NRC Research Press

ARTICLE

The influences of drought and humans on the fire regimes of northern Pennsylvania, USA

Patrick H. Brose, Daniel C. Dey, Richard P. Guyette, Joseph M. Marschall, and Michael C. Stambaugh

Abstract: Understanding past fire regimes is necessary to justify and implement restoration of disturbance-associated forests via prescribed fire programs. In eastern North America, the characteristics of many presettlement fire regimes are unclear because of the passage of time. To help clarify this situation, we developed a 435-year fire history for the former conifer forests of northern Pennsylvania. Ninety-three cross sections of fire-scarred red pines (*Pinus resinosa* Aiton) collected from three sites were analyzed to determine common fire regime characteristics. Prior to European settlement, fires occurred every 35–50 years and were often large dormant-season burns that sometimes initiated red pine regeneration. American Indians probably ignited these fires. Fire occurrence had a weak association with multiyear droughts. After European settlement started around 1800, fires occurred every 5–7 years due to widespread logging. Fire size and seasonality expanded to include small growing-season fires. The weak drought–fire association ceased. In the early 1900s, logging ended and wildfire control began. Since then, fires have been nearly absent from the sites despite several multiyear droughts in the 20th century. The human influences of cultural burning, logging, and fire exclusion are more important than the influence of drought to the fire regimes of northern Pennsylvania.

Résumé : Il est nécessaire de comprendre les régimes des feux passés pour justifier et procéder à la restauration des forêts dont l'origine est due à des perturbations via des programmes de brûlage dirigé. Dans l'est de l'Amérique du Nord, on connaît mal les caractéristiques de plusieurs régimes des feux antérieurs à la colonisation parce qu'ils remontent loin dans le temps. Pour aider à clarifier cette situation, nous avons élaboré un historique des feux étalé sur 435 ans pour les anciennes forêts de conifères de la Pennsylvanie. Quatre-vingt-treize sections radiales de pin rouge (*Pinus resinosa* Aiton) portant des cicatrices de feu ont été récoltées dans trois stations et ont été analysées pour déterminer les caractéristiques communes des régimes des feux. Avant la colonisation par les européens, les feux survenaient tous les 35 à 50 ans, durant la saison dormante; ils étaient souvent vastes et déclenchaient parfois la régénération du pin rouge. Ces feux étaient probablement allumés par les amérindiens. L'occurrence des feux était faiblement associée à des périodes de sécheresse qui duraient plusieurs années. Après le début de la colonisation par les européens vers 1800, les feux survenaient à tous les 5 à 7 ans à cause des coupes qui étaient très répandues. La taille des feux a augmenté et leur caractère saisonnier s'est développé pour inclure de petits feux durant la saison de croissance. La relation faible qui avait été notée entre la sécheresse et le feu a disparu. Au début des années 1900, les coupes ont cessé et la suppression des feux de forêt a débuté. Depuis, il n'y a pratiquement pas eu de feux dans les stations qui faisaient partie de l'étude bien que plusieurs périodes de sécheresse étalées sur plusieurs années soient survenues au cours du 20^{e} siècle. L'influence de l'homme via le brûlage culturel, la coupe et l'exclusion du feu est plus importante que l'influence de la sécheresse sur les régimes des feux dans le nord de la Pennsylvanie. [Traduit par la Rédaction]

Introduction

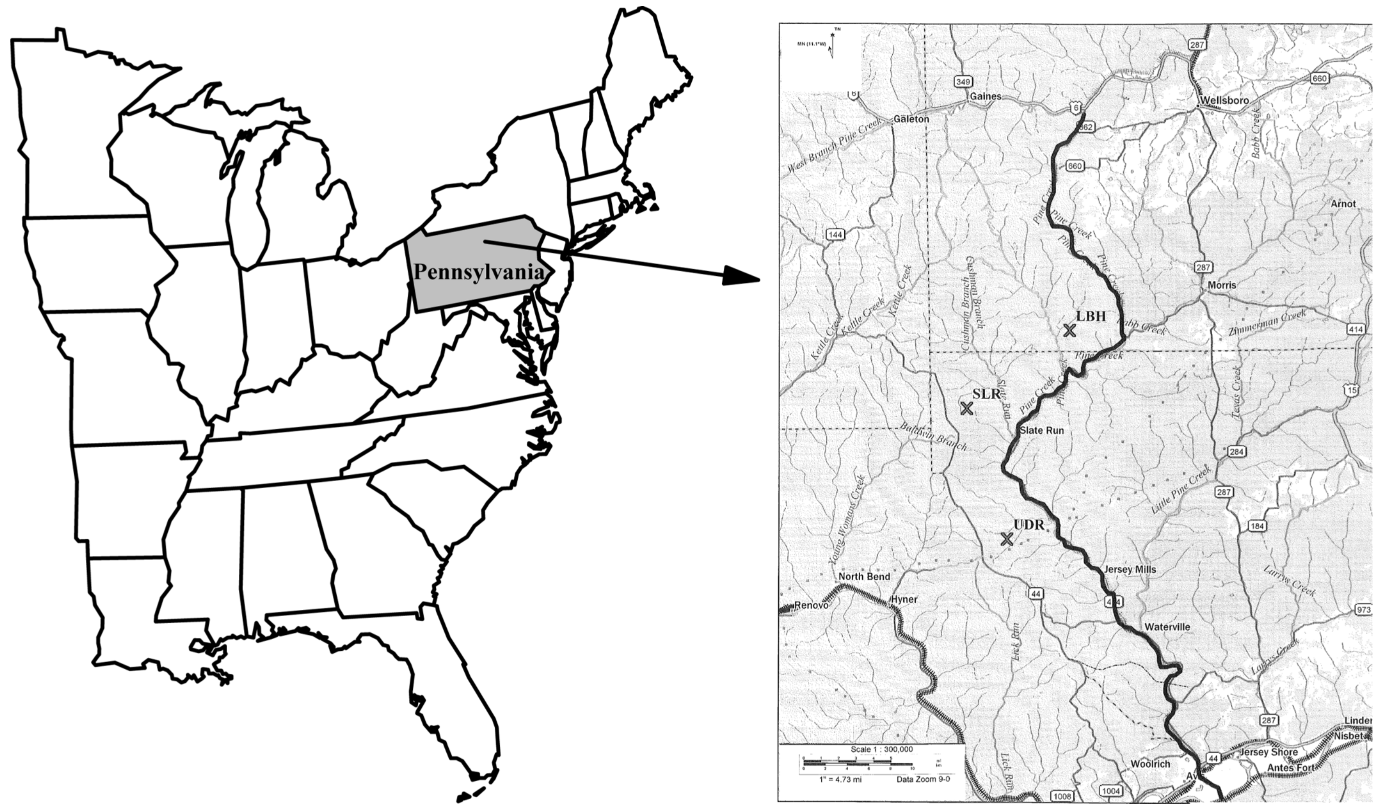
The advent of ecosystem management has sparked considerable interest among natural resource practitioners and researchers regarding past disturbance regimes, especially historic fire regimes (Boyce and Haney 1997; Chapin et al. 2009). This interest in past fire by natural resource professionals arises for several reasons. First, many natural resource agencies in numerous countries originated during times when wildfires were a major concern to the public and that legacy continues today in the fire suppression responsibilities of those agencies (Pyne 1982). Second, is the growing realization that fire is an integral ecological process in many ecosystems and its extended absence leads to the degradation of many of the attributes and services that we desire from those ecosystems. For example, the pre-eminent role of periodic fire in the long-term dominance and perpetuation of the longleaf pine (*Pinus palustris* Mill.) forests of southeastern North America is well-known, and its absence leads to large losses in biodiversity (Landers et al. 1995; Van Lear et al. 2005). Similar examples can be found on nearly every continent (Pyne 1995). Third, fire is the one disturbance we can reasonably mimic through prescribed burning. Ecosystem management utilizes prescribed burning to meet biodiversity objectives in fire-associated plant communities throughout the world (Pyne 1995; Boyce and Haney 1997).

An integral part of ecological burning is an understanding of historic fire regimes as these often serve as justification for burning as well as restoration targets. Deciphering past fire regimes requires understanding the relative influences of climate and humans and the interactions between these two factors. Climate works as a predisposing factor in fire regimes by influencing the vegetative community, i.e., fuel type, determining when and how long fuel is suitable to support combustion, and causing ignitions via lightning. Human actions are inciting factors that influence ignitions and spread. The relative influence of climate and humans on fire regimes varies by location and through time. In northern Sweden, Niklasson and Granstrom (2000) reported that

Received 14 November 2012. Accepted 1 June 2013.

P.H. Brose. USDA Forest Service, Northern Research Station, 335 National Forge Road, Irvine, PA 16329, USA.
D.C. Dey. USDA Forest Service, Northern Research Station, 202 ABNR, University of Missouri, Columbia, MO 65211, USA.
R.P. Guyette, J.M. Marschall, and M.C. Stambaugh. School of Natural Resources, University of Missouri, Columbia, MO 65211, USA.
Corresponding author: Patrick H. Brose (e-mail: pbrose@fs.fed.us).

Fig. 1. The location of Pennsylvania in the eastern United States; Pine Creek (dark black line) within that state; and the three study sites, Long Branch Hill (LBH), Slate Run (SLR), and Upper Dry Run (UDR), along the western side of Pine Creek.



humans drove the fire regime and that climate contributed little because lightning started few fires. Conversely, Johnson et al. (1990) found climate to be more important than humans in the interior wet forests of British Columbia, Canada. In western Argentina, Veblen et al. (1999) found that humans and climate both strongly influenced the fire regimes. The human factor was evident in fluctuations in fire frequency through time corresponding with changes in human cultures, whereas the climatic influence was manifest in more fires occurring at lower latitudes than at higher ones and widespread fires followed El Niño – Southern Oscillation events by 3– 5 years. In Russia, Drobyshev et al. (2004*a*) determined that human activity accounted for 50% of the variability in his fire regime model and that the climatic contribution was decreasing through time because of an increasing human population. In the western USA, numerous climate – fire history studies show that climate, especially drought, have exerted a strong historical influence on fire frequency and extent and continue to do so despite increased anthropogenic ignitions in the late 1800s and decreased ignitions since the early 1900s (Veblen et al. 2000; Donnegan et al. 2001; Grissino-Mayer et al. 2004).

In the eastern USA, fire history studies are much less common because of the centuries of European settlement, extensive and intensive land use, and a humid climate that makes long-term preservation of fire-charred wood unlikely. Fire history studies that include a climate component are especially rare. An exception to this trend is Drobyshev et al. (2004*b*). In their 300-year fire history of mixed-conifer forests in northern Michigan, they showed that while human activity drove ignitions, it was primarily drought that determined subsequent fire size. In the central Appalachian Mountains, Lafon et al. (2005) examined the recent fire history (1970–2003) of montane oak (*Quercus* spp.) and pine forests in relation to regional climate patterns. They found that seasonal weather patterns and multiyear droughts had a strong impact on fire activity, despite fire exclusion policies and efforts. In central Vermont, Engstrom and Mann (1991) and Mann et al. (1994) developed fire histories from the dead and living pines of mixed-conifer forests. They found weak correlations between single- and multi-year droughts and the occurrence of fires in these stands. Unfortunately, they did not delve deeply into the local history of American Indian tribes or European settlers.

In 2010, the opportunity arose for us to add to this meager collection of drought – fire history studies in the eastern USA with the discovery of numerous fire-scarred red pine and pitch pine (*Pinus resinosa* Aiton and *Pinus rigida* Mill., respectively) snags and stumps at three sites in north-central Pennsylvania. These sites were especially attractive for this study because this area of Pennsylvania had scant American Indian influence, the European settlement history was well-documented, and an 800-year reconstructed Palmer Drought Severity Index (PDSI) chronology from a nearby site was available. Our research questions were (1) what were the characteristics (frequency, seasonality, and spatial extent) of the fire regime before European settlement?; (2) How did these characteristics change with European settlement?; and (3) What were the contributions of drought and humans to the fire regimes in these periods? Improving our understanding of historical fire will aid in the acceptance of fire as an important ecological disturbance, facilitate ecological restoration efforts, and increase our appreciation of the cultures of the American Indians and early European settlers.

Materials and methods

Study site

This study took place in the Pine Creek Valley (PCV) of north-central Pennsylvania (41°30.241′N, 77°28.603′W; Fig. 1). This valley extends 76 km in a north-to-south orientation and ranges in depth from 250 to 500 m, with the distance between the east and west rims averaging 1200 m (Owlett 1993; Dillon 2006). Pine Creek and its accompanying tributaries form a watershed of approximately 2500 km^2. Within this watershed, the physiography is a dissected plateau consisting of broad flat hills, steep slopes, and numerous streams. Hilltop elevations range from 600 to 700 m a.s.l. and Pine Creek's elevation is approximately 250 m a.s.l. Climate is humid continental consisting of warm, humid summers and cold, snowy winters (Kohler 1986). Average annual temperature is 8.0 °C with an average minimum mean of –10.0 °C in January and an average maximum mean of 25.6 °C in July. Annual precipitation averages 1500 mm and is distributed evenly throughout the year.

PCV was heavily forested before European settlement (Owlett 1993; Dillon 2006). Prior to 1800, eastern white pine (*Pinus strobus* L.) and hemlock (*Tsuga canadensis* (L.) Carrière) were the dominant species throughout the watershed. Associated hardwood species included American beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), American chestnut (*Castanea dentata* (Marsh.) Borkh.), and various oaks, especially northern red oak (*Quercus rubra* L.). Pitch and red pine were minor conifer species found on xeric ridges.

Because of the rugged physiography of northern Pennsylvania, PCV was not permanently inhabited by American Indian tribes (Meginness 1892; Owlett 1993; Wallace 1998; Dillon 2006). Instead, they traveled through the region on footpaths and used it for seasonal hunting. European settlement of PCV and logging of the forests began in the late 1700s (Meginness 1892; Owlett 1993; Dillon 2006); first along Pine Creek and the major tributaries and gradually up to the higher elevations as technology permitted. Railroad logging started in the 1870s and, by the early 1900s, the entire watershed had been harvested. Since then, an oak-dominated forest has replaced the previous pine–hemlock forest.

With the help of Pennsylvania Bureau of Forestry personnel, we found three 5- to 9-ha oak–pine stands with numerous fire-scarred snags and stumps of pitch and red pine on the west side of PCV (Fig. 1). One stand, Long Branch Hill (LBH; 41°33.734′N, 77°26.711′W) was on Tioga State Forest land. Slate Run (SLR; 41°30.229′N, 77°33.709′W) and Upper Dry Run (UDR; 41°23.452′N, 77°29.710′W) were on Tiadaghton State Forest land. All of the sites were 2–3 km from Pine Creek, and SLR was near the center of PCV's west side, with LBH and UDR situated approximately 12 and 14 km to the northeast and southeast, respectively.

All of these stands occurred along the upper shoulder of northwest-facing ridges at an approximate elevation of 550 m a.s.l. (Fig. 2). They were steep (>20% slope), dry, and rocky. The stands were fully stocked and had an overstory of pitch, red, and white pines, northern red oak, red maple (*Acer rubrum* L.), and sweet and paper birch (*Betula lenta* L. and *Betula papyrifera* Marshall, respectively). Mountain laurel (*Kalmia latifolia* L.) dominated the understory to the degree that moving through these stands was difficult.

Sampling procedures

We systematically scouted each stand for fire-scarred pine snags and stumps as well as fire-scarred living trees. When a suitable snag or stump (recorder tree) was located, its location was established with a hand-held GPS receiver and we determined the aspect, slope, and slope position of each recorder tree. A cross section was then cut from the base of the recorder tree using a chainsaw. Multiple cuts were made successively higher up the bole of the snag or stump to determine if additional fire scars were present. When they were present, multiple cross sections were taken from a single remnant. We sampled fire-scarred living pines by cutting a partial cross section (10%–15% of the tree's circumference) of similar thickness from the interface of the fire scar with the undamaged wood (Arno and Sneck 1977). When appropriate, samples were wrapped in duct tape before cutting to prevent handling and vibration from damaging the cross section. Of particular concern were the fragile scar faces that tend to separate when cutting. All samples were transported to the Missouri Tree Ring Laboratory at the University of Missouri for dating and examination of the fire scars. We sampled LBH and UDR in fall 2010 and SLR in winter 2011–2012. Also at UDR, we cored 18 living old-growth red pines to develop a master chronology for cross-dating purposes. This red pine master chronology covered the years 1760–2010 and had an intracorrelation of 0.506, indicating substantial agreement among the cores.

In the lab, the cores and cross sections were sanded using a handheld orbital sander with progressively finer sandpaper, up to 1200 grit, until the cellular details of the annual rings and fire scar injuries were revealed. Fire scars were identified by the presence of callus tissue, charcoal, traumatic resin canals, liquefaction of resin, and cambial injury. For each cross section, a radius (pith-to-bark tree-ring series) with the least amount of ring-width variability from fire injuries was chosen for skeleton plotting (Stokes and Smiley 1968; Speer 2010). Skeleton plots help identify signature years, missing rings, and false rings, and determine the year of a fire when visually cross-dated with the master red pine chronology. The COFECHA computer program (Holmes 1983; Grissino-Mayer 2001) was used to verify the accuracy of cross-dated tree-ring series. Correlations between the cross-section chronologies and the master chronology ranged from 0.331 to 0.695, indicating that the fire years were correctly identified.

Statistical analysis

We used the FHX2 fire history software (Grissino-Mayer 2004) to record the calendar years and seasons of each tree's response to cambial injury. For each site, we summarized the fire event data (number of fires, mean fire interval (MFI), Weibull fire interval (WFI), lower and upper exceedance intervals (LEI and UEI, respectively), seasonality, and spatial extent). MFI is the time in years between successive fires. The WFI is quite similar to MFI, but adjusted to account for the skewedness that is sometimes present in fire interval data. LEIs and UEIs delineate a range above and below which a fire interval is considered statistically different from the mean. Seasonality is determined by the position of the fire scar in the annual ring. Dormant-season fires occur between the annual rings, whereas spring fires produce scars in the earlywood and summer fires scar the latewood (Grissino-Mayer 2004). In northern Pennsylvania, the dormant season is from October to late-April, spring is in May and early June, and summer runs from mid-June through September based on the seasonality of tree diameter growth as indicated by anatomical changes during the production of bole wood. Spatial extent is the proportion of the stand burned by the fire. We determined spatial extent by creating a map of each fire showing the locations of all recorder trees present at the time of a fire and which ones were scarred by that fire. The proportion of the site burned was recorded as 5%, 25%, 50%, 75%, and 95%, as these were the midpoint values of five coverage classes (0%–10%, 11%–40%, 41%–60%, 61%–90%, and 91%–100%). Data summaries were developed for the periods 1590–2010 for LBH and SLR and 1575–2010 for UDR. Each chronology was divided into two eras: before and after 1790, because this year marks the beginning of European settlement in PCV (Meginness 1892; Dillon 2006). For the remainder of this paper, we will refer to these two eras as presettlement and settlement, respectively.

We used the statistics subroutine in the FHX2 software (Grissino-Mayer 2004) to calculate the MFI and WFI for all fires of (1) each site chronology, (2) presettlement and settlement eras of each site chronology, (3) a composite chronology (all three sites combined), and (4) the presettlement and settlement eras of the composite chronology. We also calculated the MFI and WFI for just the large fires (≥50% of a site burned) for each site chronology and landscape-level fires (impacted at least 2 sites) for the composite chronology. We also used FHX2 to conduct *t* tests to determine whether the MFI and WFI changed between the two eras. We used the LEI and UEI as calculated by FHX2 and *t* tests to determine

Fig. 2. Topography of each of the three study sites and locations of the red pine recorder trees within each site. Some recorder trees are hidden from view by other recorder trees that are nearby. Note the consistency of slope, slope position, and aspect of the three sites.

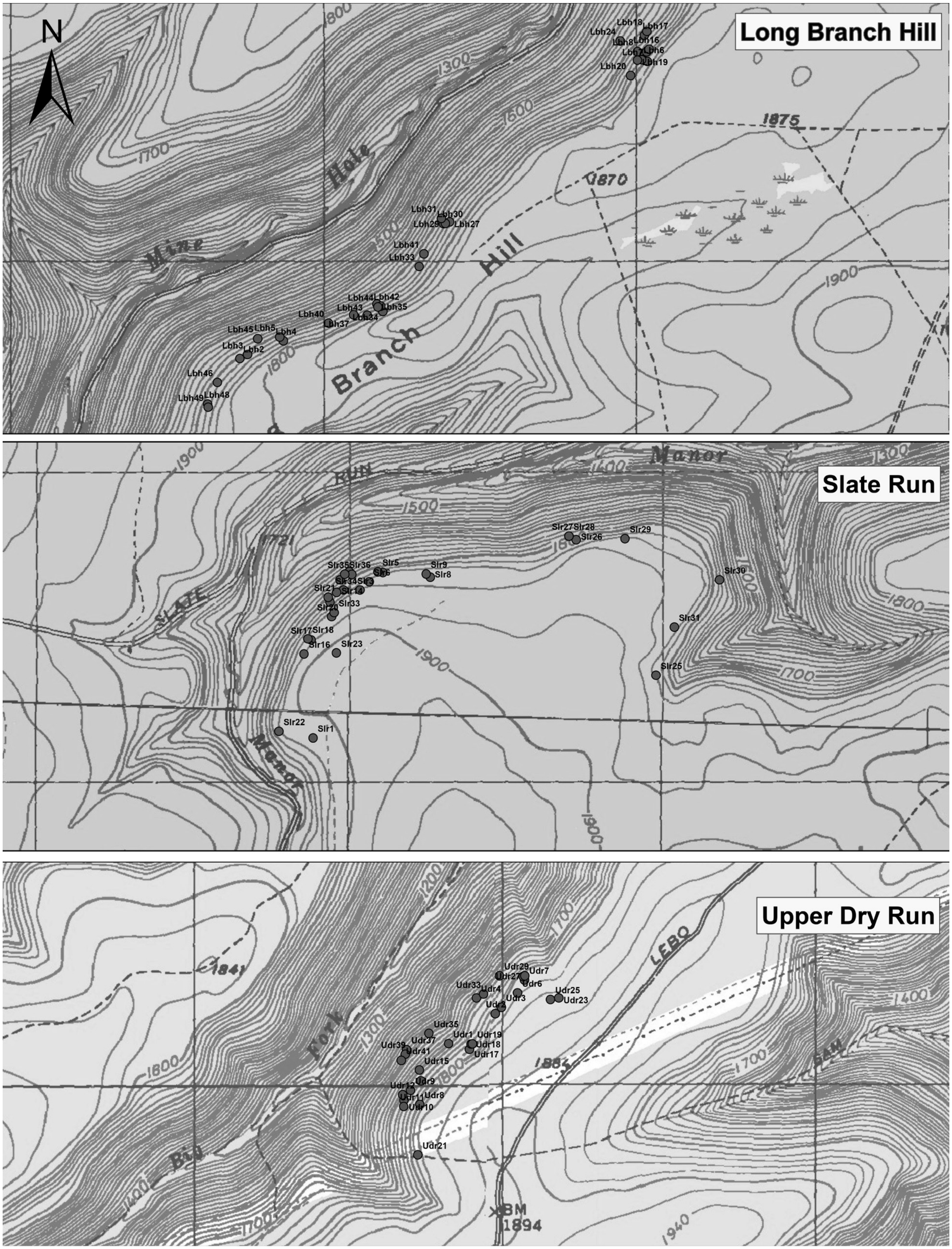
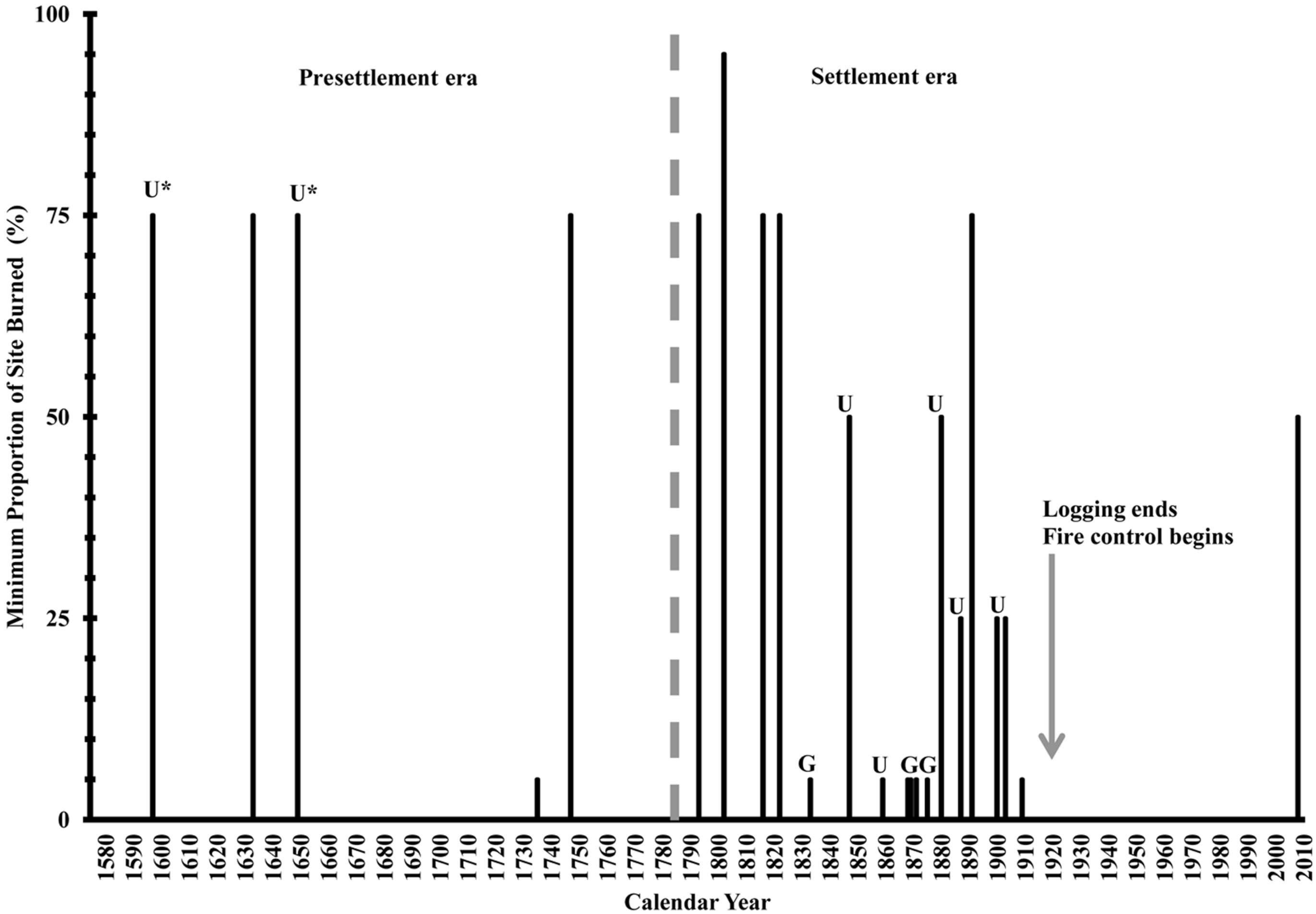


Fig. 3. Fire chronology of Long Branch Hill (LBH) from 1575 to 2010. The black vertical bars represent the fires. All fires were dormant-season burns unless designated as growing-season (G) or undeterminable (U). The gray broken line separates the chronology into the presettlement and settlement eras. The asterisks (*) denote fires identified from formation of a red pine cohort, not from fire scars.



whether any fire intervals were longer or shorter than normal. The FHX2 default setting of α = 0.125 was used for all tests.

Testing of the association of drought to PCV's fire history was done with χ^2 analysis, *t* tests, and superposed epoch analysis (SEA) (Zar 1999; Grissino-Mayer 2004). To quantify drought, we obtained the actual and reconstructed PDSIs for northern Pennsylvania (gridpoint 254) for the period 1575–2010 inclusive (Cook et al. 2004, National Climatic Data Center 2013), and sorted these 435 years into three categories: dry, (PDSI < –1.0), normal (PDSI between –1.0 and +1.0), and wet (PDSI > +1.0) years. The PDSI-category distribution for the 435 years was 165 dry years (0.379), 173 normal years (0.397), and 97 wet years (0.224). We consolidated the three site chronologies into one composite chronology to increase the sample size of fire years (N = 59) and represent the entire PCV area. We sorted the 59 fire years by PDSI category and used χ^2 analysis to determine whether the fire years were distributed as expected among the three PDSI categories. This test was initially done on the entire chronology and then on each era. Because χ^2 analysis can be misleading with small sample sizes, we also conducted *t* tests with unequal variances to determine whether the PDSI for the fire years was different from that of the nonfire years. Like χ^2, this test was initially done on the entire chronology, then on each era. SEA was conducted to determine the degree, strength, and influence of regional climate to fire events. Data were bootstrapped for 1000 simulated events to derive confidence limits. Fire event data were compared with PDSI to determine if drought conditions were significantly different from average during the six years preceding and four years succeeding fire events. We conducted the SEA analysis on both eras of the composite chronology when fires scarred at least 20% of the recorder trees. An α of 0.05 was used in all statistical tests.

Results

The three sites produced 132 samples, of which 93 (70%) were datable. Thirty-nine samples were unable to be included in the analysis because of extensive rot and (or) too few rings for reliable dating. The datable samples were rather evenly divided among the three sites, with LBH having the most (35) samples, UDR having the least amount (28) of samples, and SLR having an intermediate amount (30) of samples.

Between 1630 and 2010, we identified 21 fires at LBH based on fire scars (Fig. 3). Furthermore, we identified two other possible fires (~1595 and ~1650) based on the similar pith dates of 9 and 19 recorder trees, respectively, because cohorts of red pines frequently form shortly after a severe fire opens the forest canopy (Rudolf 1990). Twelve of these 23 fires were widespread, burning at least half the site, and most of these large fires occurred before 1850. The others were small fires that burned <25% of the site. We could determine the seasonality of 18 of the 23 fires, and 13 of those (72%) burned during the dormant season. The dormant-season fires primarily occurred before 1850 or after 1880, whereas the growing-season fires burned between those two years. Since 1910, only one fire has occurred at LBH: a widespread dormant-season fire that

Table 1. Fire frequency data (individual site and collectively) for the Long Branch Hill, Slate Run, and Upper Dry Run areas of the Pine Creek Valley of northern Pennsylvania.

Site	Characteristic	Presettlement	Settlement	Overall	Large fire
Long Branch Hill	Fires (No.)	5	18	23	12
	Intervals (No.)	4	17	22	9
	MFI (years)	49.0	7.3*	19.4	30.0
	WFI (years)	40.0	6.7*	11.2	17.7
	LEI (years)	11.1	2.8	1.6	2.6
	UEI (years)	94.0	12.0	41.5	63.7
Slate Run	Fires (No.)	6	18	24	9
	Intervals (No.)	5	17	23	6
	MFI (years)	35.6	6.9*	14.0	32.1
	WFI (years)	26.3	6.4*	9.4	24.7
	LEI (years)	5.8	3.0	1.7	5.9
	UEI (years)	72.5	21.0	29.2	64.2
Upper Dry Run	Fires (No.)	6	26	32	12
	Intervals (No.)	5	25	31	8
	MFI (years)	37.4	4.9*	10.9	30.2
	WFI (years)	25.5	4.6*	6.3	18.7
	LEI (years)	4.7	1.9	0.9	3.0
	UEI (years)	78.2	8.3	23.0	63.5
All Three Sites	Fires (No.)	17	62	79	26
	Intervals (No.)	11	43	54	20
	MFI (years)	14.8	4.9*	7.3	20.9
	WFI (years)	8.7	2.6*	3.7	13.1
	LEI (years)	0.9	1.0	0.5	1.8
	UEI (years)	30.8	5.1	11.5	34.7

Note: MFI, mean fire interval; WMI, Weibull mean interval; LEI, lower exceedance interval; and UEI, upper exceedance interval. Presettlement refers to the period before 1790 and settlement refers to the period after 1790. Large fires burned at least half of the site. Asterisks (*) denote settlement means that are different from the corresponding presettlement means at the 0.05 level.

burned on 19 April 2008 (R. Siefert, district forester, Tioga State Forest (personal communication, 2012)).

Overall, the 23 fires at LBH produced an MFI of 19.4 years and a WFI of 11.2 years for the entire chronology (Table 1). Considering just the 12 large fires (>50% coverage), their MFI was 30.0 years and their WFI was 17.7 years. The overall UEI (41.5 years) indicated three abnormally long fire-free intervals in the chronology. These occurred between 1650 and 1735 (P = 0.034), 1747 and 1793 (P = 0.108), and 1909 and 2008 (P = 0.016). The five fires of the presettlement era (before 1790) had an MFI and a WFI of 49.0 and 40.0 years, respectively. Of these five fires, three occurred during the dormant season, whereas two had an undeterminable seasonality. Four of the five fires burned at least 50% of the site. In the settlement era (after 1790), we identified 18 fires. All but one of these occurred before 1910, resulting in an MFI and a WFI of 7.3 and 6.7 years, respectively. Both of these values were less than their corresponding presettlement values.

At SLR, we identified 23 fires from the fire scars between the years 1620 and 2010 (Fig. 4). Additionally, there appears to have been another fire just prior to 1600 based on the similar pith dates of 13 recorder trees. Of these 24 fires, 21 (88%) burned during the dormant season, whereas two occurred during the growing season and one was undeterminable. Nine of the fires were widespread, burning at least half of the site, and all of these large fires occurred before 1850. We found no evidence of fire after 1911 at SLR.

The 24 fires at SLR produced an overall MFI and an overall WFI of 14.0 and 9.4 years, respectively (Table 1). The large fires at SLR had an MFI of 32.1 years and a WFI of 24.7 years. The overall UEI (29.2 years) indicated just one abnormally long fire-free interval, 1649–1755 (P = 0.001), but two other intervals, 1768–1793 and 1806–1827, were nearly significant (P = 0.149 and P = 0.162, respectively). Six of SLR's fires occurred before European settlement commenced in the 1790s, resulting in an MFI of 35.6 years and a WFI of 26.3 years. The other 18 fires burned after 1790. The MFI and WFI for this era were 6.9 and 6.4 years, respectively, and both were significantly less than their corresponding values of the presettlement era.

At UDR, 31 fires occurred between 1630 and 2010 (Fig. 5). The actual and estimated piths of the oldest recorder trees suggested an additional fire about 1580. The 32 fires primarily occurred during the 1800s and early 1900s, with only 6 fires occurring during the presettlement era and none after 1915. Twelve of the 32 fires burned at least 50% of the site and most of these occurred before 1850. We could only ascertain seasonality for 8 of the 32 fires (25%), and these were evenly divided between dormant-season and growing-season burns. However, most of the undeterminable fire scars appeared to be dormant-season scars, but decay made it impossible to be absolutely certain.

The 32 fires at UDR produced an overall MFI and an overall WFI of 10.9 and 6.3 years, respectively (Table 1). The 12 large fires had an MFI of 30.2 years and a WFI of 18.7 years. The overall UEI was 23.0 years and this indicated two abnormally long fire-free intervals, from 1635 to 1735 (P = 0.001) and from 1763 to 1791 (P = 0.057). In the presettlement era, the MFI and WFI were 37.4 and 25.5 years, respectively. These decreased significantly in the logging and settlement era to 4.9 years for MFI and 4.6 years for WFI.

The overall PCV chronology spanned from 1575 to 2010 and included 55 years in which 79 fires occurred (Fig. 6, Table 1). The composite MFI for all fires was 7.3 years and the composite WFI was 3.7 years. For large fires, these values were 20.9 and 13.1 years, respectively. In the presettlement era, we found evidence for 17 fires. The earliest of these fires burned in the late 1500s and established the oldest recorder trees at each site. After that, fires occurred in two distinct periods: 1623–1649 and 1735–1768. Overall, the presettlement era fires produced an MFI of 14.8 years and a WFI of 8.7 years, but the standard deviation was 23.2 years because of the multidecadal fire-free periods. Of those 17 fires, 11 (65%) were large fires that burned at least half of one of the sites. The 1590s, 1649, and 1755 fires may be single fires that impacted multiple sites. Between 1790 and 2010, at least 62 fires occurred at the PCV sites, resulting in an MFI and a WFI of 4.9 and 2.6 years,

Fig. 4. Fire chronology of Slate Run (SLR) from 1575 to 2010. The black vertical bars represent the fires. All fires were dormant-season burns unless designated as growing-season (G) or undeterminable (U). The gray broken line separates the chronology into the presettlement and settlement eras. The asterisk (*) denotes fires identified from formation of a red pine cohort, not from fire scars.

respectively. Both means were significantly less relative to the preceding era ($P < 0.01$). At least 26 of these fires (42%) were large and these generally occurred before 1850. Nine of these fires may have impacted two sites, and two fires, 1802 and 1891, may have burned all three sites. Since 1915, only one fire has occurred at the three sites.

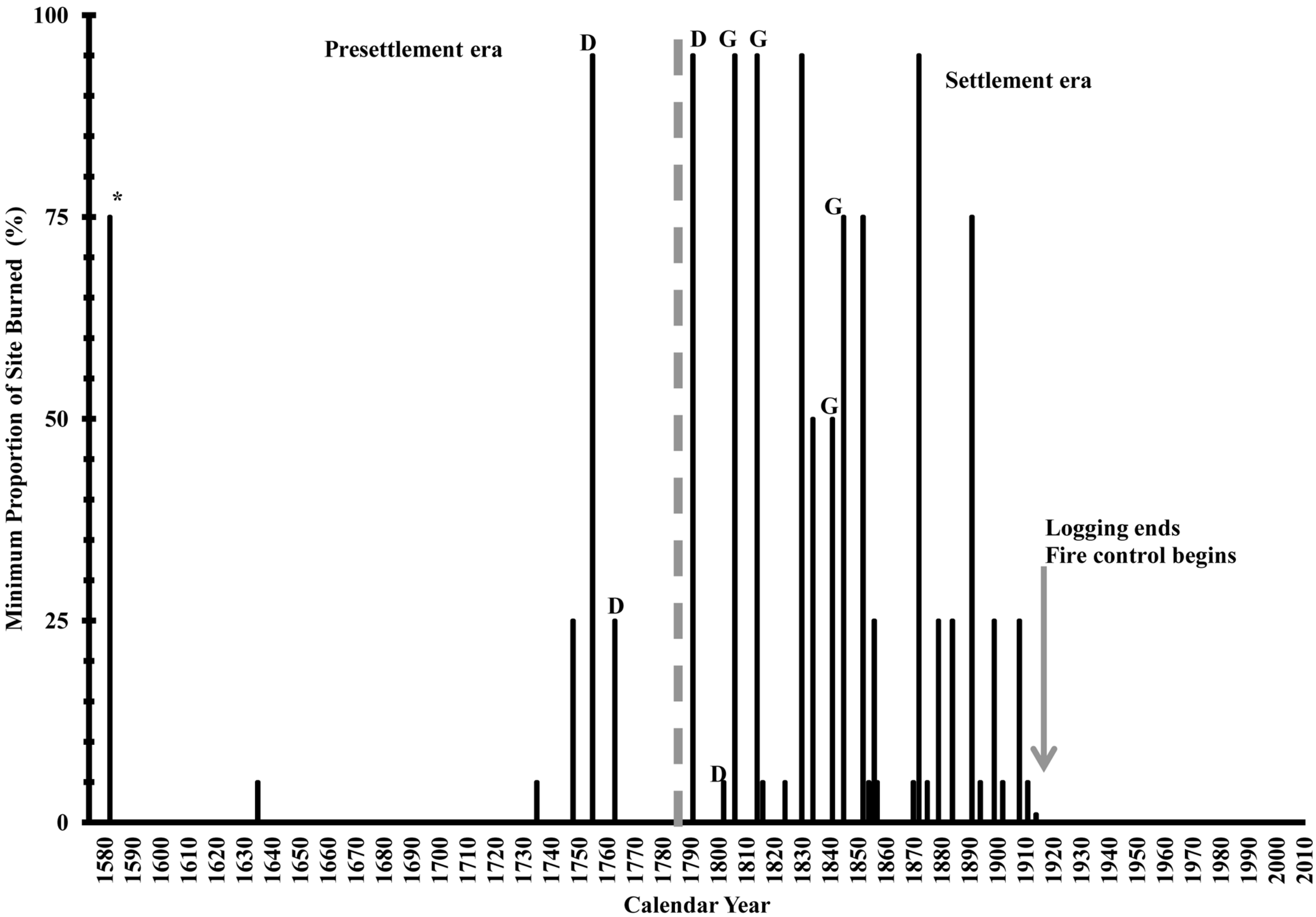
Drought years (annual PDSI < –1.0) comprised 165 of the 435 years (38%) with a mean PDSI of –1.72. Single- or two-year droughts comprised 90 of those 165 years (55%) with a mean PDSI of –1.55. The remaining years occurred in 15 multiyear droughts with a PDSI of –1.82 (Fig. 6). χ^2 analysis of the entire chronology indicated that the fires were distributed as expected among dry, normal, and wet years ($\chi^2 = 5.94$, critical value = 5.991) although there was a trend of more fires occurring in dry years. χ^2 analysis of each era revealed the same finding: fires were distributed as expected among the three PDSI categories, but the trend of more fires in dry years was only present in the presettlement era. *t* tests of the mean PDSI of all fire and nonfire years found no difference ($P = 0.28$) between the two groups: –0.66 PDSI for fire years and –0.42 PDSI for nonfire years. The same was also true for both eras: no difference detected between the mean PDSI for the fire and nonfire years, but the presettlement era *P* value was 0.11 compared with a *P* value of 0.45 for the settlement era. Finally, SEA found no significant relationships. None of the years preceding or following a fire was found to be drier than expected at a confidence level of 95%.

Discussion

Some of the enduring questions about the eastern USA before European settlement are "what were the characteristics of the various fire regimes?", "how did these regimes change with subsequent European settlement?", and "what were the contributions of drought and local human history to these regimes?" Paleoecological studies and historical records establish that American Indian tribes used fire for millennia for numerous reasons and European settlers adopted many of these practices (Williams 2003). However, specifics regarding frequency, seasonality, and spatial extent of fires are lacking and such details are important to land managers engaged in forest ecosystem restoration efforts. The results of this study answer the these three questions for the fire regimes of the conifer-dominated forests of northern Pennsylvania.

The presettlement fire regime of northern Pennsylvania consisted of sporadic, large, dormant-season fires separated by decades of no fire. Each of the sites averaged a fire every 35–50 years between the late 1500s and late 1700s. This is similar to the fire frequency reported for red pine stands in Vermont (Engstrom and Mann 1991, Mann et al. 1994) and in the Great Lakes region (Drobyshev et al. 2004*a*; Guyette et al. 2009), but is in stark contrast to other fire history studies conducted in the eastern USA (Shumway et al. 2001; Guyette et al. 2009; Aldrich et al. 2010). The Pennsylvania presettlement fires occurred in early- to mid-spring (late March to early May) as evidenced by many of the scars being located between

Fig. 5. Fire chronology of Upper Dry Run (UDR) from 1575 to 2010. The black vertical bars represent the fires. Fires marked with a “D” or “G” occurred in the dormant or growing season, respectively, and all other fires had an undeterminable seasonality. The gray broken line separates the chronology into the presettlement and settlement eras. The asterisk (*) denotes fires identified from formation of a red pine cohort, not from fire scars.

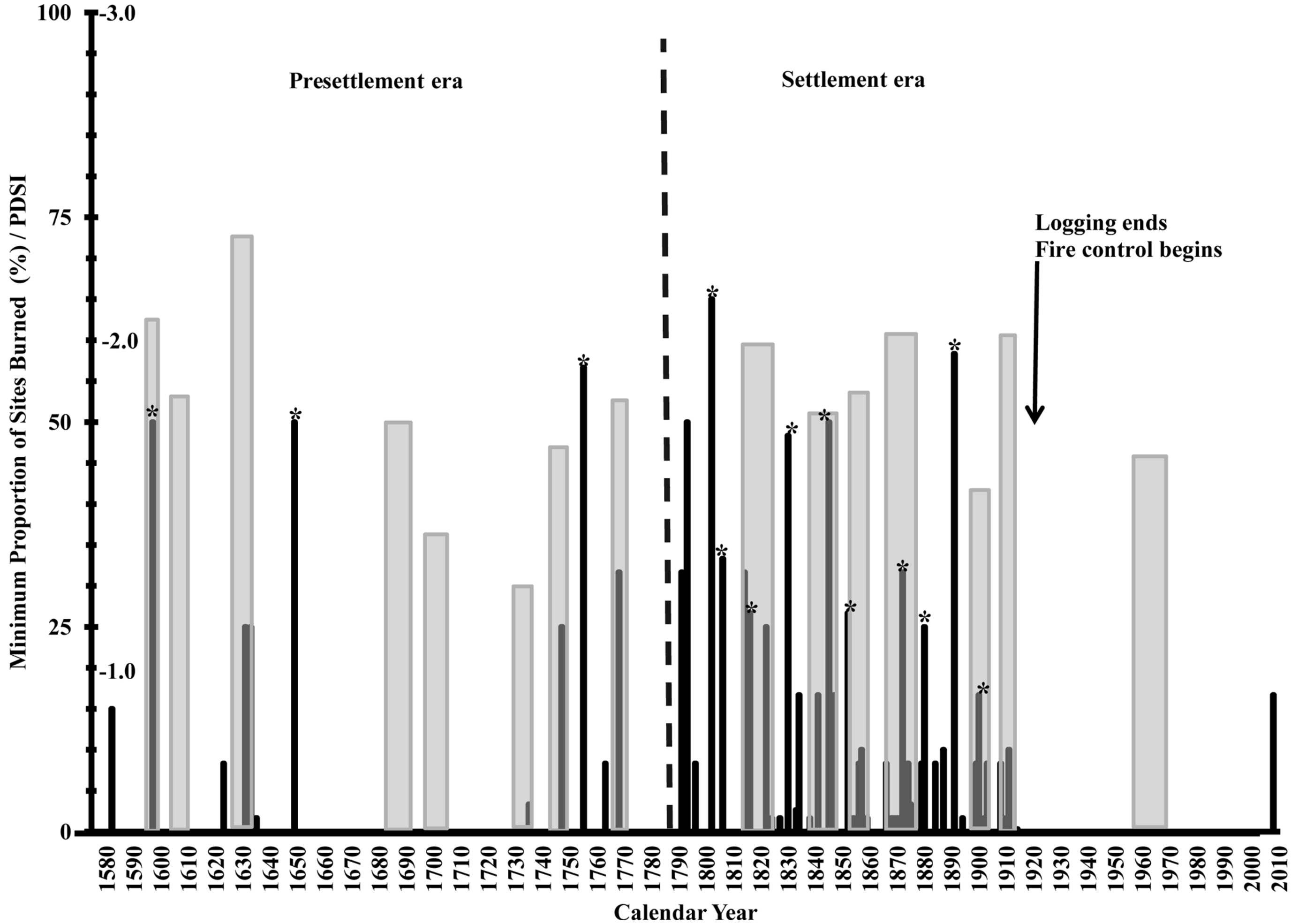


the annual rings, but a few being positioned in the earlywood. Apparently most of the trees were still dormant when burned, but a few had begun growing for that year. This is consistent with Shumway et al. (2001) and Aldrich et al. (2010) who reported that presettlement fires in montane oak–pine forests in western Maryland and Virginia burned almost exclusively during the dormant season. The Pennsylvania presettlement fires tended to be large, impacting at least half of a site. Additionally, the scarred recorder trees were generally on the upper portions of the sites, whereas the unscarred ones were located downslope. This suggests that the presettlement fires originated elsewhere, burned across the tops of the hills, and began backing down through the northwest-facing sites before extinguishing. This was clearly the case of the 2008 fire at LBH, an arson-ignited fire that originated more than a mile from the site (R. Siefert, district forester, Tioga State Forest (personal communication, 2012)).

What was the contribution of drought to this the presettlement fire regime? Apparently, drought had little influence as we detected only weak evidence of a drought–fire relationship. This finding is consistent with those of Engstrom and Mann (1991) and Mann et al. (1994) in Vermont, but contrasts with the climate–fire associations reported by Lafon et al. (2005) for western Virginia. There was a weak trend of fires occurring during or after droughts, but some large fires (1649 and 1755) occurred during wet years. This implies that short-term weather conditions may have a strong impact on the fire regime. It also suggests that other factors may have been predisposing the sites to burning by severely disturbing the canopy. Potential canopy-disturbing factors include ice and (or) wind storms as well as nesting and (or) roosting by large flocks of the now extinct passenger pigeon (*Ectopistes migratorius*) (Ellsworth and McComb 2003). Finally, the lack of detectable drought influence may indicate that drought simply was not a major environmental stress in the presettlement forests of northern Pennsylvania. The reconstructed PDSI data show that most droughts were 1- to 2-year events of mild to moderate intensity. Longer droughts happened about three to four times a century, but these were also of mild to moderate intensity. Droughts in northern Pennsylvania may have been too infrequent, too short, and too mild to produce a strong influence on the fire regime.

What was the role of humans in this presettlement fire regime? It was probably substantial because American Indians likely started most to all of the fires. We reached this conclusion based on the fact that nearly all fires burned during the dormant season (October–April inclusive) when lightning is uncommon and, when it does occur, it is almost always accompanied by rain. Weather data from nearby Williamsport, Pennsylvania, indicate that only 13% of lightning strikes occur during the dormant season (Weatherspark 2013). Additionally, lightning-caused fires are rare in Pennsylvania, accounting for just 1.4% of all fires annually and 1.5% of the total area burned (PA Department of Conservation and Natural Resources 2013). Therefore, American Indians are a more logical explanation than lightning as the primary ignition

Fig. 6. A composite fire chronology of the three study sites along the western side of Pine Creek Valley. The black vertical bars represent the fires and the gray areas represent multiyear droughts. Asterisks (*) denote years when two or more sites had a fire year in common. Note how the multisite fire years increase from the presettlement era to the settlement era.



source for the presettlement fires. American Indians traveled through the PCV region, and historical writings show that the Iroquois tribe burned the forests to promote fruiting ericaceous shrubs such as blueberries and huckleberries (*Vaccinium* spp. and *Gaylussacia* spp., respectively) and kill rattlesnakes (*Crotalus horridus*) (Tome 1854; Pringle 1880; Hulbert 1910). The PCV watershed has widespread heath shrubs and a large rattlesnake population, so the fires of the 1600s and 1700s may have resulted from those practices.

A new fire regime began with the start of European settlement in the late 1700s. The occurrence of fires increased significantly. The MFI range decreased to 4.9–7.2 years, a range consistent with other fire history research in the Appalachian Mountains region (Shumway et al. 2001; Aldrich et al. 2010). Seasonality remained dominated by dormant-season fires, but mid- to late-spring fires also became common. The variability of the spatial extent of these fires increased relative to the preceding era with more small fires scarring less than 50% of the recorder trees, suggesting ignitions in or near the sites. However, the sites now had more fire years in common, suggesting landscape-size burns or synchronous ignitions.

This marked increase in fire occurrence was entirely due to human activity, specifically, the logging of the northern conifer forest. For more than a century, the PCV watershed was logged (Taber 1972; Dillon 2006). The increased human presence coupled with the logging slash led to numerous fires throughout the watershed regardless of drought conditions. Consequently, the weak drought–fire relationship of the presettlement era was overwhelmed and became irrelevant in the 1800s.

The settlement-era regime of frequent fires of varying seasonality, severity, and size ceased abruptly about 1915 because of the end of logging and the advent of forest protection policies (Taber 1972). Since then, fire has been an infrequent disturbance in the PCV region as evidenced by just one site experiencing a fire (LBH in 2008). This new infrequent fire regime is human-mediated in that burning conditions continue to occur, but fires do not start because ignitions are intentionally withheld via public education and strict fire control laws. Efforts to prevent fires become especially pronounced during droughts, so the drought influence of human behavior on this new fire regime is inconsequential.

An interesting aside to this study was the discovery of multidecadal fire-free intervals at all three sites, a finding reported by other fire history studies in eastern North America (Guyette et al. 2003, 2009). The exact causes of these periods are unknown, but they appear to be linked to disruptions in the American Indian and early settler cultures that removed humans as an ignition source for some time. More research is warranted to understand the causality of these fire-free periods and their ramifications to forest development and succession.

Like any study, this one has limitations. The individual site and overall composite chronologies have small sample sizes at both ends, so we may have missed small fires in the early 1600s or in the

1900s. Our assumption that the oldest red pine cohorts at each site were created by fires may be erroneous because severe canopy disturbance in red pine stands can initiate regeneration. The identification of 12 landscape-level fires affecting two or more sites may be an overestimation as there is no means of distinguishing between one large fire and two or three smaller synchronous fires. Approximately 30% of the fire scars could not be assigned to a season because of decay. Finally, caution must be exercised in extrapolating the lack of fire during the presettlement era to other parts of eastern North America. PCV was a hinterland with scant American Indian influence, so the lack of fires may not be representative of other locations that were closer to American Indian villages and major travel routes.

Conclusion

The Pine Creek Valley of northern Pennsylvania has experienced markedly different fire regimes in the past 400 years. Prior to 1800, fires were sporadic. When they did occur, they usually burned during the dormant season, were widespread, and occasionally burned intense enough to initiate pulses of forest regeneration. American Indian tribes were the driving force behind these fires with drought playing a minor role. European settlement started about 1800 and created a new regime as fire frequency increased fivefold relative to the before 1800, while seasonality expanded to include some growing-season burns and spatial extent became quite variable. In this fire regime, the human influence overwhelmed the drought influence. This frequent fire regime persisted until logging ended and forest protection began in the early 1900s. Since then, fires have been virtually nonexistent. This current lack of fire is due to deliberate prevention of ignitions, especially during droughts, making the current infrequent fire regime a human-mediated condition. It is likely to remain in place into the foreseeable future because of the numerous cultural, legal, operational, and social restrictions to forest burning in the 21st century.

Acknowledgements

We thank the Pennsylvania Bureau of Forestry, especially Doug D'Amore, whose initial enthusiasm and guidance spurred this study and the finding of the first study site. Additionally, we thank the staffs of the Tiadaghton and Tioga State Forests for their permission to conduct this research on their lands, their help with locating other potential sites, and access to the sites. We also thank Eric Baxter and Greg Sanford of the USDA Forest Service, Northern Research Station, for all their hard work in collecting the samples. We are indebted to Tim Fox of the Northern Research Station for preparing the maps used in the spatial analysis as well as in this manuscript. Funding for this project was provided by the Joint Fire Science Program and the USDA Forest Service, Northern Research Station.

References

Aldrich, S.R., Lafon, C.W., Grissino-Mayer, H.D., DeWeese, G.G., and Hoss, J.A. 2010. Three centuries of fire in montane pine–oak stands on a temperate forest landscape. Appl. Veg. Sci. **13**: 36–46. doi:10.1111/j.1654-109X.2009.01047.x.

Arno, S.F., and Sneck, K.M. 1977. A method for determining fire history in coniferous forests of the mountain West. USDA For. Ser. Gen. Tech. Rep. INT-42.

Boyce, M.S., and Haney, A. 1997. Ecosystem management: applications for sustainable forests and wildlife resources. Yale University Press, New Haven, Conn.

Chapin, F.S., Kofinas, G.P., and Folke, C. 2009. Principles of ecosystem stewardship. Springer-Verlag Publishing, New York.

Cook, E.R., Meko, D.M., Stahle, D.W., and Cleaveland, M.K. 2004. North American summer PDSI reconstructions: IGBP PAGES/World Data Center for Paleoclimatology. Data Contribution Series No. 2004-045. NOAA/NGDC Paleoclimatology Program, Boulder, Colorado.

Dillon, C.W. 2006. Pennsylvania's Grand Canyon: a natural and human history. Pine Creek Press, Wellsboro, Penn.

Donnegan, J.A., Veblen, T.T., and Sibold, J.S. 2001. Climatic and human influences on fire history in Pike National Forest, central Colorado. Can. J. For. Res. **31**(9): 1526–1539. doi:10.1139/x01-093.

Drobyshev, I., Goebel, P.C., Bergeron, T., and Corace, R.G. 2012. Detecting changes in climate forcing on the fire regime of a North American mixed-pine forest: a case study of the Seney National Wildlife Refuge, upper Michigan. Dendrochronologia, **30**: 137–145. doi:10.1016/j.dendro.2011.07.002.

Drobyshev, I., Niklasson, M., Angelstam, P., and Majewski, P. 2004. Testing for anthropogenic influence on fire regime for a 600-year period in the Jaksha area, Komi Republic, East European Russia. Can. J. For. Res. **34**(10): 2027–2036. doi:10.1139/x04-081.

Ellsworth, J.W., and McComb, B.C. 2003. Potential effects of passenger pigeon flocks on the structure and composition of pre-settlement forests in eastern North America. Conserv. Biol. **17**: 1548–1558. doi:10.1111/j.1523-1739.2003.00230.x.

Engstrom, F.B., and Mann, D.H. 1991. Fire ecology of red pine (*Pinus resinosa*) in northern Vermont, U.S.A. Can. J. For. Res. **21**(6): 882–889. doi:10.1139/x91-123.

Grissino-Mayer, H.D. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Res. **57**(2): 205–221.

Grissino-Mayer, H.D. 2004. FHX2 user's manual. University of Tennessee, Knoxville, Tenn.

Grissino-Mayer, H.D., Romme, W.H., Floyd, M.L., and Hanna, D.D. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, U.S.A. Ecology, **85**: 1708–1724. doi:10.1890/02-0425.

Guyette, R.P., Dey, D.C., and Stambaugh, M.C. 2003. Fire and human history of a barrens-forest mosaic in southern Indiana. Am. Midl. Nat. **149**: 21–34. doi:10.1674/0003-0031(2003)149[0021:FAHHOA]2.0.CO;2.

Guyette, R.P., Stambaugh, M.C., and Dey, D.C. 2009. Developing and using fire scar histories in the southern and eastern United States. Missouri Tree-Ring Laboratory, Columbia, Missouri. Final Report of Project 06-3-1-16 to the Joint Fire Science Program.

Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. **43**: 69–78.

Hulbert, A.B. 1910. David Zeisberger's history of the northern American Indians in 18th century Ohio, New York, and Pennsylvania. Wennawoods Publishing. Lewisburg, Penn.

Johnson, E.A., Fryer, G.I., and Heathcott, M.J. 1990. The influence of man and climate on frequency of fire in the interior wet belt forest, British Columbia. J. Ecol. **78**: 403–412. doi:10.2307/2261120.

Kohler, C.D. 1986. Soil survey of Lycoming County, Pennsylvania. U.S. Soil Cons. Ser.

Lafon, C.W., Hoss, J.A., and Grissino-Mayer, H.D. 2005. The contemporary fire regime of the central Appalachian Mountains and its relation to climate. Phys. Geogr. **26**: 126–146. doi:10.2747/0272-3646.26.2.126.

Landers, J.L., Van Lear, D.H., and Boyer, W.D. 1995. The longleaf pine forests of the southeast: Requiem or renaissance? J. For. **93**: 39–44.

Mann, D.H., Engstrom, F.B., and Bubier, J.L. 1994. Fire history and tree recruitment in an uncut New England forest. Quat. Res. **42**: 206–215. doi:10.1006/qres.1994.1070.

Meginness, J. 1892. The early history of Lycoming County, Pennsylvania. Wennawoods Publishing. Lewisburg, Penn.

National Climatic Data Center. 2013. Palmer Drought Severity Index. Available from www.ncdc.noaa./paleo/pdsi.html [accessed January 2013].

Niklasson, M., and Granstrom, A. 2000. Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. Ecology, **81**: 1484–1499. doi:10.1890/0012-9658(2000)081[1484:NASOFL]2.0.CO;2.

Owlett, S.E. 1993. Seasons along the Tiadaghton: an environmental history of the Pine Creek Gorge. Pine Creek Press, Wellsboro, Penn.

PA Department of Conservation and Natural Resources. 2013. Wildfire statistics. Available from www.dcnr.state.pa.us/forestry/fire/firestatistics/index.html [accessed January 2013].

Pringle, C.G. 1880. The forests of Pennsylvania. *In* Report on the forests of North America. *Edited by* C.S. Sargent. Government Printing Office, Washington, D.C. pp. 506–511.

Pyne, S.J. 1982. Fire in America: a cultural history of wildland and rural fire. University of Washington Press, Seattle, Wash.

Pyne, S.J. 1995. World fire: the culture of fire on earth. Holt Publishing, New York.

Rudolf, P.O. 1990. *Pinus resinosa* Ait. (Red pine). *In* Silvics of North America. Volume 1: Conifers. *Edited by* R.M. Burns and B.H. Honkala. USD A Handb. **654**. pp. 442–455.

Shumway, D.L., Abrams, M.D., and Ruffner, C.M. 2001. A 400-year history of fire and oak recruitment in an old-growth oak forest in western Maryland, U.S.A. Can. J. For. Res. **31**(8): 1437–1443. doi:10.1139/x01-079.

Speer, J.H. 2010. Fundamentals of tree ring research. University of Arizona Press, Tucson, Ariz.

Stokes, M.A., and Smiley, T.L. 1968. Introduction to tree-ring dating. University of Chicago Press, Chicago, Ill.

Taber, T.T. 1972. Logging railroad era of lumbering in Pennsylvania. Volume 4: Sunset along the Susquehanna. Lycoming Printing Company, Williamsport, Penn.

Tome, P. 1854. Pioneer life or thirty years a hunter. Aurand Press, Harrisburg, Penn.

Van Lear, D.H., Carroll, W.D., Kapeluck, P.R., and Johnson, R. 2005. History and restoration of longleaf pine–grassland ecosystems: implications for species at risk. For. Ecol. Manage. **211**: 150–165. doi:10.1016/j.foreco.2005.02.014.

Veblen, T.T., Kitzberger, T., Villalba, R., and Donnegan, J. 1999. Fire history in northern Patagonia: the roles of humans and climatic variation. Ecol. Monogr. **69**: 47–67. doi:10.1890/0012-9615(1999)069[0047:FHINPT]2.0.CO;2.

Veblen, T.T., Kitzberger, T., and Donnegan, J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado front range. Ecol. Appl. **10**: 1178–1195. doi:10.1890/1051-0761(2000)010[1178:CAHIOF]2.0.CO;2.

Wallace, P.A. 1998. Indian paths of Pennsylvania. Historical and Museum Commission, Harrisburg, Penn.

Weatherspark. 2013. Weather averages for Williamsport, Pennsylvania. Available from www.weatherspark.com/averages/Williamsport-Pennsylvani-UnitedStates.html [accessed January 2013].

Williams, G.W. 2003. References on the American Indian use of fire in ecosystems. USDA Forest Service, Washington, D.C.

Zar, J.H. 1999. Biostatistical analysis. Prentice-Hall Publishing, Upper Saddle River, N.J.