using that approach, descriptive fire interval statistics or non-parametric comparison of means tests are employed to assess differences in fire occurrence or climate-fire relationships

between time periods, such as "pre-European settlement" or "suppression era". In contrast, I used quantitative methods (PCA and *k*-means cluster analysis) to group time periods based on the *interactions* of both fire and non-fire parameters. Although it is difficult to assess statistical significance, this approach and the results presented herein identify interacting trends in fire and non-fire parameters (see Figure 5) and support a more flexible definition of "fire regime" described by Krebs et al. (2010) and Whitlock, Higuera, McWethy, and Briles (2010). Furthermore, this study describes the range of socioecological conditions under which the barrens complex on Spring Mountain has been maintained in the absence of formal management practices.

It is not possible to capture all of the socioecological complexities that characterize a region dominated by one industry for more than a century and a half. However, the FRCs identified in this study do conceptualize temporal patterns in human-climate-fire interactions for a landscape in which humans are the primary ignition source. Most notably, fires occur under a variety of moisture conditions and increases in fire activity on Spring Mountain are strongly associated with abrupt downturns in the regional anthracite industry and times of socioeconomic instability. Individual fire events were not associated with significant departures in PDSI, but decadal trends suggest that climate-independence in the fire regime was not fully complete and that drought may have amplified fire activity during times of socioeconomic instability (i.e. "Drought and socioeconomic instability" of the 1960s/early 1970s). The relationship between regional socioeconomic conditions and fire is further supported by the timing of major layoffs that signified the collapse of the anthracite industry. For example, approximately 4000 mineworkers employed by Lehigh Coal and Navigation Company in the nearby Panther Valley lost their jobs when mine operations ceased in March–April 1954 (Dublin & Licht, 2005). The coincidence cannot be confirmed, but it is highly probable that the timing of this layoff event is associated with the 1954 dormant (likely spring) season fire on Spring Mountain. Investigations of the contemporary fire record elsewhere show a positive association between unemployment and fire occurrence (Bühler, de Torres Curth, & Garibaldi, 2013; Butry & Prestemon, 2005; Leone, Lovreglio, & Martinez Fernandez, 2002; Martínez, Vega-Garcia, & Chuvieco, 2009). However, other studies found that fire occurrence decreased with higher unemployment in Florida (Mercer & Prestemon, 2005; Prestemon & Butry, 2005), while Maingi and Henry (2007) detected no relationship between unemployment and fire occurrence in eastern Kentucky, another coal producing region. These differences likely reflect local vegetation types and cultural attitudes toward fire. For instance, across Pennsylvania, there is a long history of starting fires on ridgetops to promote blueberry or huckleberry growth, first by Native Americans and later by Euro-Americans (Hulbert, 1910; Pennsylvania Department of Forestry, 1914). In the late nineteenth and early twentieth century, wives and children of anthracite mineworkers regularly harvested berries to supplement income. In a New York Times article published in 1900, the author wrote, "The huckleberry crop is a godsend to the families of coal miners at and in the vicinity of Hazleton" and, furthermore, "It is believed that nearly 1,000,000 quarts [~94,325 L] will be picked and disposed of in the Hazleton market alone this year" (Anonymous, 1900). Increased incidence of fire on Spring Mountain during the 1950s/1960s may be linked to incendiary fires set to promote larger berry harvests as unemployment rates skyrocketed. Although high unemployment and dry conditions are associated with the Great Depression (1930s; Figure 5(c) and (e)), incendiary activities may have been buffered by high population density (Figure 5(d)) and

access to social support systems (e.g. churches). Additional study sites within the region, on private and public land, are necessary to test these hypotheses.

Unemployment may not be the only explanation for the abrupt mid-twentieth century increase in fire activity on Spring Mountain. Incendiary fires motivated by political or economic protest (Kuhlken, 1999) or fires set for the informal management of natural resources (Coughlan, 2016) may have also contributed to the observed patterns of fire. These causes are more difficult to assess in the context of this study, however, given that no relatable statistics exist for analysis. Nevertheless, Haines, Main, and McNamara (1978) note that "incendiary fires were an incidental percentage of total fires [in Pennsylvania] until the early 1950s". This timing corresponds to the abrupt increase in fires recorded by pitch pine on Spring Mountain, suggesting the few scars prior to 1954 accurately represent a period of infrequent fire. Fires, however, have continued to burn on Spring Mountain following the mid-twentieth century collapse of the anthracite industry despite above normal long-term moisture conditions and a further decrease in population density (see Figure 5(a)–(e)). Previous research indicates that the relationship between population density and fire activity is typically positive (Cardille, Ventura, & Turner, 2001) or non-linear (Guyette, Muzika, & Dey, 2002), relating to historical land-use practices and policy decisions. The observed patterns of late twentieth century and early twenty-first century fire activity on Spring Mountain may be associated with a sparse, mobile population with cultural ties to burning unique to the Pennsylvania Anthracite Region. Regardless of the motive, frequent fire since the 1950s has maintained the barrens complex on Spring Mountain (see Figure 1(c)–(e)) when many of the region's ridgetop barrens have been degraded by landscape fragmentation and fire exclusion. A regional network of fire history sites is necessary to elucidate landscape patterns in fire activity related to industrial decline and synoptic-scale climate variation, including ocean-atmosphere teleconnections (e.g. ENSO, NAO). This study also identifies a regional opportunity for further research in the realm of socio-ecological systems: addressing links between individual actions and culturally-mediated human-fire relationships (Coughlan & Petty, 2012).

Conclusions

Fire activity on Spring Mountain is primarily a reflection of trends in the regionally-dominant anthracite coal industry and population density. Fire-scar data and local fire records indicate weak or non-existent relationships between fire and drought, although some major fire events occurred during uniquely dry years/seasons. Increased fire frequency, particularly in the 1950s/1960s, corresponds to the collapse of the regional anthracite industry and statewide increases in incendiary fire. Fires continue to burn on Spring Mountain in the twenty-first century, although population levels are approximately equal to those at the turn of the twentieth century when fire was infrequent. This pattern may be associated with cultural ties to landscape burning and is not seen in other Pennsylvania or greater CHF fire histories. Additionally, four FRCs were identified using PCA and k-means cluster analysis. This approach, with its statistical limitations, provides a useful framework for describing temporal dynamics in fire regime characteristics and offers an alternative or supplement to the change point approach (Pezzatti, Zumbrunnen, Bürgi, Ambrosetti, & Conedera, 2013), which identifies abrupt shifts in individual variables. My results also suggest that informally managed ridgetop barrens can be maintained by an anthropogenic disturbance regime that

promotes habitat diversity. In a region lacking fire history information, additional fire-scar data sourced from both private and public lands will be necessary to describe human influences on fire regime dynamics.

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Disclosure statement

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