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Wave of fire: an anthropogenic signal in historical fire regimes across central Pennsylvania, USA

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Abstract. Increasingly detailed records of long-term fire regime characteristics are needed to test ecological concepts and inform natural resource management and policymaking. We reconstructed and analyzed twelve 350+ yr-long fire scar records developed from 2612 tree-ring dated fire scars on 432 living and dead pine (*Pinus pungens*, *Pinus rigida*, *Pinus resinosa*, *Pinus echinata*) trees from across central Pennsylvania. We used multiple spatial and time series analysis methods to quantify fire regime characteristics (frequency, seasonality, percentages of trees scarred, extent) and fire–climate–human associations. Prior to the 20th-century fire suppression, fire regimes at the majority of sites consisted of frequent, low-to-moderate severity, dormant season fires. Fires were often regionally synchronous when preceded by significantly dry years. Using documentary archives, we provide the first description of a "wave of fire"—an anthropogenic signal in fire frequency that progressively moved across the region. This "wave of fire" reflects a changing progression of anthropogenic fire regimes from Native American occupation and depopulation, to Euro-American settlement, to industrialization and declining fire use up to the 20th century era of fire suppression. The wave of fire provides a new perspective on historical and modern fire regime dynamics and identifies socio-ecological impacts since North American colonization. Because the anthropogenic wave of fire exists at sites across North America, we emphasize the need for a broader determination of its geographic prevalence and variability as such determinations could influence historical ecology interpretations and perspectives on past and future roles of humans in managing ecosystems with fire.

Key words: Appalachian Mountains; climate; dendrochronology; fire regimes; fire scar; pitch pine; red pine; shortleaf pine; Table Mountain pine.

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INTRODUCTION

Throughout the world, wildland fire science provides context for natural resource management and policymaking (Bradstock 2010, Moritz et al. 2012, Scott et al. 2013). Understanding how fire influences ecosystem biodiversity, biogeochemistry (Archibald et al. 2012, Noss et al. 2015), and global change (Krawchuk et al. 2009) is at the forefront of natural resource management and earth and social sciences (Knorr et al. 2016). Despite strong interconnections, emphasis has been placed on understanding wildland fire in physical and biological contexts, with social contexts being less understood and developed (Pyne 2007). For all of these contexts, multi-century fire records have provided perspective and a foundation for advancement, including managing fire regimes in the future (Swetnam et al. 1999).

Multiple lines of evidence indicate that climate and humans have been primary drivers of fire regimes during recent millennia. Historical linkages among climate, humans, and fire regimes are complex and difficult to disentangle without robust evidence and causal mechanisms. Anthropogenic fire is increasingly recognized as having significant influence on past ecosystems, especially vegetation conditions (Bowman et al. 2011, Holz et al. 2016, Taylor et al. 2016). In recent centuries, global fire regime alterations by humans since the Industrial Revolution appear unprecedented in magnitude and dynamics compared to recent millennia (Marlon et al. 2008, Bowman et al. 2009).

Pursuits toward determining the relative roles of climate and humans in fire regimes have led to debates on diverse topics such as wilderness ideology, ecosystem processes, and modern era fire management. Separating historical climate and human influences on fire is confounded by the inability to distinguish ignition sources since no tools or techniques are available to discriminate between human- and lightning-caused fires detected by natural archives (e.g., charcoal and fire scar records). Little hope for improving this distinction exists since concomitant responses occur among lightning and human ignitions. For example, lightning ignitions commonly co-occur with coherent weather controls (Bartlein et al. 2008), while anthropogenic ignitions can result from diverse activities and potentially be forced to overcome otherwise limiting weather and environmental controls (Williams 2003). Extreme climate and weather conditions can limit or enhance both lightning and anthropogenic ignition rates. Further, within relatively small spatial extents, both ignition types may be dominant (Muzika et al. 2015). For these reasons and others, studies have focused on identifying associations, signatures, and signals to distinguish climate and human forcing of fire regimes. Examples of these include the following: frequency of modern era fire causes, spatial patterns of historical fires (Niklasson and Granstrom 2000, Flatley et al. 2011), variance characteristics in fire activity at decadal to century scales (Kitzberger et al. 2007, Bowman et al. 2009), fire seasonality comparisons from historical to modern eras (Evett et al. 2007), strength and changes in climate–fire associations (Muzika et al. 2015), and associations among human occupations and vegetation types (Black et al. 2006).

Fire regimes and fire-dependent forests in the northeastern USA

For many social, biological, and geophysical reasons, U.S. fire science, management, and policy have often been divided into eastern and western regions at the transition of the Great Plains and Rocky Mountains (Pechony and Shindell 2010). In recent decades, the regions have differed in that fire emphasis in the eastern USA has been more commonly placed on prescribed fire management, particularly in ecological restoration contexts (Nowacki and Abrams 2008, 2014, Noss et al. 2015, Pederson et al. 2015, Freeman et al. 2017), while western U.S. emphasis has been more commonly on wildfire management, particularly in risk and suppression contexts (Miller et al. 2012, Stephens et al. 2016). Within the eastern USA, fire research and management has been perhaps least emphasized in the northeastern regions (Hart and Buchanan 2012, Lafon et al. 2017), despite presence of fire-dependent ecosystems and potential for frequent, extensive, and high-severity fires (Little 1979).

A synthesis of paleoecological and dendrochronological studies from northeastern USA shows a paucity of historical fire regime information, even compared to adjacent Great Lakes and southern Appalachian regions (Brose et al. 2014). Paleoecological (pollen, charcoal) studies suggest that, during the late Holocene, anthropogenic fire use overrode climatic controls on vegetation at broad scales (Abrams and Nowacki 2015). Prehistoric increases in sedimentary charcoal in the eastern USA have been shown to be coincident with periods of cultural transition (Hart and Buchanan 2012); however, the roles of human and lightning ignitions continue to be debated (Parshall and Foster 2002, Nowacki and Abrams 2008, Matlack 2013). While strong human controls on fire regimes have been documented in pre- to post-Euro-American settlement (EAS) fire regimes of the Central Hardwoods and Appalachian regions, the evidence has been less consistent in more northeasterly regions.

Site-to-site variability in charcoal records makes it difficult to apply results from one site to the entire northeastern USA. Charcoal data from Trout Pond in eastern West Virginia (Lynch and Clark 2002, Lafon et al. 2017) indicated frequent, low-severity fires with occasional mixed- or high-severity fires over the last millennium. Sedimentary charcoal data from across New England also consistently showed fire activity significantly increased following EAS (Parshall and Foster 2002, Patterson 2006). Some examples link Native American (i.e., Iroquois) activity to increased fire frequency and vegetation changes (Clark and Royall 1995).

Many early written descriptions of Native American fire use exist in the eastern USA (Day 1953). Descriptions tend to be geographically biased in that early explorations and settlements were concentrated along coastal margins or major river valleys, near where Native American populations were concentrated (Hutch 2000, Lorimer and White 2003, Black et al. 2006). Further, descriptions typically lack information about fire causes or characteristics. Descriptions of contact-era upland interior forests are much more obscured. Witness trees used for early land surveys can provide indirect evidence of fire's importance in these locations, but do not reveal fire regime characteristics.

Dendrochronological fire scar studies in the eastern USA, though relatively sparse, provide annually resolved fire regime information spanning up to five centuries. Some studies have documented significant fire regime changes associated with EAS (Brose et al. 2015), while others have not (Shumway et al. 2001, Aldrich et al. 2010). From the central Appalachians northward, historical fire regimes are estimated to have trended toward decreased frequency due to lower annual temperatures which directly decrease combustion potential (Guyette et al. 2012). More northerly latitudes also experience decreased fire frequency as a result of shortened fire seasons and increased occurrence of frozen precipitation. These factors, combined with strong seasonal changes in fuel flammability, cause fire seasonality to be confined closer to the growing season in northerly extents than in the central USA (Brose et al. 2015).

Despite lightning ignitions being relatively uncommon and climate conditions being conducive to infrequent fires in the northeastern USA, many locations had frequent fire regimes and many vegetation communities were fire-dependent (Nowacki and Abrams 2014). Fire-dependent tree species in the northeastern USA include pitch pine (*Pinus rigida*), shortleaf pine (*Pinus echinata*), red pine (*Pinus resinosa*), jack pine (*Pinus banksiana*), and Table Mountain pine (*Pinus pungens*; Ledig and Little 1979, Carey 1992, Keeley and Zedler 1998, Gucker 2007, DeWeese 2007, Reeves 2007, Hauser 2008). Except on extremely exposed sites, these tree species fail to regenerate and recruit into canopy positions without recurring fires due to competition and seed, seedbed, and light requirements.

Over the last century, the combined effects of harvesting and fire suppression have caused many fire-dependent communities in the eastern USA to be replaced by a less diverse suite of shade-tolerant and fire-intolerant vegetation (Nowacki and Abrams 2014). Fire management of these communities is essential to maintaining biodiversity from stand to landscape scales (Anand et al. 2013) and, although biodiversity in these forest types can occur at many taxonomic levels (Carleton and Arnup 1993, Frelich et al. 2003), little is known about their natural stand dynamics or historical fire regimes.

The primary objective of this study was to document historical fire regime characteristics (frequency, severity, seasonality, extent) at sites throughout central Pennsylvania that previously supported fire-dependent pines. Our core hypothesis was that frequent and recurring fires were associated with these remnant pine forests. Lightning-ignited fires, even in droughty conditions, are relatively uncommon and unlikely to maintain fire regimes to any extent (PA Statistics 1979–2015). Where human ignitions have continued to be somewhat frequent (e.g., fires occurring once per decade or two through arson or prescribed fire management), fire-adapted pines show potential to be sustained through the promotion of suitable seedbeds for regeneration, selection against competing fire-intolerant vegetation, and maintenance of open canopy conditions (Pennsylvania Game Commission [PGC] management document; Saladyga 2017). Thus, we hypothesized that these were strongly anthropogenic fire regimes and, as such, changes in fire regime characteristics corresponded to changing human activities. The geography and history of Pennsylvania are uniquely suited to address this hypothesis owing to (1) relatively early and well-documented colonization and settlement including times preceding Native American removal and (2) the abundance of old, preserved, remnant pine trees available to reconstruct records of past fire events from fire scars.

MATERIALS AND METHODS

Study sites

From 2014 to 2016, we surveyed 55 PGC management areas (Gamelands) for evidence of remnant fire-dependent pine forests and evidence of fire scars on trees. From this survey, seven study sites were identified in an approximately 65,000-km^2 area of central Pennsylvania that included the Ridge and Valley and Appalachian Plateaus Physiographic Provinces (Fig. 1; Appendix S1). We deemed sites suitable if forty or more fire-scarred dead and live trees existed within approximately 1-km^2 areas. Sampling areas of 1 km^2 allows fire history data to be comparable to other sites (Falk et al. 2007, Stambaugh et al. 2016). We attempted to separate study sites by at least 10 km, including those we previously reported (Brose et al. 2014, Marschall et al. 2016), to produce a broad, spatially distributed site network. Of the seven new sites, five were located in the Ridge and Valley Physiographic Province and two in the Appalachian Plateaus Physiographic Province (Sevon 2000, Table 1, Fig. 1; Appendix S1). Three of the Ridge and Valley study sites were located in the Appalachian Mountains Section, and two were located in the Anthracite Uplands Section (Sevon 2000). Both of the Appalachian Plateaus study sites were located in the Deep Valleys Section (Sevon 2000). Data from sites previously reported were used in comparisons and regional-extent analyses. All sites occurred at higher elevations, on side slope and ridgetop positions, and had moderate to steep topography, and stony to sandy loam soils (Table 1; Appendix S1).

Field and laboratory work

Field sampling involved collecting full and partial cross-sections near the ground level of dead and live pines (stumps, down and standing trees) using a chainsaw. Collections included hard pine species because of their ability to survive fire scarring and resist decay due to high resin content. Tree species varied by site (Table 1) and, at some sites, may have been mixed. Most trees sampled showed external evidence of callus tissue and charcoal from past fires. We were especially careful to ensure that all fire scars evidenced on outer tree portions were captured on cross-sections which, for some trees, required collecting multiple samples from individual trees. We did not sample trees whose wood was severely decomposed (i.e., tree rings and fire scars obscured) or when fewer than sixty tree rings were present, which would limit ability to crossdate them. Cross-sections were marked to indicate orientation (aspect) and slope of surrounding terrain (direction and degree). We recorded sample locations with a GPS unit (3-m accuracy) and photographed them to document scarring, sample conditions, and physical settings. Following sampling, we measured study site areas using ArcGIS (ESRI 2016) with a polygon bounded by the sample extent.

In the laboratory, we sanded cross-sections with progressively finer sandpaper (80–1200 grit) to reveal the cellular detail of annual rings and fire scars. We measured tree rings in sequence to 0.01 mm precision using a Velmex TA measuring system (Velmex, Bloomfield, New York, USA), and then, we plotted tree ring-width series and visually crossdated them following standard techniques (Stokes and Smiley 1968). Due to the lack of existing multi-century pine ring-width chronologies in the region, we developed new master dating chronologies for each site by crossdating sample ring-width series against each other. Ring-width plots and the software program COFECHA (Holmes 1983, Grissino-Mayer 2001*a*) were used to perform quality control on crossdating accuracy. For each site, all sample tree-ring measurements were developed into standardized master chronologies by detrending and standardizing ring-width series using ARSTAN software (Cook 1985). This process progressively led to construction of absolutely dated master chronologies with the inclusion of samples from living trees. In addition, we assessed and confirmed dates by crossdating new master dating chronologies against those developed for previous studies in Pennsylvania (*unpublished data*, Missouri Tree-Ring Laboratory, University of Missouri; Brose et al. 2013, Marschall et al. 2016).

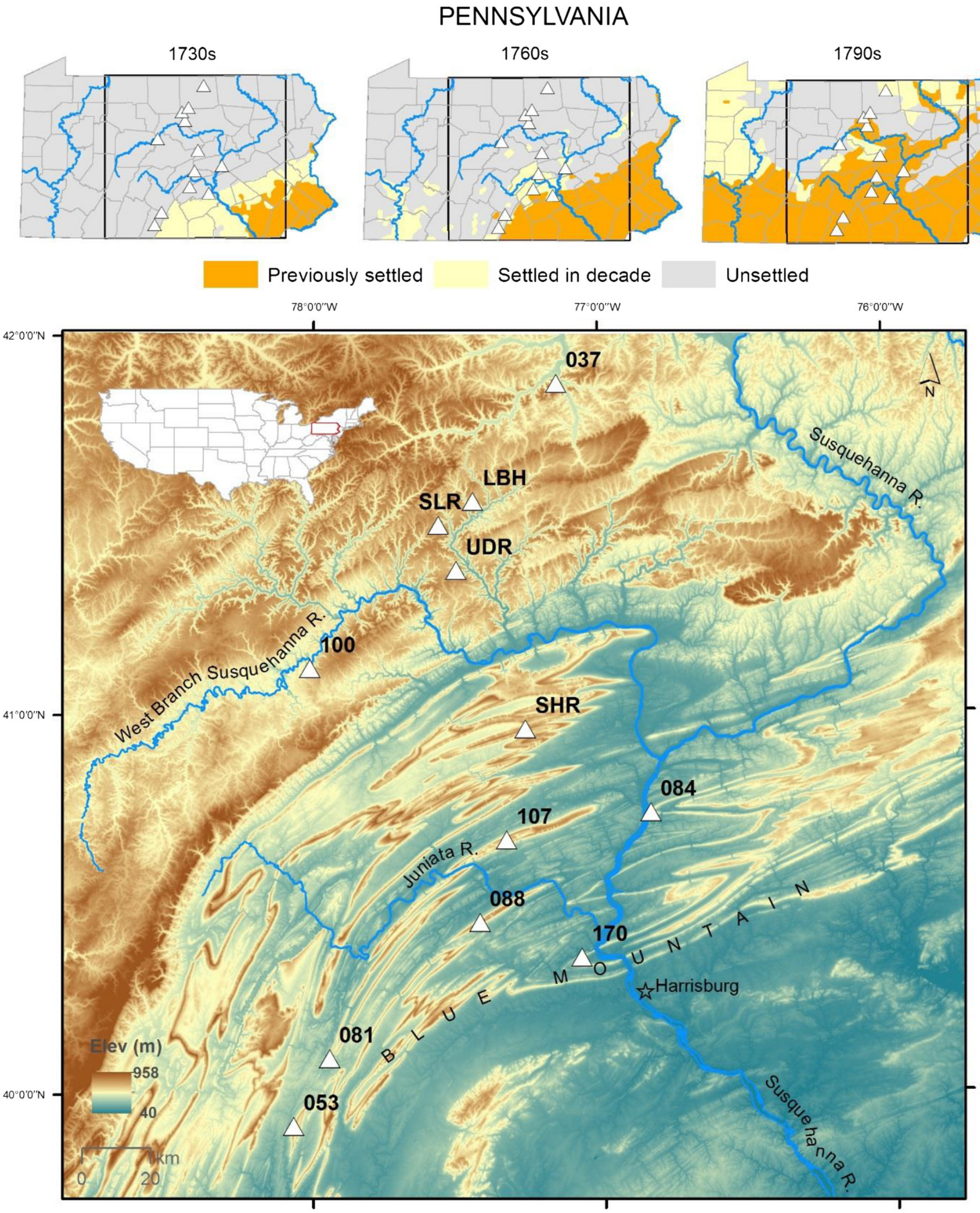

Fig. 1. Top: Maps showing progression of Euro-American settlement across Pennsylvania during the 18th century (adapted from Florin 1977). White triangles represent study site locations, and blue lines are major rivers. Area of central Pennsylvania outlined in black (enlarged below). Bottom: study sites (white triangles; includes sites used in analysis from Brose et al. 2013 and Marschall et al. 2016) relative to central Pennsylvania topography and major riverways.

Table 1. Study site characteristics.

Site	Latitude	Longitude	Samples (n)	Tree species	Site area (km^2)	Site length (km)	Elev. (m)	Province/ Section[1]	Soils	Settlement date
053	N39 55.151	W78 04.016	33	TMP	0.11	1.45	545	RV/AM	EStSL[2]	1755[9,19]
081	N40 05.870	W77 56.640	48	PP, TMP, SLP	0.22	0.78	433	RV/AM	EStSL[2]	1755[9,10,19]
088	N40 27.319	W77 25.448	32	PP	0.70	1.56	606	RV/AM	EStSL[4]	1755[10,11]
170	N40 21.737	W77 04.351	43	PP, TMP	0.83	3.22	367	RV/AU	EStSL[5]	1755[10,12]
107	N40 40.363	W77 19.856	33	PP	0.61	1.14	513	RV/AM	EStSL[4]	1755[10]
084	N40 44.571	W76 49.697	47	PP, TMP	0.80	1.97	418	RV/AU	EStSL[3]	1768[13,18]
SHR	N40 57.872	W77 15.746	33	PP	0.22	1.78	646	RV/AM	EStSL[6]	1786[14]
UDR	N41 23.452	W77 29.710	28	RP	0.13	0.67	~550	AP/DV	VStSL[19]	1790
SLR	N41 30.229	W77 33.709	30	RP	1.18	1.69	~550	AP/DV	VStL[19]	1790
LBH	N41 33.734	W77 26.711	35	RP	0.31	1.85	~550	AP/DV	VStL[19]	1790
037	N41 51.720	W77 10.440	38	RP	0.21	1.34	500	AP/DV	VStL[7]	1795[15,16]
100	N41 07.612	W78 00.777	32	PP	2.44	3.58	499	AP/DV	EStSL[6]	1820[14,17]

Notes: Abbreviations for tree species are TMP, Table Mountain pine (*Pinus pungens*); PP, pitch pine (*Pinus rigida*); SLP, shortleaf pine (*Pinus echinata*); RP, red pine (*Pinus resinosa*). Abbreviations for province/section are RV, Ridge and Valley; AP, Appalachian Plateaus; AM, Appalachian Mountain; AU, Anthracite Uplands; DV, Deep Valleys. Other abbreviations are EStSL, extremely stony sandy loam; VStL, very stony loam; EAS, Euro-American settlement. Sources appear as superscripted numbers: 1, Sevon (2000); 2, Knight (2004); 3, Eckenrode (1985); 4, Lipscomb and Farley (1981); 5, Zarichansky (1986); 6, Braker (1981); 7, Rayburn and Braker (1981); 8, Greathead (1936); 9, Unkn. (1884); 10, Jordan (1913); 11, Ellis (1886); 12, Hain (1922); 13, Bell (1891); 14, Linn (1883); 15, Brown (1897); 16, Unkn. (1883); 17, Quay (1860); 18, Unkn. (1876); 19, Kohler (1986).

We identified all fire scars on cross-sections based on presence of cambial injuries often associated with charcoal, callus tissue, traumatic resin canals, and zones of resin liquefaction (Gutsell and Johnson 1996). If viewable, we recorded fire scar seasonality following methods described by Kaye and Swetnam (1999), whereby scars are classified based on their position within the annual ring anatomy. Seasonality classes were dormant season (i.e., scar located between rings), four growing season positions progressing through the ring (i.e., early earlywood, middle earlywood, late earlywood, and latewood), or unknown when scar position could not be determined. We dated all fire scars to the calendar year of cambial response to injury. In this way, fire events occurring in the dormant season were assigned the subsequent, not prior, calendar year. We compiled fire event data by tree and entered fire scar data into both the FHX2 software (Grissino-Mayer 2001*b*) and Fire History Analysis and Exploration System (FHAES; Brewer et al. 2016) to facilitate data stratification and statistical analysis at site and regional levels.

Historical fire regimes

We characterized site-level fire regimes based on fire frequency, seasonality, and percentage of trees scarred (fire severity/extent). All metrics were calculated for the full periods of record and three sub-periods corresponding with changes in human cultures and populations: pre-EAS, post-EAS, and fire suppression (Table 2). Sub-period dates were determined through review of historical documents for fire history sites (see *Humans* below and Appendix S1). Fire frequency was described through ranges of fire intervals, mean fire intervals (MFIs), and Weibull median intervals (WMIs). Mean fire intervals were calculated as the average number of years between fire events based on the composite fire interval data—the record of fire events based on all fire scars on all trees at a site (Grissino-Mayer 2001*b*). For WMIs, we modeled fire interval distributions at each site using a two-parameter Weibull distribution and Kolmogorov–Smirnov goodness-of-fit test and, when significant, reported WMIs as another metric of fire interval central tendency. All fire frequency statistics were calculated for the periods of record when a minimum of three trees were in the record. Fire seasonality of events was summed by class and described as percentages of all fire events. We also reported the proportion of dormant vs. all growing season events, regardless of timing. Percentage of trees scarred was calculated for all fire event years. Presumably, all identified/recorded fires

Table 2. Fire interval statistics by site for four time periods.

Site	Years	Scars (*n*)	Fire years (*n*)	MFI (yrs)	SD	Range (yrs)	WMI (yrs)	LEI (*n*)	UEI (*n*)	Mean % scarred
All years										
053	1627–2013	132	37	7.47	7.42	1–43	6.07	1.63 (1)	14.55 (4)	22.3
081	1638–2014	272	39	8.26	8.09	1–45	6.64	1.75 (2)	16.15 (3)	27.0
088†	1663–2013	200	56	5.07	4.22	1–21	4.30	1.31 (5)	9.53 (5)	18.7
170	1621–2010	169	55	5.65	6.13	1–34	4.30	1.00 (1)	11.37 (5)	14.7
107†	1644–2013	387	44	5.74	6.95	1–37	4.32	0.98 (0)	11.66 (3)	46.1
084	1623–2014	172	38	6.41	5.23	1–22	5.43	1.65 (1)	12.03 (3)	20.6
SHR	1592–2010	288	37	5.09	3.82	1–19	4.44	1.46 (2)	9.29 (4)	39.2
UDR‡	1632–1950	217	31	9.30	17.89	1–100	5.69	0.90 (0)	19.51 (2)	37.9
SLR‡	1594–2010	147	23	13.09	21.56	3–106	8.68	1.55 (0)	27.39 (1)	41.7
LBH‡	1603–2010	144	21	18.75	29.49	1–102	10.41	1.39 (1)	39.95 (3)	47.1
037	1614–2014	250	36	7.89	8.92	1–40	5.79	1.25 (1)	16.12 (4)	35.2
100	1660–2014	234	34	6.82	11.03	1–61	4.26	0.67 (0)	14.40 (4)	35.2
Pre-Euro-American settlement era										
053	1627–1754	19	10	12.22	12.10	4–43	10.06	2.79 (0)	23.67 (1)	30.1
081	1638–1754	73	11	10.20	12.58	1–45	7.43	1.57 (1)	20.91 (1)	29.0
088†	1663–1754	39	15	5.64	4.86	1–21	4.82	1.49 (1)	10.56 (1)	14.6
170	1621–1754	55	20	6.26	7.50	2–34	4.68	1.05 (0)	12.74 (2)	14.8
107†	1644–1754	39	10	12.00	12.09	2–37	9.23	2.20 (1)	23.98 (2)	51.2
084	1623–1767	26	11	6.20	5.90	2–21	5.05	1.37 (0)	12.04 (1)	10.4
SHR	1592–1785	117	10	8.11	5.37	3–19	7.38	2.81 (0)	14.06 (1)	47.1
UDR‡	1632–1789	14	5	32.00	45.41	7–100	19.19	2.86 (0)	68.34 (1)	37.5
SLR‡	1594–1789	53	5	36.25	46.68	8–106	24.38	4.44 (0)	75.96 (1)	60.8
LBH‡	1603–1789	19	3	57.00	n/a	12–102	n/a	n/a	n/a	43.7
037	1614–1794	62	10	15.78	14.12	2–40	12.19	2.97 (1)	31.25 (2)	39.9
100	1660–1819	49	5	17.75	3.50	14–22	18.01	14.00 (1)	21.30 (1)	50.8
Euro-American settlement era										
053	1755–1914	113	27	5.96	4.39	1–19	5.22	1.75 (1)	10.82 (3)	19.0
081	1755–1914	188	25	6.25	4.50	1–19	5.52	1.89 (1)	11.26 (3)	24.3
088†	1755–1914	156	38	4.22	2.94	1–15	3.76	1.33 (4)	7.51 (6)	19.7
170	1755–1914	103	32	4.74	5.35	1–27	3.59	0.82 (0)	9.59 (3)	12.9
107†	1755–1914	348	34	3.97	3.51	1–21	3.40	1.06 (3)	7.43 (2)	44.7
084	1768–1914	137	25	5.42	3.23	1–12	5.01	2.03 (3)	9.16 (3)	22.9
SHR	1786–1914	171	27	3.85	2.36	1–10	3.55	1.41 (2)	6.55 (1)	36.3
UDR‡	1790–1914	203	26	4.92	2.94	1–13	4.55	1.85 (1)	8.32 (2)	38.0
SLR‡	1790–1914	94	18	6.94	4.31	3–21	6.43	2.60 (0)	11.77 (1)	37.6
LBH‡	1790–1914	123	17	7.25	4.09	1–14	6.72	2.81 (2)	12.03 (2)	47.0
037	1795–1914	186	25	4.50	2.99	1–11	4.07	1.50 (1)	7.90 (4)	33.7
100	1820–1914	184	28	3.22	1.89	1–8	2.98	1.22 (6)	5.42 (4)	33.0
Fire suppression										
053	1915–2013	0	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a
081	1915–2014	11	3	32.33	21.50	14–56	n/a	n/a	n/a	41.1
088†	1915–2013	5	3	25.50	24.28	8–61	n/a	n/a	n/a	26.2
170	1915–2010	11	3	31.00	39.05	6–76	n/a	n/a	n/a	33.6
107†	1915–2013	0	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a
084	1915–2014	9	2	46.0	38.18	19–73	n/a	n/a	n/a	47.5
SHR	1915–2010	0	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a
UDR‡	1915–1950	0	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a
SLR‡	1915–2010	0	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a
LBH‡	1915–2010	2	1	50.50	68.59	2–99	n/a	n/a	n/a	66.7

(Table 2. *Continued*)

Site	Years	Scars (n)	Fire years (n)	MFI (yrs)	SD	Range (yrs)	WMI (yrs)	LEI (n)	UEI (n)	Mean % scarred
037	1915–2014	2	1	52.0	59.40	10–94	n/a	n/a	n/a	25.0
100	1915–2014	1	1	52.5	12.02	44–61	n/a	n/a	n/a	20.0

Notes: MFI, mean fire interval (yr); SD, standard deviation (yr); WMI, Weibull median interval (yr); LEI, lower exceedance interval (number of occurrences); UEI, upper exceedance interval (number of occurrences). Fire years is number of years with fire scars.

† Data from Marschall et al. (2016).

‡ Data from Brose et al. (2013).

were non-stand-replacing events since trees were present in all portions of the records.

We characterized the regional-level fire regime using all site data including data from five previously published sites (Brose et al. 2013, Marschall et al. 2016, Table 2, Fig. 1). Fire interval statistics previously published by Brose et al. (2013) were re-calculated to have methodological consistency with the other sites reported here (e.g., consistent pre-EAS and settlement time periods, same statistics reported), but the data were preserved as originally published. Regional fire records were developed iteratively as: years with fires occurring at two sites, years with fires occurring at three sites, up to years where fires occurred at 10 sites. We expected that if fire regimes were influenced by site to regional influences (e.g., synoptic-scale climate patterns, topography, human settlement), then spatial correlation would exist in fire event data. To test this, we calculated Jaccard similarity (SJ) indices as

$$\mathrm{SJ} = \frac{A}{A+B+C} \tag{1}$$

where A is the number of years in which both sites record fire (1, 1), B is the number of years only one of two sites record fire (1, 0), and C is the number of years only the other site records fire (0, 1). All Jaccard similarity values were calculated with FHAES. We calculated Pearson correlations and conducted regression analyses to test and model the relationship between Jaccard similarity of fire years among paired sites and their Euclidean distance. This analysis was conducted over a common period of 1663–2010. To supplement this analysis, we constructed a heat map to visualize spatial relatedness in Jaccard similarity between sites with colored gradients of Jaccard similarities. For these, we ordered sites by EAS date, approximately southeast to northwest (Fig. 1).

Climate

Climate of central Pennsylvania is humid and continental, generally lacking dry summers or winters (Peel et al. 2007). Mean annual precipitation ranges from ~86 to 127 cm across the region, while mean annual temperatures range from 6.1° to 12.2°C (1981–2010; Daly et al. 2004). Precipitation is distributed throughout the year with May being the wettest month. Maximum temperatures occur in July with average temperatures maintained above 26.7°C in the summer (June, July, August). Vegetation production is such that ample fuels exist for fires to occur throughout the region allowing fire activity to positively respond to increases in drought severity. For these reasons, we chose drought conditions as the climate parameter to analyze spatio-temporal fire occurrence patterns.

Over the periods of fire event records, we compiled annual Palmer Drought Severity Index (PDSI; Palmer 1965) reconstructions in the region of central Pennsylvania (grid points 254, 255; Cook et al. 2004, Fig. 2). Because the drought variability from these two sites is very similar (Fig. 2) and our fire records covered a large region, we conducted fire-drought analyses using annual mean PDSI value of both grid points. We analyzed fire-drought associations using superposed epoch analysis (SEA). Superposed epoch analysis tested whether drought conditions associated fire events were significantly different (wetter or drier) than expected. In this analysis, we considered lagged conditions including six years preceding and four years after fire events. We conducted SEA for fire records at each study site considering all years in the tree-ring record and then by two sub-periods

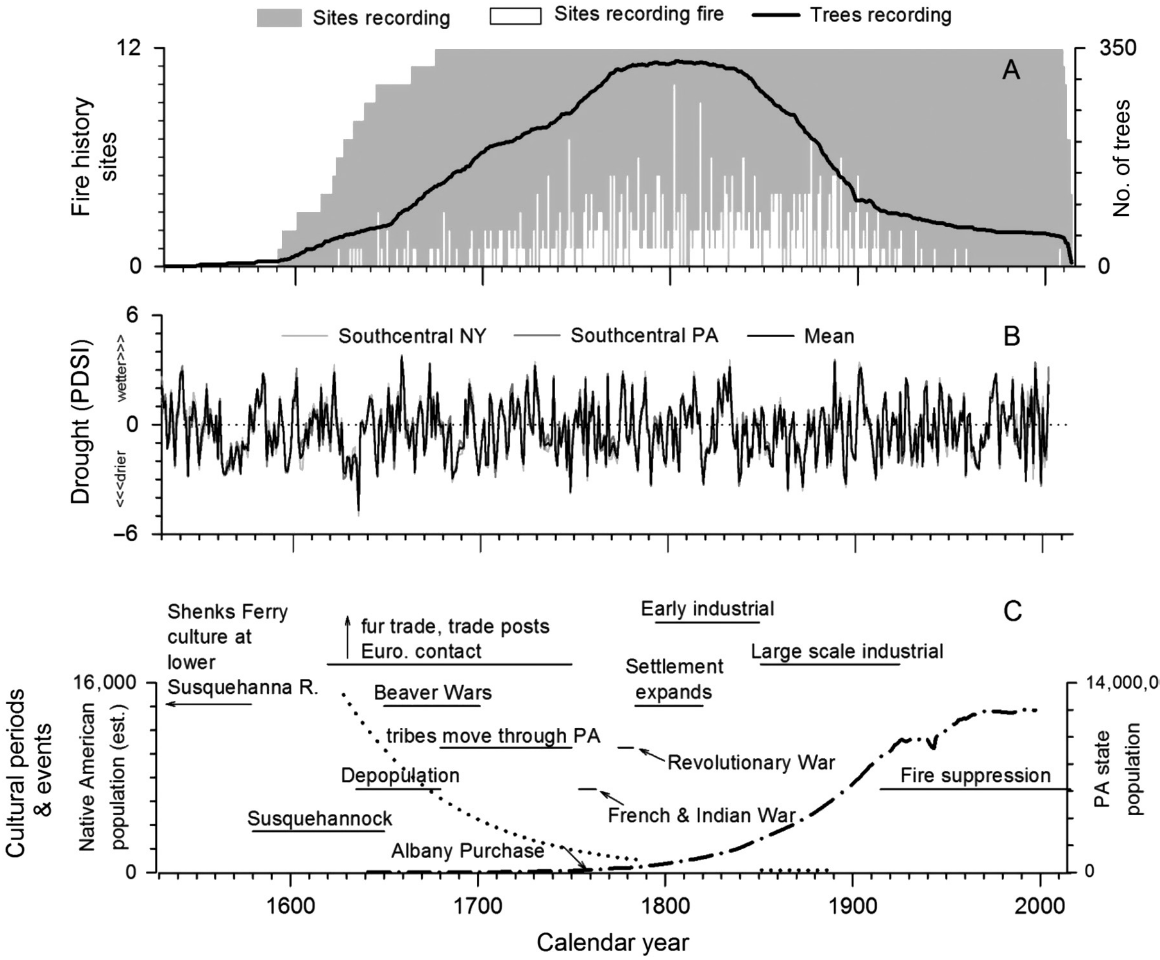

Fig. 2. (A) Fire history data characteristics through time. (B) Reconstructed summer season Palmer Drought Severity Index (Cook et al. 2004) for two grid points (southcentral New York [NY] and southcentral Pennsylvania [PA]) and the mean drought condition. (C) Historical cultural periods, significant events, and population changes (dotted = Native American, dash-dot = state-level) in Pennsylvania.

corresponding with pre- and post-EAS (see *Humans* below). We conducted SEA separately using drought data from individual grid points and then mean PDSI of the two grid points. We tapered drought reconstruction datasets to begin in year 1500 common era (CE) and considered climate conditions significantly different than expected when exceeding the 95% confidence intervals. Confidence intervals were derived by bootstrapping data for 1000 simulated events. In addition, we also conducted SEA iteratively for years when fires occurred at two sites, three sites, up to six sites. Although there were years when fires occurred at seven, nine, and 10 sites, the number of years was too few to test. Based on prior analyses of networks of fire scar data (Stambaugh et al. 2014), we hypothesized that by iteratively conducting SEA with years of increasing fire occurrence, a significant relationship between regional drought and fire occurrence would be detected at a broader scale.

Humans

We synthesized the regional human history of the past five centuries through a literature review that focused on identifying cultural groups and changes in their locations, populations, and land uses. Generally, our fire history records begin during a period when Native American populations were declining due to disease epidemics and conflict including the initial effects of U.S. colonization (Hulbert 1910, Cronon 1983, Williams 1989, Stewart 2002). The Native American population of Pennsylvania at the earliest times of EAS (~1636) has been conservatively estimated at 15,000 (Florin 1977). At this time, Native American populations in Pennsylvania were associated with the major river systems (Fig. 1). The Delaware River basin, forming the eastern border of Pennsylvania, was home to the Lenape tribe. The pre-Colonial Lenape population was estimated to have been 8000–12,000 (Brandon 2003), though the portion residing in an area that is presently southeastern Pennsylvania is estimated at 1000 or less (WPA 1940). The Susquehanna River was occupied by the Susquehannock, who inhabited scattered villages along the river and were estimated to have numbered about 5000–7000 in 1608 (Minderhout 2013). The Monongahela culture occupied southwestern Pennsylvania, and Iroquoian-language groups occupied lands along the Allegheny River. Other Native American groups existed along the west branch of the Susquehanna and along the Juniata River, though relatively little is known about them (Kent 1984).

We reviewed multiple documentary sources associated with each study site (Appendix S1). A primary objective was to determine a site-specific calendar year of EAS that could be used to stratify fire records and investigate temporal fire regime changes. Sources consisted of treaty and land purchase documents that stated when areas were opened for legal settlement. We augmented these data by county history publications which added local detail of the patterns and timing of EAS, usually at a Township level (~16–104 km^2). We investigated, where possible, the establishment dates of towns and cities near to study sites. This information was considered and compared with the works of Florin (1977) and Simkins (1995) to determine a year that reflected the timing at which Euro-American settlers began populating the local region of each study site. The amount and level of detail of information available on the history of settlement varied by site, with more topographically rugged and remote sites generally being less well documented. We stratified fire regime analyses into a pre- and post-EAS period using settlement dates.

European settlement of Pennsylvania began in 1636 with the first colony of Dutch and Swedes along the Delaware River. They existed in small numbers for about 40 yr, until the first British colonists arrived in Penn's Woods in 1683. The population of Pennsylvania expanded rapidly, advancing from the southeast corner in a north and westerly direction (Fig. 1). By 1740, southeastern Pennsylvania was settled to Blue Mountain, approximately 100 km northwest of Philadelphia. A second era of rapid population expansion occurred at the end of the French and Indian War in 1763, pushing European settlers another 100–150 km west and northwest through current day Juniata, Huntingdon, and southern Centre Counties. A final era of settlement occurred in the 1790s after the Land Act of 1792 opened northwestern Pennsylvania to settlers and land speculators (Florin 1977). By this time, Native American populations in Pennsylvania had been reduced to around 1000 (WPA 1940, Florin 1977).

The post-EAS period represented an era of varied land use and industrialization with perhaps the greatest impact on fire regimes being fire suppression policies of the early 20th century. Large fires and increased burning is documented during this period. While fire suppression efforts gradually increased in effectiveness over a period of several decades, we chose to designate 1915 as the end of the post-EAS period and beginning of the suppression era, based on the establishment of the Pennsylvania Bureau of Forest Fire Protection in that year (Decoster 1995, Brose et al. 2001).

Analysis of changes in human–fire relationships often occur at decadal or longer time scales (Guyette et al. 2002, Marlon et al. 2008, Brose et al. 2015, Lafon et al. 2017). For this reason, we calculated the number of fires per decade (FPD) for each site from fire event records. Summary statistics of FPD were calculated to visualize decadal variability and amplitude whereby exposing a waveform in FPD records repeated among sites. We utilized multiple signal processing and detection techniques to explore time series waveforms. First, we further smoothed FPD records with a 17-yr moving average to visualize lower frequency variations and explore waveform persistence. We hypothesized that waveforms were caused by changes in human cultures, populations, and land uses, since patterns like this have been documented in other regions with anthropogenic fire regimes (Guyette et al. 2002), and waveform changes were generally consistent with timing of other human–fire histories in Pennsylvania (Brose et al. 2013, Marschall et al. 2016, Saladyga 2017). To address this hypothesis, we tested for significant changes in fire interval lengths and serial variance in FPD. Next, we calculated lower and upper exceedance intervals (LEIs, UEIs; 95% exceedance intervals) based on the probability distribution function of a fitted Weibull distribution and plotted their occurrence through time and associated with EAS timing. Due to the preponderance of short intervals, LEIs were rarely exceeded. Upper exceedance intervals were plotted by pre- and post-EAS periods. Lastly, we realigned fire records by EAS dates instead of by calendar year (i.e., records aligned with dates of EAS = 0) to conduct serial variance tests. If humans were influencing fire activity, we expected that realignment by dates of EAS would result in increased coherency and reduced serial variance in FPD records among study sites. Serial variance was measured as the standard deviation of FPD among all sites. Following realignment, we also measured changes in serial variance by calculating the first difference of FPD (i.e., year-to-year rate of FPD changes) and expected that high rates of change in serial variance would be concomitant with EAS.

RESULTS

Historical fire regimes

Fire-scarred remnant trees were present across the majority of the 55 PGC lands surveyed. Generally, fire scar faces on trees were <1.5 m tall. Most fire-scarred trees exhibited multiple scars with 10 fire scars per century being common. Across the seven new study sites, a total of 1517 fire scars on 274 trees were crossdated and compiled into fire event records (Table 2, Figs. 2, 3). Site tree-ring chronologies ranged from 354 to 418 yr in length with a maximum time span of calendar years 1592–2014 CE.

The number of unique fire event years recorded at sites ranged from 34 to 55. Across all sites, fire intervals ranged from 1 to 61 yr. Annual burning (fires in subsequent years) occurred at all sites and most commonly during the mid- to late-19th century. Fire intervals longer than 61 yr existed at the beginnings and ends of records but were not assigned lengths due to being "open" intervals. Considering these, the longest fire interval at any site prior to EAS was 118 yr (site SHR, period: 1592–1710 CE). Relatively long fire intervals at the beginning of fire records were also observed at site 100, where there were 69 yr (1676–1745 CE) before the first fire scar, and at site 084, where there were 81 yr (1623–1704 CE) before the first fire scar. In times post-EAS (with the exception of site 100 which had a fire scar occurring on one tree in 1970), at the time of sampling, all of the study sites were in the longest fire-free period of their entire record with the number of years since the last fire ranging from 56 to 119 (mean = 74.0). For all years in the records, site MFIs ranged from 5.1 to 8.3 yr, while WMIs ranged from 4.3 to 6.6 yr (Table 2). Also for all years in the records, the mean percentage of trees scarred during fire years ranged from 14.7 to 39.2 among sites (Table 2). Overall, the most frequently burned sites prior to 1915 (i.e., prior to fire suppression era) were those located in the center of our study region (i.e., Ridge and Valley; sites 084, 088, 107, 170). Fire intervals at sites located in the northern and southern extents were generally longer, especially in the pre-EAS time period.

In the pre-EAS period, a total of 401 fire scars (range 19–117) and 77 fire years (range 5–20) were identified across the seven study sites. Pre-EAS MFIs at these sites ranged from 6.2 to 17.8 yr, while WMIs ranged from 4.7 to 18.0 yr (Table 2). The mean percentage of trees scarred ranged from 10.4 to 50.8 (Table 2). Percentages of trees scarred declined for most sites from the pre- to post-EAS periods. For the period spanning post-EAS through the beginning of the fire suppression era (1914), a total of 1082 fire scars (range 103–188) and 189 fire years (range 25–32 among sites) were identified across the seven new study sites (Table 2). During this period, fires were more frequent and had lower percentages of trees scarred compared to the pre-EAS period. Site MFIs ranged from 3.2 to 6.3 yr. WMIs were also shorter, ranging from 2.9 to 5.5 yr. The mean percentage of trees scarred at sites ranged from 12.9% to 36.3%.

Fire scar seasonality was determined for 1165 of the 1517 fire scars. The majority of fire scars occurred in the dormant season across all sites and across all time periods (Table 3). For

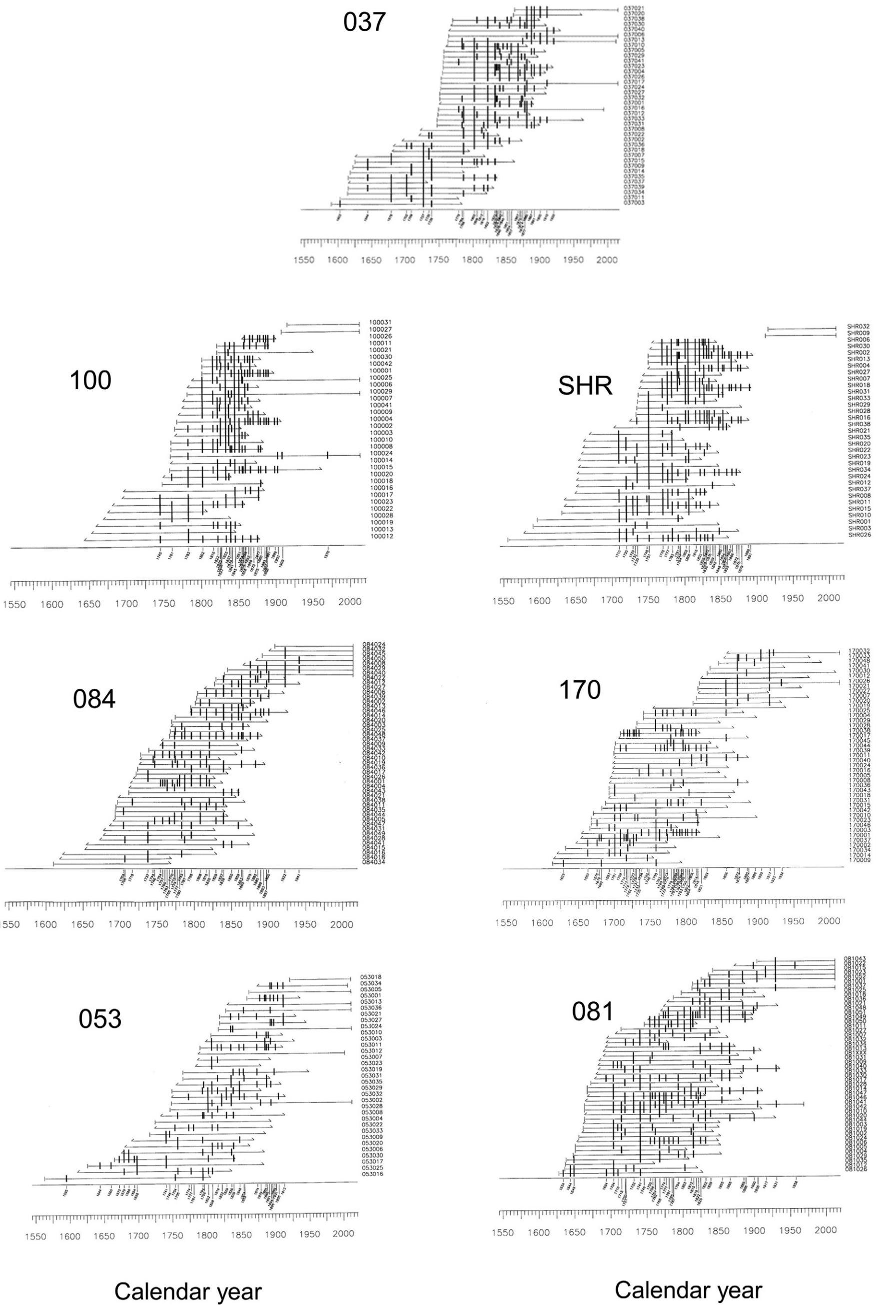

Fig. 3. Fire scar history data from seven new study sites across central Pennsylvania, USA, based on Pinus species (037 = *Pinus resinosa*; 053 = *Pinus pungens*; 100, SHR = *Pinus rigida*); 084, 170 (mixed *P. pungens*, *P. rigida*); 081 (mixed *Pinus echinata, P. pungens, P. rigida*). On each chart, horizontal lines represent the periods of tree-ring record for individual trees. Bold vertical ticks on horizontal lines indicate fire scar years. On the left ends of lines, vertical ends indicate pith years, while diagonal ends indicate inner ring year (rings missing to pith). On the right ends of lines, vertical ends indicate bark years while diagonal ends indicate outer ring years (rings missing to bark). A composite of all fire years at the site is given at the bottom of charts.

Table 3. Seasonality of fires at each study site for three time periods (time periods defined in Table 2).

Site	D	E	M	L	A	U	Percentage of fire years with growing season scar (*n* yrs)
All time							
053	74.2	3.0	0.8	0.0	0.0	22.0	10.8 (4)
081	66.9	4.0	6.6	0.0	0.0	22.4	25.6 (10)
088†	57.5	1.0	0.0	0.0	0.0	41.5	2.0 (1)
170	72.2	0.0	5.9	0.0	4.1	17.8	9.1 (5)
107†	54.5	2.1	0.8	0.0	0.0	42.6	9.1 (4)
084	72.7	1.7	4.1	1.2	0.0	20.3	18.0 (7)
SHR	70.5	1.4	0.0	0.0	0.0	28.1	2.7 (1)
UDR‡	6.5	8.3	15.7	2.3	0.5	66.8	38.7 (12)
SLR‡	56.5	0.7	8.8	0.0	0.0	34.0	13.0 (3)
LBH‡	55.6	4.2	4.9	0.0	2.8	32.6	47.6 (10)
037	68.4	2.8	0.4	1.6	0.0	26.8	16.7 (6)
100	65.8	1.7	11.5	0.0	0.0	20.9	11.8 (4)
Pre-settlement era							
053	52.6	21.1	5.3	0.0	0.0	21.1	40.0 (4)
081	67.1	8.2	4.1	0.0	0.0	20.5	36.4 (4)
088†	53.8	5.1	0.0	0.0	0.0	41.0	6.7 (1)
170	67.3	0.0	14.5	0.0	0.0	18.2	15.0 (3)
107†	33.3	2.6	2.6	0.0	0.0	61.5	20.0 (2)
084	46.2	11.5	19.2	0.0	0.0	23.1	36.4 (4)
SHR	62.4	3.4	0.0	0.0	0.0	34.2	10.0 (1)
UDR‡	7.1	0.0	0.0	0.0	0.0	92.9	0.0 (0)
SLR‡	50.9	1.9	11.3	0.0	0.0	35.8	20.0 (1)
LBH‡	68.4	0.0	0.0	0.0	0.0	31.6	0.0 (0)
037	51.6	1.6	1.6	6.5	0.0	38.7	30.0 (3)
100	75.5	0.0	0.0	0.0	0.0	24.5	0.0 (0)
Euro-American settlement era							
053	77.9	0.0	0.0	0.0	0.0	22.1	0.0 (0)
081	67.0	2.1	8.0	0.0	0.0	22.9	20.0 (5)
088†	58.3	0.0	0.0	0.0	0.0	41.7	0.0 (0)
170	72.8	0.0	1.9	0.0	6.8	18.4	6.3 (2)
107†	56.9	2.0	0.6	0.0	0.0	40.5	5.9 (2)
084	76.6	0.0	1.5	1.5	0.0	20.4	12.0 (3)
SHR	76.0	0.0	0.0	0.0	0.0	24.0	0.0 (0)
UDR‡	6.4	8.9	16.7	2.5	0.5	65.0	46.2 (12)
SLR‡	59.6	0.0	7.4	0.0	0.0	33.0	11.1 (2)
LBH‡	54.5	4.9	5.7	0.0	3.3	31.7	58.8 (10)
037	74.2	3.2	0.0	0.0	0.0	22.6	12.0 (3)
100	63.6	2.2	14.7	0.0	0.0	19.6	14.3 (4)
Fire suppression era							
053	0.0	0.0	0.0	0.0	0.0	0.0	0.0
081	63.6	9.1	0.0	0.0	0.0	27.3	33.3 (1)
088†	60.0	0.0	0.0	0.0	0.0	40.0	0.0
170	90.9	0.0	0.0	0.0	0.0	9.1	0.0
107†	0.0	0.0	0.0	0.0	0.0	0.0	0.0
084	88.9	0.0	0.0	0.0	0.0	11.1	0.0
SHR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UDR‡	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SLR‡	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LBH‡	0.0	0.0	0.0	0.0	0.0	100.0	0.0
037	50.0	0.0	0.0	0.0	0.0	50.0	0.0
100	0.0	0.0	0.0	0.0	0.0	100.0	0.0

Note: D, dormant season (%); E, early earlywood (%); M, middle earlywood (%); L, late earlywood (%); A, Latewood (%); U, undetermined (%).

† Data from Marschall et al. (2016).

‡ Data from Brose et al. (2013).

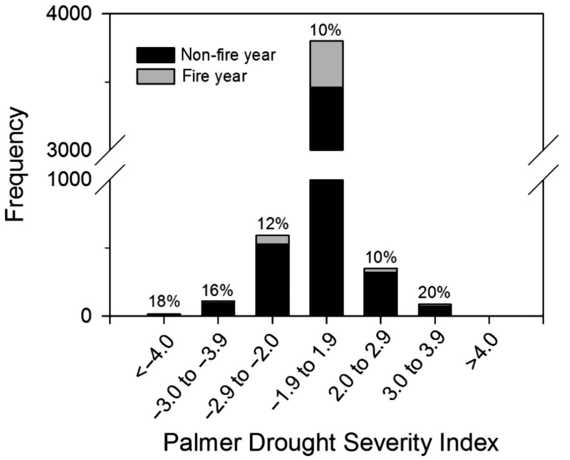

Fig. 4. Frequency distribution of fire occurrences by drought condition. Percentages above bars represent the percent years with fire.

individual sites, the percent of dormant season fires ranged from 65.8 to 74.2 (mean = 70.1). The dominance of dormant season scars was consistent for both the pre-EAS (mean = 60.4%) and post-EAS periods (mean = 72.6%). Differences existed among sites in the percent growing season fires with a higher mean percent across all sites in the pre-EAS (mean = 24.0) than the post-EAS period (mean = 9.2). Among all sites, six years had growing season scars that were replicated at two or more sites.

Drought and fire occurrence

Since the year 1500 CE, PDSI varied from −4.7 (extreme drought) to 3.7 (very wet). Drought conditions have been normally distributed, and fire events have occurred across the full range of drought conditions (Fig. 4). The proportions of fires occurring in each drought class (from dry to wet) have been nearly equal and ranged from 10% to 20% of the cases. At the individual study sites, SEA results commonly showed no significant relationship between fire occurrence and PDSI. In the limited cases when drought conditions exceeded expected levels and were associated with fire event years, results were inconsistent with conditions varying in their lag (i.e., conditions both before and after fires were found significant) and their departure (i.e., both drier and wetter conditions were found significant). Stratifying site-level SEA by sub-periods associated with cultural changes did not improve the consistency of our PDSI-fire results. Only one site, UDR in the northern Allegheny Plateau, showed that conditions in the year of fires were significantly drier than expected.

At the regional level, the relationship between PDSI and fire occurrence was significant and more consistent. Superposed epoch analysis results for years in which multiple sites recorded fire showed that conditions 1 yr prior to fire events were significantly drier than expected. This result was found for those years when ≥2 sites recorded fire, ≥3 sites recorded fire, up to years when ≥5 sites recorded fire. During the common period for all 12 study sites (1663–2010 CE), the most extensive fire year was 1802, when 10 of 12 sites recorded fire and the second most extensive fire year was 1816, when 9 of 12 sites recorded fire. Drought conditions during these years (and their preceding year) were near normal to incipient wet.

Fire synchrony between sites was spatially dependent with Jaccard similarity between sites being negatively correlated with distance (Fig. 5). The regression model predicting similarity from distance suggests that sites 10 to 20 km apart had about 20% similarity, while those with greatest separation (>200 km) had <5% similarity. Heat maps displaying the strength of Jaccard similarity further evidenced the spatial structure in fire synchrony with a gradation of Jaccard similarity values with the timing of EAS (Fig. 5).

Wave of fire

Fires per decade timelines produced consistent, multi-decadal waveforms (Fig. 6). Waveforms transitioned from lower fire frequency (0–2 FPD), to increasing fire frequency (up to 7 FPD), to lower fire frequency (0–1 FPD). Progressing in time, the passing of the wave of fire across central Pennsylvania occurred from the 18th to the 20th century. Fire intervals that exceeded UEI thresholds occurred at all sites (Fig. 7). No UEIs spanned EAS dates. More (62%) and longer UEIs occurred pre-EAS and UEIs were generally absent within the first six or more decades following EAS. The longest UEIs in the pre-EAS period occurred in the topographically rough Pine Creek Valley (sites LBH, SLR, UDR; Brose et al. 2013). Peak FPD occurred within the period from the mid-18th to early 19th century.

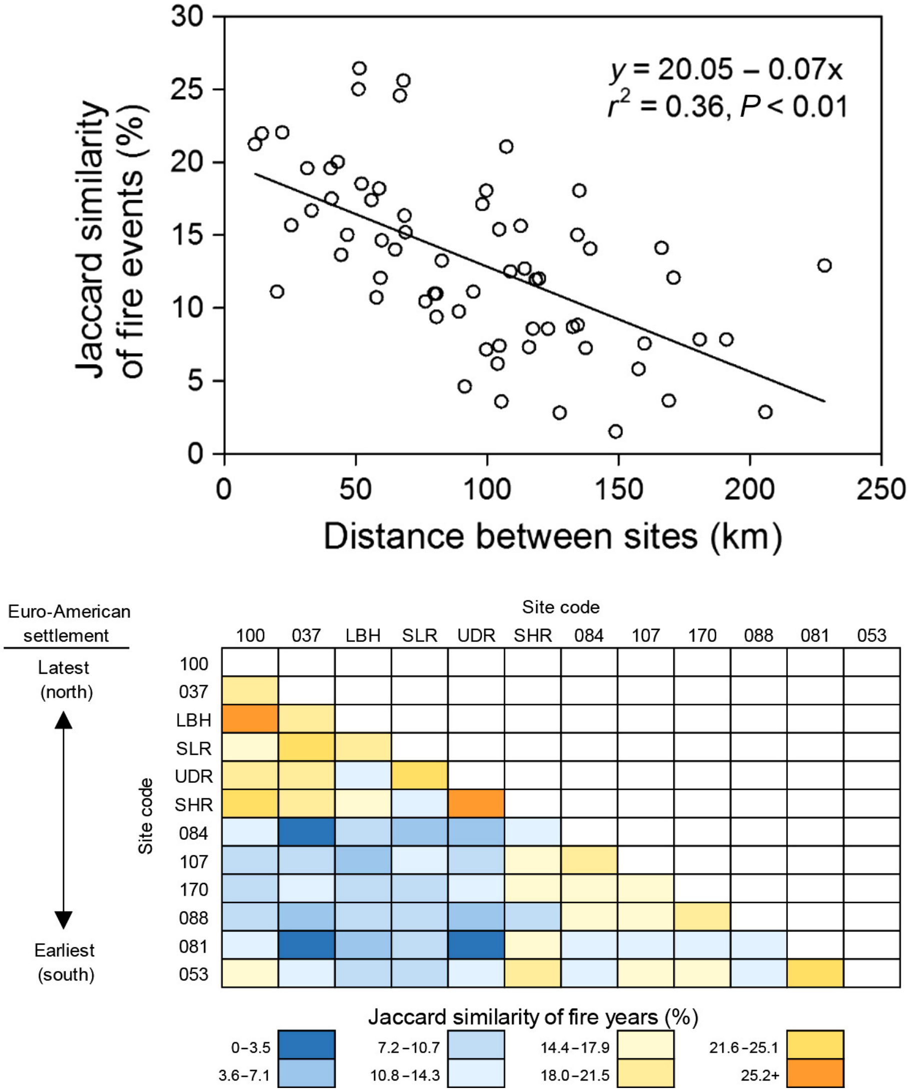

Fig. 5. Top: significant negative relationship between distance between study sites and Jaccard similarity of shared fire event years. Analysis was performed for a common period for all sites (1663–2010 CE). Bottom: heat map of Jaccard similarity of shared fire event years among sites. Sites are sorted by Euro-American settlement date which generally occurs along a southeast to northwest direction across central Pennsylvania.

Waveforms were lagged from south to north, matching both the direction and timing of EAS (Figs. 1, 6). At the time of EAS, FPD were trending upward at 10 of the 12 sites. Sites 053 and 081, both located in the southern portion of the study region, had the least amount of change in FPD, while sites in the central and northern portions showed greatest change. Peaks in the wave of fire occurred as early as the 1750s in the southeastern portion of the region (site 088) and as late as the 1860s in the northwestern (site 100). Upper exceedance intervals corroborated the wave and its propagation based the preponderance of UEIs prior to EAS and lack thereof following EAS (Fig. 7).

Time series analysis of FPD further corroborated the synchronous wave of fire as an attribute of anthropogenic influence. Realignment of waveforms by EAS reduced serial variance in the regional mean by 21% (Fig. 8). Realignment by

EAS timing also altered the mean waveform shape compared to that produced when aligned by calendar year. From realignment, the regional mean FPD showed to be exponentially increasing beginning ~130 yr prior to EAS and increasing at the highest rate coincident with EAS. In some cases, the rate of increase in FPD at the time of EAS was higher than at any other time in the record. First-differencing of the mean FPD showed, at the time of EAS and immediately following, mean FPD underwent two 2–3 decade long cycles where FPD increased and decreased (Fig. 8). Conversely, realignment of FPD by EAS dates appeared to have reduced the signal associated with 20th century fire suppression because it was not dependent upon EAS, but on a calendar year-based (i.e., 1915) fire suppression policy.

DISCUSSION

Fire regimes of central Pennsylvania

Across the study region, fire regimes, though variable in frequency, have undergone similar changes and trends. The greatest variability among sites occurred during the pre-EAS period. Sites in the topographically rough Pine Creek Valley, whose pre-EAS MFIs ranged from 35.6 to 49.0 yr, contrasted sharply with the other nine Pennsylvania sites across the Appalachians (range 5.6–17.8 yr). As discussed in Brose et al. (2013), pre-EAS fire frequency at the Pine Creek Valley sites was more similar to those reported in red pine stands in Vermont and the Great Lakes than those of Appalachia (Engstrom and Mann 1991, Mann et al. 1994, Drobyshev et al. 2008). With the exception of the Pine Creek Valley, fire frequencies at our sites were more comparable to sites in the central Appalachians and more distant central U.S. regions (Shumway et al. 2001, Aldrich et al. 2010).

These data contribute significantly to a limited, but growing set of fire records in the northeastern USA. As more historical fire data become available, it appears that evidence for relatively frequent fire regimes exists throughout region, particularly in the Appalachians. Generally, fires at our Appalachian sites were not as frequent as those reported in other, more southerly locales; some of this contrast may be due to the fact that very few other Appalachian studies precede EAS (Shumway et al. 2001, Aldrich et al. 2010). Among our study sites, fire frequencies in the Ridge and Valley Province were most frequent. These fire frequencies are comparable to Ridge and Valley oak-pine sites in Virginia reported by Aldrich et al. (2010, 2014, Mill Mountain, 1704–1930, MFI = 5.4 yr; Reddish Knob, 1671–2005, MFI = 4.8 yr) and an Appalachian Plateau oak site, in western Maryland reported by Shumway et al. (2001; Savage Mountain, 1616–1959, MFI = 8.2 yr). Although abbreviated periods of very frequent fire occurred at our sites, these were not sustained as was the case for sites supporting montane longleaf pine (*Pinus palustris*) at the southern terminus of the Appalachians (Bale 2009).

Euro-American settlement had a significant impact on fire frequency throughout the region. Following EAS, fires were more frequent and less variable. As Euro-American settlers spread throughout the region, their fire use (for land clearing, forage production, pest control; Cronon 1983, Whitney 1994) resulted in as or more frequent fire than occurred during any other time of the record. As settlements became further developed and industries advanced, new sources of fire included charcoal and iron industries, railroads, and logging operations.

Regardless of time, fires predominantly occurred in the dormant season which is consistent with other studies in the both the Appalachian and Central Hardwoods regions (Shumway et al. 2001, Flatley et al. 2013, Aldrich et al. 2014). Though other studies have shown changes in fire seasonality from pre- to post-settlement times, we did not observe this. Instead, some sites had more growing season fires before EAS, some sites had more following EAS, and others had equal occurrence of growing season fire before and after EAS. Presumably, dormant season fires occurred in the fall and early spring seasons, due to the limited fire potential during winter when temperatures are low and snow cover is common. Time periods or geographic regions with these limiting winter conditions being more common or longer may cause fires to be more closely confined to the growing season. Fires at UDR and LBH had by far the highest proportion of growing season fires, but they only occurred in the post-EAS era with more occurring in the early, rather than the late, growing season. Increased numbers of growing season

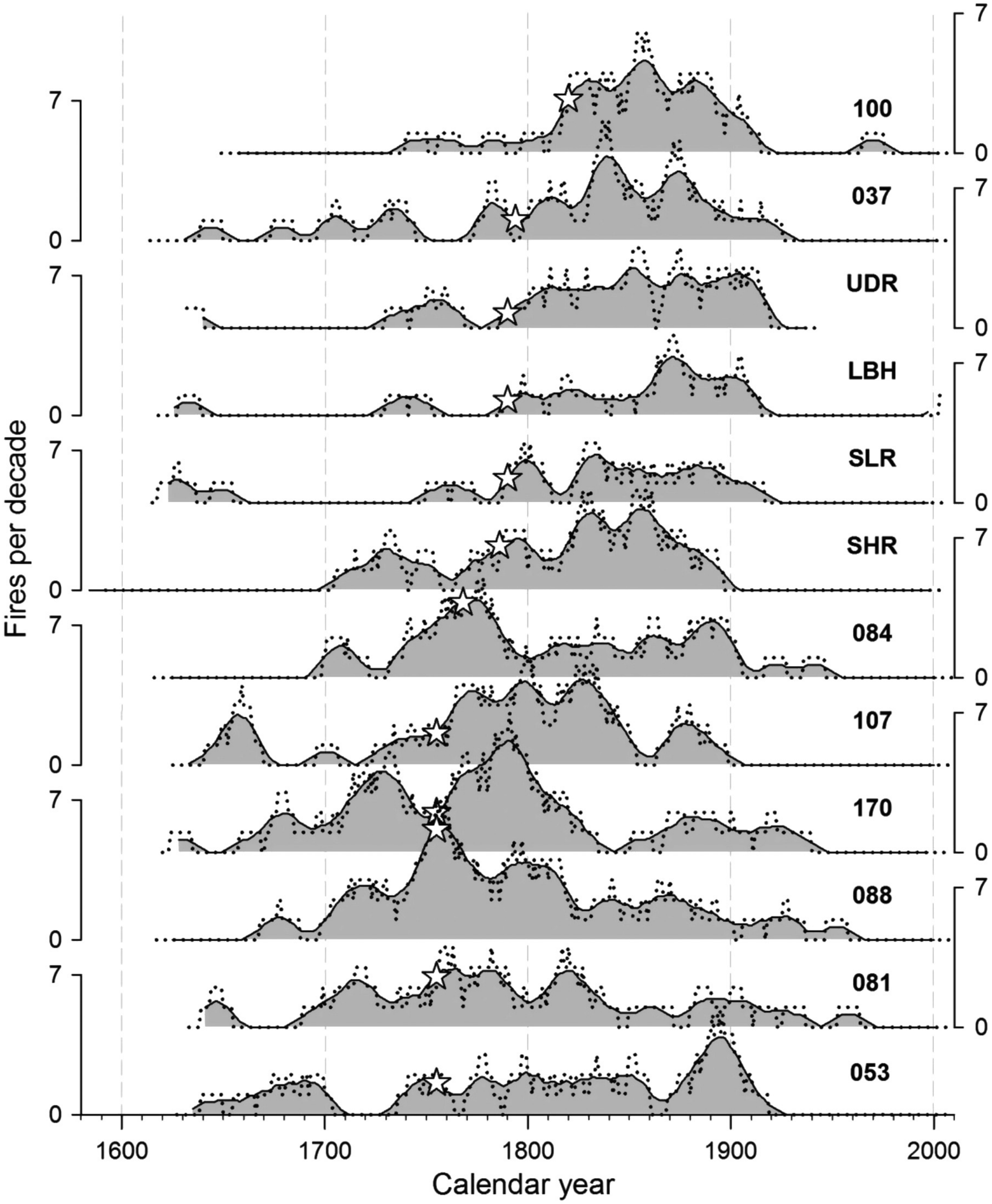

Fig. 6. Decadal-scale fire frequency across central Pennsylvania. Fires per decade (FPD, dotted line) was calculated using a moving window. The longer-term wave form (gray shaded areas) represents a 17-yr moving average of FPD. Study sites are sorted by Euro-American settlement dates and indicated by stars.

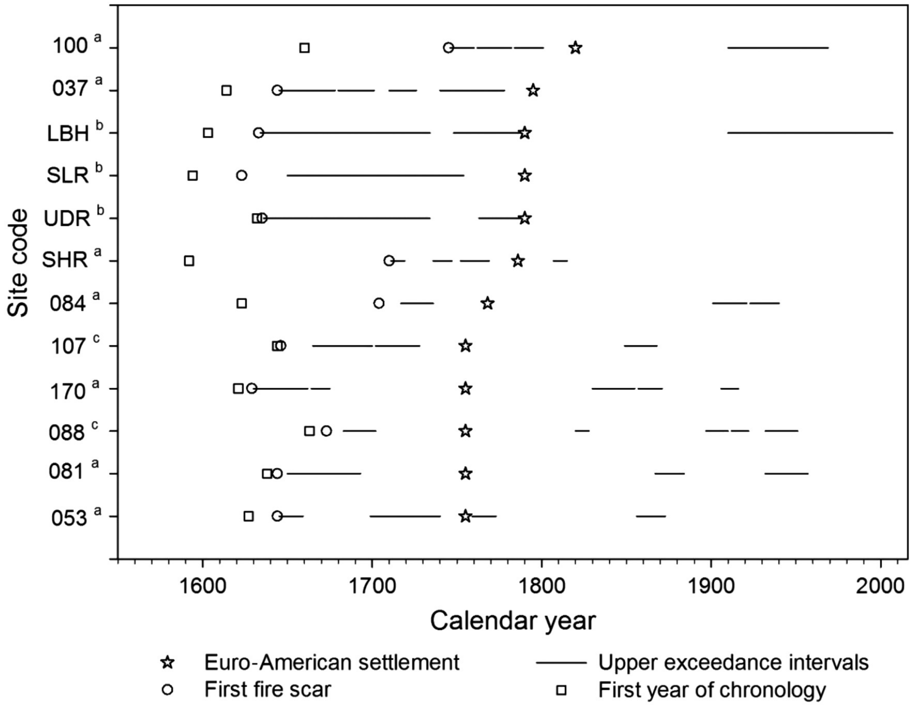

Fig. 7. Timing of upper exceedance intervals (horizontal lines) for individual study sites. Study sites are sorted by Euro-American settlement (EAS) dates from earliest (bottom) to latest (top). Site code superscripts denote the following: (a) new site data, (b) data from Brose et al. (2013), (c) data from Marschall et al. (2016). Years of EAS (stars) were independently determined from historical documents (Appendix S1). First year of tree-ring records are indicated by squares, and first fire scar years at sites are indicated by circles.

fires may have been caused by human influences (e.g., changing cultures, land uses); however, without more evidence, this is difficult to ascertain, especially since some sites (e.g., SGL081) had a relatively high percentage of growing season fires, but they occurred equally pre- and post-EAS.

No evidence existed for high-severity, stand-replacing fires. Often these events leave evidence such as dead trees with similar death dates, subsequent major cohort establishment, and, in some places, trees in otherwise protected sites having fire scars. Nevertheless, under conditions of extreme fire danger (e.g., combined drought, low humidity, high winds, high fuel loading) areas of Pennsylvania have potential for extensive and high-severity fires to occur. However, evidence of extensive fires during wet or cold years (e.g., 1802 and 1816) suggests that drought is not a requisite for extensive fires. Cultural factors such as increased agricultural practices, societal upheaval, and conflict likely led to widespread fire occurrence in these years. Our results suggest that fires historically occurred in burnable periods regardless of being a wet or dry year. Overall, extensive fire years were significantly dry in the year prior to fire events. Unfortunately, with fire scar data the seasonal characteristics of the prior year drought conditions cannot be determined since the dormant season is limited by lack of cell production (i.e., tree-ring formation).

Regardless of this fire occurrence-fire scar timing issue, from a fire management perspective, the evidence for regional fire activity during droughts emphasizes the importance of identifying the potential for regional fires to occur, since examples of these are rare and limited in written history. Understanding of the potential and probability for regional fires may be improved by further climate analyses associated with these years. For example, across the northeastern USA, large-scale climate patterns such as the North Atlantic

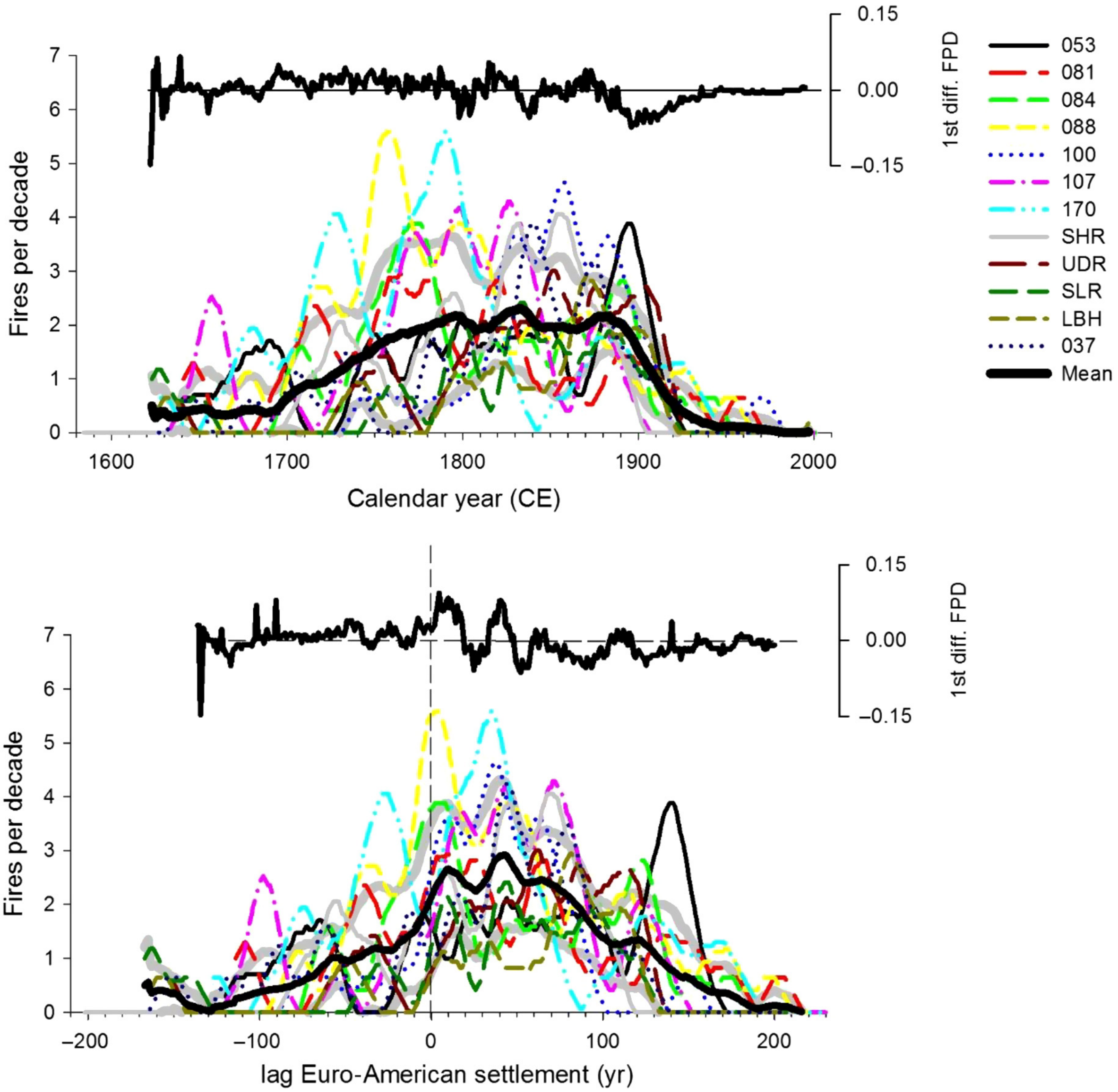

Fig. 8. Top: time series of fires per decade (FPD, 17-yr moving average) for 13 sites across central Pennsylvania between 1620 and 2016 CE. Mean and standard deviation shown by bold black line and gray shade, respectively. Bottom: FPD aligned by Euro-American settlement date. Annual change in mean FPD shown in first difference.

Oscillation and the Pacific-North American index have been associated with precipitation patterns (Bradbury et al. 2002, Huntington et al. 2004).

Wave of fire across Pennsylvania

Overwhelmingly, our results showed that central Pennsylvania fire regimes during at least the past four centuries were influenced by changes in human populations. A wave of fire progressively moved across the region and represents changes in fire frequency from relatively infrequent fires during periods of Native American depopulation (MFIs from 5.6 to 57 yr), increasing fire frequency associated with EAS and industrialization (MFIs from 3.2 to 7.3 yr), and declining to no fire activity leading to, and including, the current era of fire suppression (MFIs from 25 to 52+ yr). Previous fire scar and charcoal studies from across the eastern USA have reached the same conclusion, including evidence for a waveform pattern in fire frequency (Guyette et al. 2002, 2006, Stambaugh et al. 2006, 2013, Muzika et al. 2015, Lafon et al. 2017). Although many eastern U.S. regions lack fire history records, to date, this waveform pattern has been less consistently found in the Appalachians; some studies report fire frequency unaffected by changes in human populations (Shumway et al. 2001, Aldrich et al. 2010, Flatley et al. 2013). Plausible reasons for this inconsistency (aside from data issues) may include European influences (e.g., disease, trade) occurring before EAS, lack of a fire regime effect from Native American depopulation, and higher incidence of lightning-caused fires and therefore masking changing human influences. Lafon et al. (2017) proposed patterns of changing fire frequency coincident with changes in human populations are an artifact of sample size and analytical methodology, and that, before fire suppression policies, fire has always been frequent in oak-pine forests of the eastern USA regardless of human land use. Although this is plausible in some situations, overwhelming evidence in fire scar and charcoal records suggests fire regimes vary through time and that variability from pre-EAS to present is unprecedented in recent millennia (Marlon et al. 2008, Pyne 2010).

Perhaps the most significant contribution of this paper is characterization of the timing, location, and degree of fire regime changes. These features provide strong evidence that historical fire regimes, and vegetation therein, were and continue to be strongly anthropogenic. Features attributed to anthropogenic controls included: fire frequency waveform replication across a broad geographic region and lagged in the direction of EAS, progressive rates of fire frequency change matching those of human populations, enhanced signal strength associated with realigning fire records by EAS timing, and synchronous regional decline in fire coincident with fire control policies. With fire scar data, we have demonstrated the ability to spatially and temporally quantify the fire regime transition due to human influences, corroborate early anthropological characterizations of human–fire associations (Eiseley 1954), and validate persistence of human–fire signals within ecosystems and natural archival datasets (Marlon et al. 2008, Bowman et al. 2011).

A regional wave of fire has been previously described in fire history narratives, but not quantitatively described as such. Eiseley (1954) insinuated that waves of fire were associated with human changes in her statement describing the rise of human civilizations: "Here again the magic of fire fed the great human wave and built up man's numbers and civilization." More recently, Pyne described the underlying anthropogenic influences of fire waves as pyric transitions, suggesting that they have moved with humans through time and affected pyrogeography (Pyne 2001). Through millennia, global charcoal records show fire activity responding to climate variations, but over the last millennium becoming increasingly controlled by anthropogenic factors (Marlon et al. 2008, Munoz et al. 2010). From the increased time perspective of charcoal records, it is not clear whether our fire scar records characterize the full waveform; periods of lowered fire frequency could extend earlier in time. After realigning our records by EAS dates, we estimate that our records begin approximately 130 yr prior to EAS. Most of our fire scar records began from relatively low levels of fire frequency and progressed forward with increased rates of fire for over a century. Fire record initiation in an era of lowered fire activity is supported by charcoal records that exhibit decreased fire activity initiating in the 16th century, but higher and more elevated fire activity in prior millennia. From this, we presume that the fire regimes characterized here begin during an era of Native American depopulation due to disease and conflict resulting from European encroachment into former coastal lands (Fig. 2). In regions that were less populated, remote, or less conducive to burn, the effects of Native American depopulation on fire regimes may have been less or insignificant.

Although we show the wave of fire progressing from southeast to northwest across central Pennsylvania with EAS, we hypothesize its extent is continental or larger following colonization and settlement patterns from the Old to the New World (Veblen et al. 1999). Approximately a century earlier than the earliest times documented in Pennsylvania, an anthropogenic fire frequency waveform existed in Fennoscandia (Rolstad et al. 2017). From Pennsylvania, later and later waveforms can be found progressing generally east to west across the eastern USA and Great Plains (Guyette et al. 2002, 2006, Stambaugh et al. 2006, 2008, 2013, 2014). Although a more thorough analysis is needed, we hypothesize coastal eastern North American locations with earlier EAS dates (e.g., New Jersey, South Carolina) underwent the earliest human-fire regime changes. If true, characterizing pre-EAS fire regimes in these locations will likely be difficult through tree-ring methods since fire scar chronologies rarely precede 1650 CE in eastern U.S. forests.

Implications for modern fire in northeastern U.S. forests

Increased understanding of anthropogenic fire regimes has much to bear on historical ecology and management. For Appalachian fire regimes specifically, fire history data contribute to our understanding of how well fire records represent conditions prior to EAS influence (Lafon et al. 2017). Addressing questions of appropriate fire frequencies for management may not be possible with fire records that include significant and changing past anthropogenic influences. For example, historical human–fire uses and resulting fire regimes may not align with present-day vegetation or prescribed fire management objectives. Instead of solely relying on historical fire regime data, fire management objectives would be better served to supplement these data with vegetation effects such as tree establishment and survival. These analyses could be further informed by observational data (e.g., permanent fire monitoring plots) capable of testing species relationships (e.g., regeneration, survival) to fire effects and characteristics (e.g., frequency, seasonality, severity). Historical fire records are particularly well suited for these questions because they provide long-term observations of fire and tree response, often including conditions (e.g., vegetation, climate, fire) that may not be observable in the modern era.

Over the last four centuries, forests in the northeastern USA have significantly changed in type at local scales due to land use history and succession (Thompson et al. 2013). Vegetation changes are often associated with land clearing for agriculture, forest logging, and fire suppression. Our study suggests that these land use activities, though important, occurred after EAS (Brose et al. 2013, Fig. 2) and were preceded by at least a century of early fire wave conditions (i.e., decreased then increased fire frequency). Lengthened fire intervals prior to EAS resulted in establishment of tree cohorts throughout the region (M. C. Stambaugh et al., *unpublished data*). Very frequent burning associated with EAS likely repeatedly consumed or top-killed small, fire-sensitive vegetation, even potentially limiting tree recruitment. A century or more later, late-19th century logging and early-20th century fire suppression caused these pine-dominated sites to convert to mixed-hardwood dominated sites, including many fire-intolerant species (Appendix S1). The present-day forest structure conditions that reflect this history consists of hardwood dominated forests with decaying, remnant pine snags and stumps, and few, if any, living pines. Pre-EAS forest characteristics such as open savannas dominated by pitch, Table Mountain, shortleaf and red pine, and mixed oaks have previously been attributed to recurring Native American burning, but with little supporting fire history data until now (Nowacki and Abrams 1992, Abrams and Ruffner 1995, Ruffner and Arabas 2000, Black and Abrams 2001).

In eastern U.S. regions, forest management goals often include ecological information and ecologically based land management objectives. In regions with centuries of anthropogenic fire influence and following multiple forest rotations, establishing ecological objectives without historical context or modern analogs can be difficult. This is a pervasive issue throughout historically fire-maintained ecosystems in the eastern USA. Fire-maintained forest communities, with their unique combination of long-lived individual trees and early successional plants and wildlife, are an important source of biodiversity (Carleton and Arnup 1993, Frelich et al. 2003, Peterson and Reich 2008). Relict and remnant fire-maintained forests have been greatly reduced in extent, yet can occur over sizeable areas, particularly in restricted and protected areas (Brose et al. 2014).

Management of fire-adapted tree species can be informed by their natural process of regeneration, growth, and survival (Gilmore and Palik 2006). Current understanding recognizes that recurring fires were important to maintaining hard pines including their common associates such as northern red oak (*Quercus rubra*; Cook et al. 1952, Cronon 1983, Crow 1988, Mann et al. 1994). However, there are few available details about the ecology, stand dynamics, and historical fire regimes of these communities (Keeley and Zedler 1998, Guyette et al. 2012, Lafon et al. 2017). In forests that have transitioned to northern hardwoods or mixed-conifer types, fire scars on remnant trees are physical evidence that significant changes in composition and disturbance have occurred in recent centuries. Compared to pre-EAS, relict hard pine stands occur in only small areas within a much-reduced historical range (e.g., red pine exists in <1% of its historical range; Anand et al. 2013). The rarity of these areas makes them frequently targeted for natural area designation (Sperduto and Nichols 2004). Although plantation management of fire-adapted hard pines found in the northeastern USA (e.g., pitch and red pine) is reasonably well understood, particularly for short rotations, the dynamics of native communities are not. Silvicultural prescriptions for restoring and sustaining mixed pine–oak–hardwood forests are needed (Kabrick et al. 2017).

Fire history and paleoecological studies show humans have used fire to influence their environment for thousands of years in North America. Purposes for burning are linked to benefits and survival such as increased food production, promotion of plants used for domestic items, improved travel, and pest control (Williams 2003). The current era of fire suppression, now over 100 yr in duration, is perhaps the longest fire hiatus in the last few millennia, yet potential benefits of returning fire to natural resources management appear to remain relevant on many levels. For example, occurrences of Lyme disease are reaching epidemic proportions; controlled burning is an effective means to control disease-carrying tick populations (Gleim et al. 2014). Meat production requires unprecedented inputs to meet demand; fire is being used effectively to improve grazing production (Duvall and Whitaker 1964). Overbrowsing by ungulates in unnatural, closed-canopy forests is causing unprecedented ecological damage; regular prescribed burning can improve browse conditions for white-tailed deer by fourfold, hence decreasing negative impacts and increasing carrying capacity for these game animals (Hallisey and Wood 1976). Noxious plants are obstructing travel and recreation in conservation areas; frequent prescribed fire on short intervals can be used to manage natural areas that receive high public use.

Relative to other land management techniques, prescribed fire is increasingly used to meet land management goals (Twidwell et al. 2013). Fire management is benefitted by historical characterization of fire regimes by providing recognition of plant and wildlife species fire requirements and attributes of fire-adapted communities. Because of fire's many potential benefits, a cultural shift away from fire suppression and toward the realization that fire can be used to improve the human environment is needed. A better understanding of historical human uses of fire and dynamics of anthropogenic fire regimes can be helpful in this regard.

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