

Historical Fire Regimes in Red Pine Forests of the Adirondack Mountains, New York, USA

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ABSTRACT: The objectives of this study were to reconstruct historical fire regime characteristics of red pine (*Pinus resinosa*) forests in the Adirondack Mountains, and to highlight potential implications for the conservation and preservation of fire-dependent natural communities. Tree-ring dating of dead and living fire-scarred trees at two sites produced records spanning from 1577 to 2015. Historical fire years spanned the years 1693 to 1913 with a concentration of events in the mid-1800s. Fires were primarily low to moderate severity, dormant-season events that were not associated with summer drought. The historical fire record establishes that fire disturbances were historically present in the Adirondack Mountains and silvicultural intervention (e.g., prescribed burning) may be needed to maintain fire-dependent red pine communities, thus preventing their inevitable succession to northern hardwoods.

Index terms: dendrochronology, EuroAmerican settlement, fire scars, Mohawk, *Pinus resinosa*

INTRODUCTION

In recent decades, wildland fire research and outreach efforts have increased in less-studied regions of the eastern United States such as New England. Despite fire-dependent communities being scattered throughout the region, little is known about fire regimes and little active prescribed fire management occurs. Quantitative and long-term fire regime information is particularly valuable in that it can provide a foundation for understanding wildfire potential, inform natural resource management, and identify opportunities for preserving unique natural communities. Long-term fire scar data, in particular, is especially useful in cases where disturbance regimes and vegetation conditions are long departed due to early and intensive land uses since European settlement. In this way, large contiguous forest landscapes, like in the Adirondack Mountains, may be particularly valuable as evidence and legacies of the deep past may be well preserved.

Charcoal studies in the northeastern United States provide evidence that fire events have occurred in this region for millennia (Patterson 2006). In the north-central Adirondacks, sedimentary charcoal records from Bloomingdale Bog show continuously fluctuating levels of microscopic charcoal deposition over the past 6000 years (LeBoeuf 2014). Large peaks in microscopic charcoal, indicative of regionally extensive upland fires, occurred about 550 y BP and again at the time of EuroAmerican land clearance (LeBoeuf 2014). Pollen records from multiple northeastern United States sites show a shift from shade-tolerant species (*Tsuga*, *Acer*, *Betula*) to xeric species (*Pinus*, *Quercus*) about 500 y BP, which has been attributed to widespread drought and

increased fire (Fuller et al. 1998; Clifford and Booth 2013; LeBoeuf 2014).

Descriptions of the Adirondacks at the time of early exploration and settlement provide somewhat inconclusive accounts of the pre-EuroAmerican settlement (EAS) fire regime. Early settlers described the Adirondacks as thickly forested, which contrasted the open, fire-maintained woodlands often described for other regions in the northeastern United States (e.g., pine barrens, oak-pine savannas; Day 1953; Stewart 2002). Day (1953) concluded that the Adirondacks were not subjected to the relatively frequent purposeful burning of woods by Native Americans like other areas, due to lower population levels and differing hunting and travel practices. However, land surveyors at the time of early EAS recorded multiple observations of burned forests in the Adirondacks, with more observations of fire disturbance in the eastern than western areas (Cogbill 2000).

Though fire has been thought to be historically rare in the northern hardwood forests of the northeastern United States (Lorimer 1977; Bormann and Likens 1979; Fahey and Reiners 1981; Frost 1998), the presence of red pine (*Pinus resinosa* Ait.)—a fire-adapted species—suggests that fire must have played some role in presettlement forests. Red pine is dependent on fire for establishment, early growth, and perpetuation (Van Wagner 1970), and several fire history studies have associated relatively frequent fire with red pine ecology (Heinselman 1973; Mann et al. 1994; Guyette and Dey 1995; Brose et al. 2013, 2015; Muzika et al. 2015; Guyette et al. 2016; Johnson and Kipfmüller 2016). Red pine requires a mineral seedbed with little or no competing vegetation to successfully

regenerate, conditions that are created by moderate to severe surface fires (Flannigan 1993). Although the species can persist in localized areas due to topoedaphic influences, some studies of red pine suggest that the species needs low to moderate severity fires every 20–40 y in conjunction with more intense crown-killing fires every 150–200 y (Bergeron and Brisson 1990).

Despite multiple lines of evidence that fires occurred in the Adirondacks prior to EAS, natural archival fire records are limited, and quantitative analyses of historical fire regimes are lacking. This study presents the first annually resolved fire history data from fire scars for the region. Our objectives were to use fire scars to reconstruct fire regime characteristics and, from this, discuss the relevance to the conservation of fire-dependent natural communities.

METHODS

Study Sites

The Adirondack Mountains in northeastern New York, USA, comprise a geologically and ecologically unique region. An ancient domed Pre-Cambrian erosion surface, the Adirondacks were highly glaciated and have a correspondingly diverse flora and fauna (Cressey 1977). The region is in the transition zone between the boreal and deciduous forest types (Goldblum and Rigg 2010), and a wide variety of natural communities exist along elevation, soil, temperature, and moisture gradients (NYSDEC 2004).

Field reconnaissance in July 2012 resulted in the identification of two fire history study sites with an abundance of fire-scarred living and remnant (dead trees either as tree stumps or snags) red pine trees. The first study site was located on Baxter Mountain (BXT) in Adirondack Park (Figure 1), central Essex County, NY (N44°13.022', W73°45.843'; elevation 708 m a.s.l.), within the Western Adirondack Foothills ecozone (Edinger et al. 2014). Shallow and very rocky soils of the Hogback-Knob Lock complex (Smith 2010) are underlain by metamorphic anorthositic bedrock of igneous origins (Isachsen and

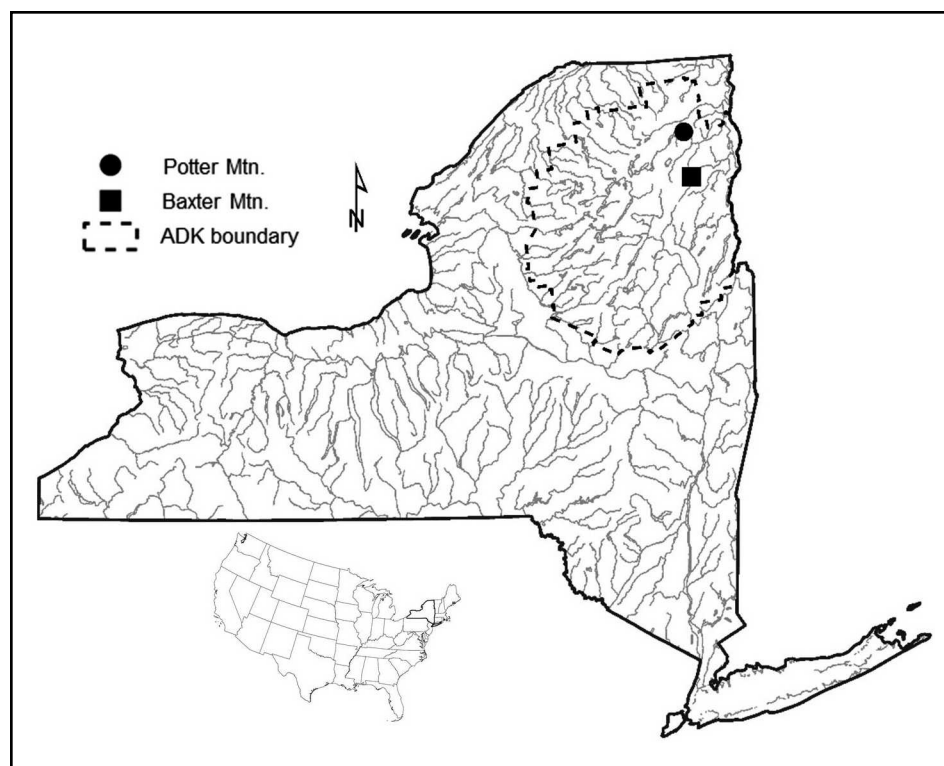


Figure 1. Map of New York with the boundary of Adirondack Park (dashed line) and study site locations separated by approximately 34 km (Baxter Mountain, square; Potter Mountain, circle).

Fisher 1970). The site is readily accessible due to the presence of trails and moderate terrain (Figure 2), and evidence of past logging activities (i.e., tree stumps) was observed at the site. Fire-scarred living and remnant red pines were located only on the south-facing shoulder landscape positions. Surrounding overstory forests were dominated by species typical for the Adirondack section of the Hemlock-Pine-Northern Hardwood forest region (e.g., red maple [*Acer rubrum* L.], beech [*Fagus grandifolia* Ehrh.], birch [*Betula* spp.], eastern hemlock [*Tsuga canadensis* (L.) Carrière], white pine [*Pinus strobus* L.], and northern red oak [*Quercus rubra* L.]; Braun 1950).

The second study site was located approximately 34 km north of BXT, on the eastern side of Potter Mountain (PMT) on privately owned timberland (Lyme Adirondack Forest Company, LLC) held in conservation easement within Adirondack Park (Figure 1), southwestern Clinton County, NY (N44°31.197', W73°49.429'; elevation 572 m a.s.l.). PMT is located within the Adirondack High Peaks ecozone (Edinger et al. 2014). Shallow and very rocky soils

of the Ricker Hogback complex (Trevail 2006) are underlain by metamorphic bedrock of uncertain origins (e.g., charnockite, granite, quartz; Isachsen and Fisher 1970). The site terrain is rugged and steep, and no evidence of past logging activities was observed. Fire-scarred living and remnant red pine trees were found only on, and immediately above, a south-facing cliff in a nearly pure red pine stand (Figure 2). Forest overstory vegetation of nearby landscape positions was similar to Baxter Mountain, with northern hardwood species being dominant. Both study sites are representative of the red pine rocky summit ecological community as classified by the New York Natural Heritage Program (Edinger et al. 2014).

The regional climate is humid continental, though local variability can be pronounced and heavily influenced by aspect, elevation, local topography, and distance from large bodies of water and mountains. Summers in the Adirondacks are generally warm with cool nights, and winters extremely cold and snowy (NYSDEC 2004). Average annual precipitation is 94 cm at BXT and 90 cm

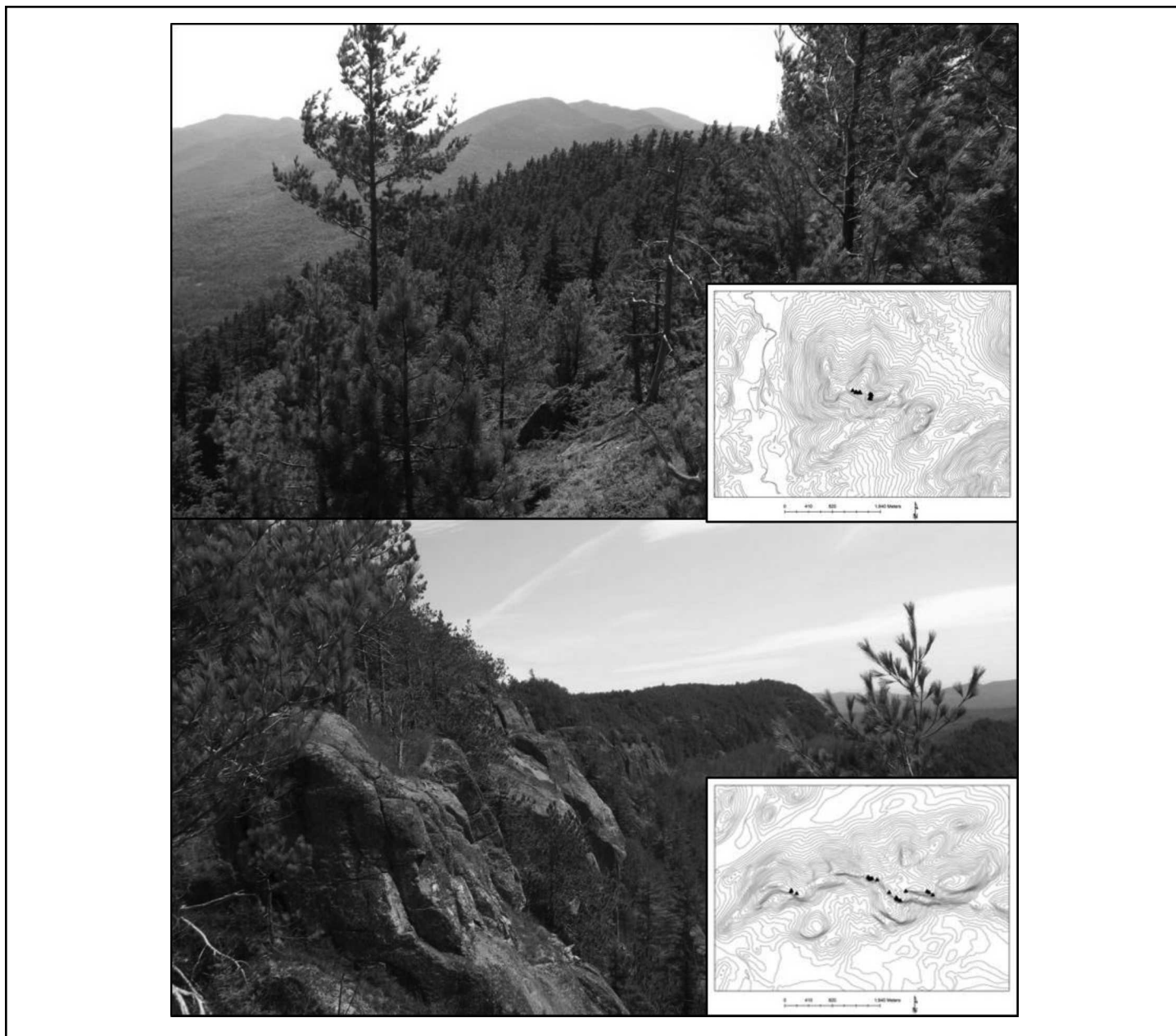


Figure 2. Photographs and topographic maps of the study sites (Baxter Mountain, top; Potter Mountain, bottom) showing the topographic differences between the sites. Sample locations are represented by black triangles.

at PMT, and average seasonal snowfall is 165 cm at BXT and 193 cm at PMT (Trevail 2006; Smith 2010). Based on climate conditions of the region, fires are expected to be relatively historically infrequent (e.g., 30–150 y; Guyette et al. 2012).

The notion that the Adirondacks were largely uninhabited prior to EuroAmerican settlement is increasingly becoming outdated. Archaeological sites are continually being discovered, and it seems likely that

Native American presence in the Adirondacks has been generally underestimated (Starbuck 2018). The rugged topography and general unsuitability for agriculture probably precluded major permanent settlements in the mountainous portions of the Adirondacks, but the region was used seasonally by Native Americans for hunting and travel purposes (Donaldson 1921). The Champlain Valley, located approximately 30 km east of the study sites, was an important travel corridor both before and

after EuroAmerican contact (Smith 1885; Schneider 1997). At the time of Euro-American contact and throughout the Fur Trade era, the area was controlled by the Mohawk tribe, the easternmost tribe of the Iroquois Confederacy (Schneider 1997).

At the end of the French and Indian War in 1763, EuroAmerican settlement began along the western shores of Lake Champlain and then gradually spread westward. The first settlers in the Keene Valley, in

the central Adirondacks near BXT, arrived in 1797 (Smith 1885), and by the early 1800s the region around the study sites was beginning to be a focal point for iron and charcoal production (Smith 1885; NYSDEC 2013). The 19th century began an era of resource extraction, with charcoal manufacturing, iron production, and logging the most important industries. By 1885, an estimated two-thirds of the Adirondack forests had been cut over at least once (Schneider 1997). Public sentiment shifted toward preservation of the Adirondack region, and the Adirondack Forest Preserve was established in 1885 (Donaldson 1921). Today, the 2.5-million hectare Adirondack Park is constitutionally protected by the state of New York as a wilderness preserve, though logging activities do occur on privately held tracts within the park. The resident population is relatively low (est. 130,000) but high numbers of tourists visit the Park each year (est. 7–10 million/year).

Sample Collection

In April 2016, study site locations were intensively searched for suitable (100+ rings, evidence of fire scars) living and remnant red pine trees for sample collection. Full and partial basal cross-sections (~20 cm thick) of trees were collected using a chainsaw. Multiple cross-sections were taken from some trees when visual inspection suggested it was necessary to capture the complete record available. Cores from live red pine trees were also collected using an increment borer at each site to assist in cross-dating (Speer 2010). Sample locations were determined using a GPS unit, and slope degree and aspect were recorded.

Fire Scar Dating

Cross-section and increment core surfaces were prepared for analysis using an electrical orbital sander with progressively finer sandpaper (80 to 1200 grit) to reveal cellular detail of annual rings and fire scar injuries. There was great variability in the structural integrity of sample surfaces. Tree-ring widths were measured along a radius (pith-to-bark) of each cross-section

with the least amount of ring-width variability due to injuries. All tree-rings were measured to 0.01-mm precision using a binocular microscope and a Velmex measuring stage (Velmex, Bloomfield, NY, USA). Tree-ring width series were visually cross-dated using ring width plots (Stokes and Smiley 1968) and verified statistically using the COFECHA computer program (Holmes 1983; Grissino-Mayer 2001a). Cores from live trees aided in the construction of absolutely dated master ring width chronologies for each site. Fire scars were identified by the presence of callus tissue, traumatic resin canals, liquefaction of resin, and cambial injury (Smith and Sutherland 1999). The entire chronology of each sample was considered to have the potential to record fire. Fire scar dates were assigned to the year and, when possible, season of cambial response to injury based on the position within or between rings (Kaye and Swetnam 1999; Smith and Sutherland 1999). Dormant-season scars were assigned the date of the ring formed after the scar, since this is the first evidence of cambial response to the injury.

Analysis

We used FHX2 software (Grissino-Mayer 2001b) to construct fire event chronologies for each site, analyze fire intervals, summarize fire scar seasonality, and graph individual tree and composite fire intervals (i.e., all fire events occurring at the site). Fire interval summary statistics were calculated for time periods when at least three samples were in the record. Mean fire intervals (MFIs) and summary statistics were calculated using the composite (site-level) fire intervals. Weibull median fire intervals were recorded when Kolmogorov-Smirnov (K-S) goodness-of-fit tests indicated that the Weibull distribution modeled the interval data better than a normal distribution (Grissino-Mayer 1999). Lower and upper exceedance intervals (LEI/UEI) were calculated to detect fire intervals significantly longer or shorter than the mean. Fire interval statistics were stratified by two sub-periods that reflected changes in human occupation and land use: pre-1797, representing the era of primarily Native American influence (NAI), and 1797–1909, representing the era of EAS.

Where a fire interval spanned both time periods, interval data were assigned to the era in which the majority of the interval occurred. This applied to the 1815 fire at PMT, which was included in the NAI period calculations, and the 1913 fire at PMT, which was included in the EAS era statistics. Statistics were generally not calculable for the NAI period due to the low number of fire events at both sites ($n = 3$ at PMT, $n = 0$ at BXT), though an MFI was calculated for PMT as a mean of the two fire intervals. Statistics were not calculable for the period of fire protection, which began ca. 1910 when a new wildfire detection, prevention, and control plan was implemented in the Adirondacks and dramatically reduced the amount of losses due to wildfire (Donaldson 1921).

Superposed Epoch Analysis (SEA) was conducted in the Fire History Analysis and Exploration System (FHAES v. 2.0.2; Brewer et al. 2016) to explore the possible association between regional drought conditions and fire occurrence. Fire event years were compared to reconstructed summer season Palmer Drought Severity Indices (PDSI) (Gridpoint 260; Cook et al. 2004) to test whether climate was significantly wetter or drier than expected the year of the fire or during any of the 6 y preceding the fire. The PDSI data were bootstrapped for 1000 simulated events to derive confidence limits. Pearson correlation analysis was also used to explore associations between the percentage of trees scarred and drought conditions for the years of fire.

RESULTS

At Baxter Mountain, cross-sections from 16 trees were collected, of which 13 were cross-dated and included in the fire history analysis. The tree-ring record spanned the period from 1687 to 2010 (323 y) and fire scar dates ranged from 1799 to 1880 (Figure 3). The average number of rings per sample was 183 and ranged from 100 to 305. Thirty-five fire scars were dated, representing a total of six fire years. Fire intervals ranged from 6 to 28 y, and the MFI was 16.2 y for the entire period of record (Table 1). All fire years occurred during the era of EAS (1797–1909).

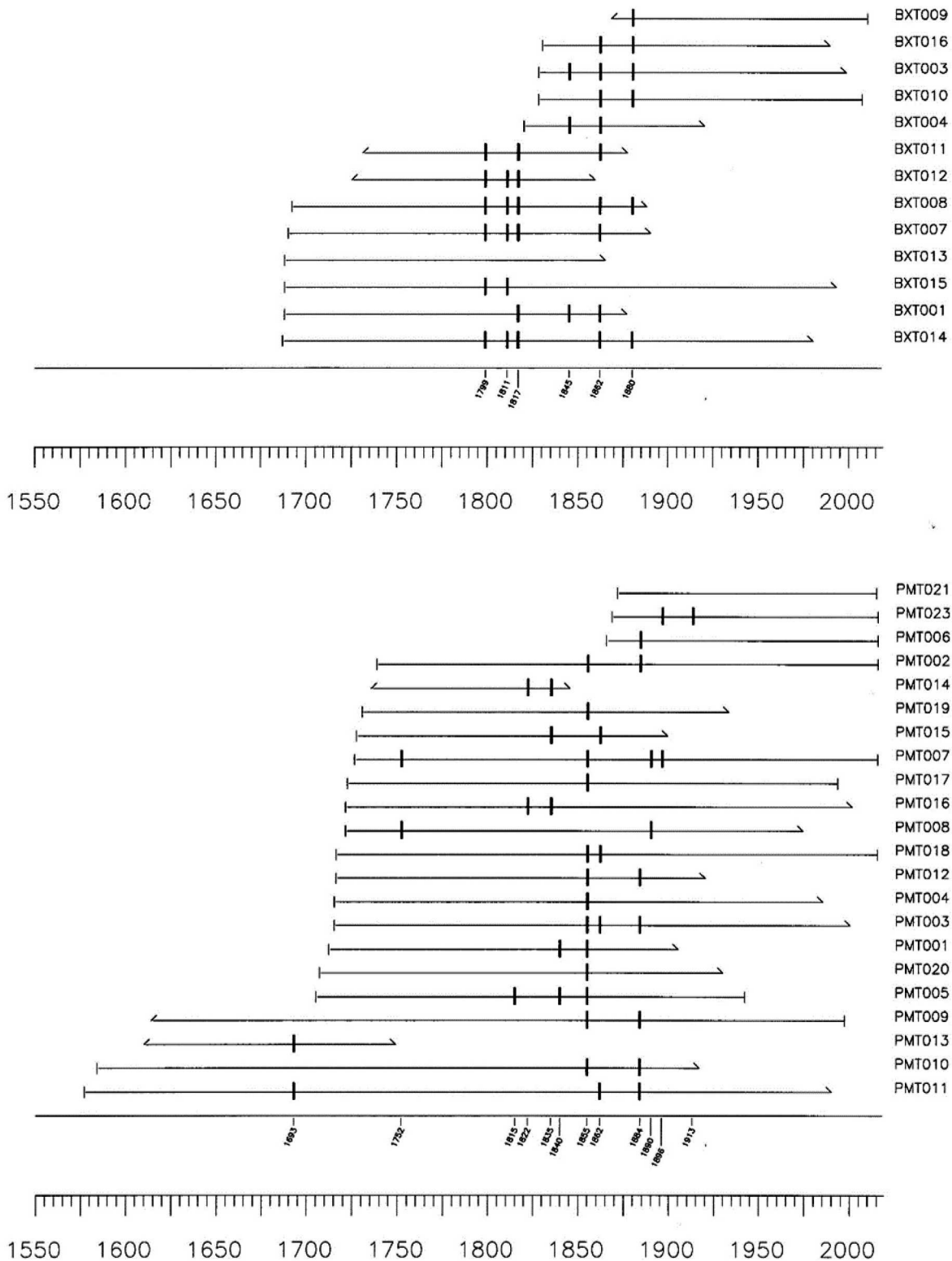


Figure 3. Fire-scar diagrams for Baxter Mountain and Potter Mountain, Adirondack Mountains, New York. Each horizontal line represents the lifespan of an individual tree (sample number on right). Slanted or vertical lines at the earliest year shown for each sample indicate either the innermost ring or pith date, respectively. Similarly, for the last year recorded, a slanted line indicates the outermost ring present, a vertical line indicates bark year. Bold vertical lines are fire-scar years.

Table 1. Summary statistics of fire scars and fire intervals by site and time periods. *Calculations include 1815 fire; **calculations include 1913 fire. NA = not available.

	Baxter Mountain			Potter Mountain		
	NAI 1689–1796	EAS 1797–1909	All Years 1689–1997	NAI 1611–1796*	EAS 1797–1909**	All Years 1611–2014
Scars (<i>n</i>)	0	35	35	5	36	41
Fire years (<i>n</i>)	0	6	6	3	9	12
MFI (years)	NA	16.2	16.2	61	10	20
SD	NA	8.1	8.1	NA	6.3	21
Range (years)	NA	6–28	6–28	59–63	5–22	5–63
WMI (years)	NA	15.7	15.7	NA	10.8	15.1
LEI (<i>n</i>)	NA	7.9 (1)	7.9 (1)	NA	4.9 (0)	3.5 (0)
UEI (<i>n</i>)	NA	24.8 (1)	24.8 (1)	NA	18.4 (1)	40.4 (2)
Mean % scarred	NA	64.3	64.3	22.4	22.2	22.2

At Potter Mountain, 23 samples were collected, of which 22 were cross-dated and included in the fire history analysis. The tree-ring record spanned the period from 1577 to 2015 (438 y) and fire scar dates ranged from 1693 to 1913 (Figure 3). The average number of rings per sample was 233 and ranged from 139 to 413. Forty-one fire scars were dated, representing a total of 12 different fire years. Fire intervals ranged from 5 to 63 y, and the MFI was 20.0 y for the entire period of record (Table 1). Seventy-five percent of fire events occurred during the era of EAS (1797–1909). Only one fire (1913) was recorded following the advent of fire protection activities in the Adirondacks.

At both sites, the majority of seasonally identifiable fire scars were formed in the dormant season (Table 2). At BXT, growing-season fires occurred in 1811 and 1880; at PMT, growing-season fires occurred in 1752 and 1862 (Figure 4). The sites had one shared fire year (1862), but seasonality of this fire year differed between the sites and likely represents two separate fire events.

The SEA revealed no significant relationships between PDSI and fire events at either site. Fire events were not associated with either wet or dry summer conditions at any of the lag years tested. No significant correlations were found between percentages of trees scarred in a fire year and reconstructed PDSI, even during fire years with high percentages of

trees scarred. PDSI values for fire years ranged from -1.7 (1840) to 3.0 (1815). The driest year during the entire period of record was 1748 (PDSI = -4.1), which preceded by four years the growing season fire at PMT in 1752.

NAI and EAS Periods

At PMT, two fire events occurred in the NAI period (1611–1796; MFI = 59.0 y; Table 1, Figure 4). One of these fires occurred during the growing season (1752). No fire scars were identified in the NAI period at BXT.

At both sites, the majority of fire events (BXT = 100%; PMT = 88%) occurred during the era of EAS. At BXT, fires were slightly less frequent (MFI = 16.2) but scarred more trees on average (64.3%) than at PMT (MFI = 10.0, mean % trees scarred = 22.2%; Table 1, Figure 4). Each site had

one significantly long fire interval during this era (1817–1845 at BXT, 1862–1884 at PMT; Figure 3). There was no evidence of a climatic effect for these intervals: the interval 1817–1845 had an average PDSI of -0.216 , and the interval 1862–1884 had an average PDSI of -0.589 .

An Additional Observation of Interest

The year 1903 is a well-documented widespread fire year in the Adirondacks, with over 240,000 ha burned in April through June (Suter 1904). No 1903 fire scars were found at the study sites, which is corroborated by a burned area map made soon after the fires (Suter 1904). Interestingly, however, a 1903 false ring was consistently observed in our samples (58% of PMT samples, 71% of BXT samples; Figure 5). A false ring is an intra-annual band of small, thick-walled latewood-type cells followed by the formation of large, thin-

Table 2. Percentages of fire scars by their position within or between rings.

Scar seasonality	Baxter Mountain	Potter Mountain
	1689–1997	1611–2014
% Undetermined	42.9	51.2
% Dormant	34.3	39.0
% Earlywood	8.6	0.0
% Middle Earlywood	0.0	7.3
% Late Earlywood	0.0	0.0
% Latewood	14.3	2.4

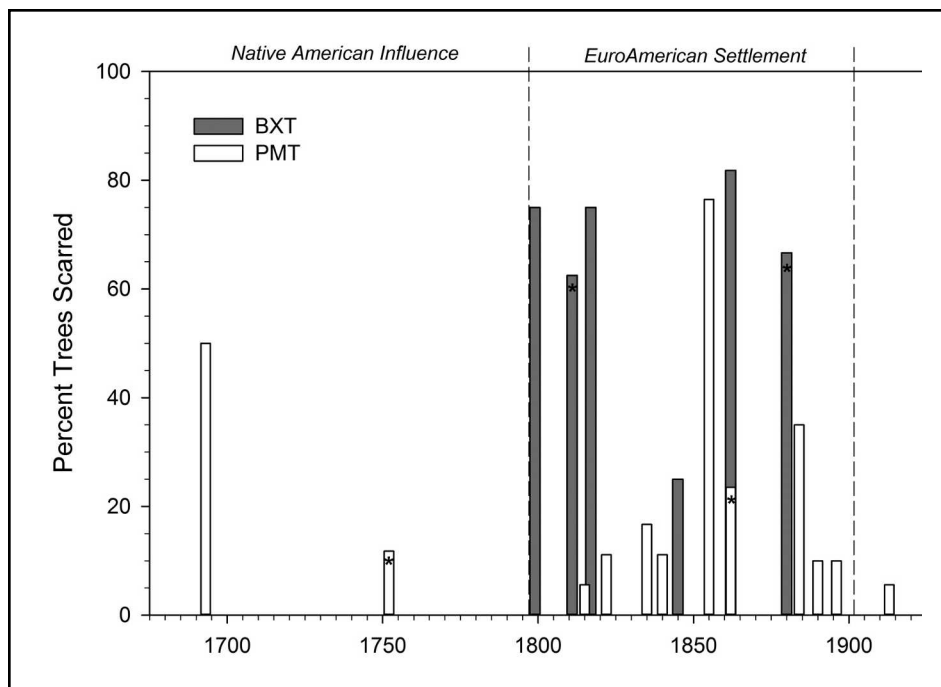


Figure 4. Percentage of trees scarred during fire years at BXT and PMT. Years with growing season fires are denoted with an asterisk (*). Time periods separated by vertical dotted lines.

walled earlywood-type cells. False rings are readily formed when a tree is young and occur less often as a tree ages, but in

this study the 1903 false ring was found in mature individuals. False ring formation can frequently be attributed to a climatic

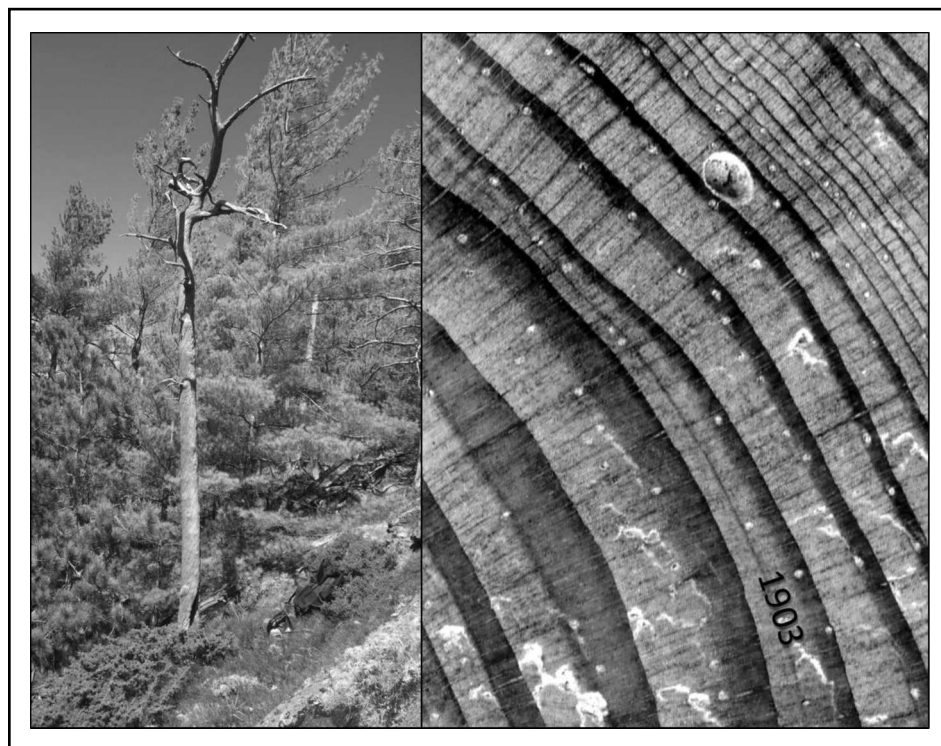


Figure 5. The 1903 false ring (right) found in many of the study samples, from a scan of sample BXT016 (left).

pattern of dry spring conditions followed by wet summer conditions (Villalba and Veblen 1996; Wimmer et al. 2000; Edmondson 2010), which appears to be the case in this situation. Over a 51-day period, from April 16 to June 7, less than five mm of rain fell in the Adirondacks (Suter 1904). The combination of this spring drought, significantly lower snowfall in the preceding winter months, high levels of logging debris, and abundant anthropogenic ignition sources led to the widespread severe fires (Suter 1904). The reconstructed summer drought index (PDSI) for 1903 is 2.568 (very wet), which does not reflect the anomalous spring drought of that year. False rings located in older portions of trees are potentially useful indicators of historical spring drought conditions conducive to extensive growing season wildfire occurrence in the Northeast.

DISCUSSION

Fire Regime

Historical fire frequency at the study sites was generally characterized by infrequent fire during the NAI period, followed by a period of increased fire frequency during EAS and associated land use changes, followed by a cessation of fire after the advent of fire protection policies. During the NAI period, only two fire events were recorded at Potter Mountain, yielding an MFI of 61.0 y. At Baxter Mountain, sample trees recorded 110 y before the first fire scar in 1799. The long fire intervals at our study sites are similar to or longer than those found by other red pine fire history studies in the northeastern United States. In northern Pennsylvania, four study sites had pre-settlement MFIs ranging from 16 to 57 y (Brose et al. 2013; Stambaugh et al. 2018). Three of the Pennsylvania sites each had one 100+ year-long fire-free interval in the presettlement era, similar to both of the Adirondack sites. In Vermont red pine stands, Mann et al. (1994) found a presettlement MFI of 23 y (Brose et al. 2014), with the longest fire-free intervals around 40 y.

These data support the notion that wildfires were relatively infrequent in the Ad-

ironclads in the century preceding EAS. Naturally ignited fires are uncommon in the Adirondacks as lightning strikes are relatively rare (<1 flash/km²/yr; Ziegler 2007) and are typically accompanied by rain. We surmise that human-caused fires in the century prior to EAS were also likely uncommon, as Native American populations were low compared to other regions of the northeastern United States (Donaldson 1921; Schneider 1997; Ziegler 2007) and the Mohawk tribe, the main inhabitants of the surrounding region, suffered substantial depopulation in the 17th century due to warfare and disease (Schneider 1997). In addition to an overall low ignition potential prior to EAS, spread of ignitions was further limited by the low flammability of the surrounding northern hardwoods forests that are predominant in the Adirondacks, which have been described as “asbestos forests” (Ziegler 2007). While fire was very infrequent at PMT, and absent at BXT in the pre-EAS fire scar record, it did occur more often at PMT than the 200–600+ year fire rotation that has been suggested for pine forests within the northern hardwoods region (Bormann and Likens 1979; Fahey and Reiners 1981). This and the other red pine studies in the Northeast suggest that pockets of more frequent fire occurred within a larger matrix of less-flammable northern hardwood forests in the northeastern United States (Bormann and Likens 1979; Engstrom and Mann 1991; Mann et al. 1994), and that existing red pine stands in the Adirondacks are an artifact of historical fire occurrence.

Definitive answers as to the source of ignitions in the NAI era remain elusive for the Adirondack sites. Seasonality of fire scars can sometimes shed light on the ignition sources of historical fires but is of limited usefulness in this study. Only two fires were recorded at one site, one growing season and one dormant. Dormant-season scars are typically associated with human ignitions due to patterns of human-caused fire seasonality in modern times. However, these scars could be formed at the very end of dormancy in late spring and, although normally outside of the lightning-strike season, could conceivably represent lightning-ignited fires (Lafon et al. 2017). Lightning has been shown to be a histori-

cally important source of ignitions at higher-elevation red pine sites within a northern hardwood landscape in Michigan (Muzika et al. 2015). Conversely, despite low human population densities in the Adirondacks, humans were hunting and travelling in the area and could have been the ignition source for fires in any season. Indeed, as perpetual “keepers of the flame,” Native Americans possessed the ability to light fires whenever and wherever they wanted, provided that conditions were conducive to burning (Abrams and Nowacki 2008).

Fire frequency increased at both sites following the arrival of EuroAmerican settlers to the region, a pattern documented at other fire history sites in the northeastern United States (Brose et al. 2015; Marschall et al. 2016; Stambaugh et al. 2018). As population density increased, the fire regime shifted to one controlled by anthropogenic ignitions, usually attributable to land clearing, promotion of browse for domestic animals and game, and also industrial activities such as logging, charcoal and iron production, and railroads. Surveyor records in Essex and Clinton counties indicate that extensive cutting and burning of red pine stands had already occurred early in the EAS period (before 1820; Cook et al. 1952). The majority of seasonally identifiable scars were formed in the dormant season (~September–May), a pattern that continues to present day. Recent wildfire statistics for New York (1992–2016) indicate a great majority of wildfires continue to occur in the late winter/early spring months and are largely attributable to human ignitions (NYSDEC 2016). The period of more frequent fire due to EAS ended around 1910 when the advent of fire control policies and practices dramatically reduced the acreage burned by wildfires (Donaldson 1921).

We found a marked contrast between the two study sites in percent trees scarred in fire events, with BXT exhibiting a generally higher percentage of trees scarred than PMT. This is likely attributable to topographic and sample spatial distribution differences between the sites (Figure 2). The local topography of PMT is characterized by steep, rugged cliffs, with extensive areas of exposed rock, which

likely disrupted fuel continuity and fire spread, whereas BXT has no cliffs and much less area composed of exposed rock. Samples at BXT were spatially clustered (max. distance between samples = 340.3 m) and were more likely to have synchronous scarring, while samples at PMT were separated by greater distances (max. distance between samples = 2446.0 m) along the cliff edges and therefore less likely to have synchronous scarring.

The relationship between summer drought conditions and fire occurrence at the study sites was not statistically significant, a result found at other red pine fire history sites in the Northeast (Brose et al. 2015; Stambaugh et al. 2018). While not statistically significant in this analysis, climate was certainly part of a suite of factors influencing fire occurrence both before and after EAS. In Vermont red pine stands similar to those in this study, Mann et al. (1994) surmised that historical fire occurrence was a function of the interaction between climate and the time required for sufficient fuel accumulation, and drought conditions corresponded to fire only when fuel conditions were optimal. In this study, prior to EAS, fires were likely similarly the result of interactions among fuel accumulation, topographic conditions, and climate, coupled with occasional lightning/human ignitions. EuroAmerican settlement increased the frequency of ignitions, disrupting the long cycle of climate and fuel accumulation that existed previously. Humans override the influence of climate on fire occurrence through increased ignitions, artificial lengthening of the fire season, fuel fragmentation, land use changes, and altered spatial occurrence of fires across the landscape (Syphard et al. 2017). While ignitions are much more suppressed in modern times compared to the era of EAS, anthropogenic ignition pressure, in conjunction with fuel conditions and weather factors (e.g., high wind speeds), remains the primary driver of large fires in the eastern United States (Nagy et al. 2018).

Red Pine Ecology and Conservation

Successful red pine regeneration requires that three conditions be met: bare mineral

seed bed, lack of competing vegetation in the understory, and openings in the forest canopy allowing increased light in the understory (Van Wagner 1970). A relatively high-severity fire is the only natural disturbance known to simultaneously provide all three conditions. On more productive sites (e.g., Great Lakes region), recurring light surface fires may also be required to control the competing hardwood brush (Gilmore and Palik 2005), but on low productivity, shallow-to-bedrock sites (e.g., mountainous Northeast sites), topoedaphic factors can naturally provide suitable understory conditions for red pine regeneration (Cook et al. 1952; Van Wagner 1970).

At PMT, many sampled trees were established during the 59-year fire-free interval following the 1693 fire, and a smaller cohort of sample trees established during the 22-year interval between 1862 and 1884. At BXT, the oldest sampled trees had similar pith dates and represent a cohort formed after an unknown disturbance (possibly fire) ca. 1675. A second cohort at BXT formed during the 28-year interval following the widespread fire of 1817. These observations of associated fire events and regeneration cohorts correspond well with the known ecological requirements of red pine (Stambaugh et al. 2019). A trend may exist whereby successful red pine regeneration and cohort establishment tends to correspond to long fire-free intervals, possibly following severe fires.

Based on red pine ecological requirements, age cohorts, and fire scars, our data suggests that high-intensity canopy-opening fires have occurred approximately once every 120–170 y prior to EAS, with more frequent low-intensity fires occurring during the EAS period. Red pine is known to thrive in rough topography where small-scale variability in fire intensity occurs (Van Wagner 1970), and this is reflected in the fire-scar records of the study sites. The presence of young, small-diameter trees with fire scars at the sites suggests that these were either light surface fires or fires with spatially variable fire intensity. Red pine bark is too thin and flammable until about age 50 to survive high-intensity fires, and young red pines are susceptible to crown scorch (Van Wagner 1970). In

addition, mature red pines are extremely vulnerable to crown scorch and death when surface fires are too intense (Van Wagner 1970). Even during the canopy-opening, regeneration-stimulating fire years, many mature sample trees survived, indicating these fires must have been patchy in their intensity. Since successful red pine regeneration is dependent on a sufficiently intense fire corresponding with a good seed crop, which only occurs approximately once every five y (Van Wagner 1970), not all canopy-opening fires necessarily lead to red pine recruitment (Engstrom and Mann 1991), so the frequency of higher severity fires may be underestimated.

CONCLUSIONS

Red pine-dominated ecological communities on rocky summits in New York are considered vulnerable and at moderate risk of extinction due to their restricted range and relatively low number of populations or individuals (Edinger et al. 2014). Red pine is unique from other pine species in that it is known to have extremely low genetic diversity, which may negatively impact the species' ability to adapt to changing environments (Mosseler 1992). The potential consequences of climate change on these vulnerable populations, including increased risk of high-severity wildfires due to warmer and drier conditions (Huntington et al. 2009; Clifford and Booth 2013; Guyette et al. 2014) and range expansion of formerly absent pathogens and pests (e.g., southern pine beetle [*Dendroctonus frontalis*]) into northeastern forests (Dodds et al. 2018), could be devastating (Mohan et al. 2009). Local extinction of small populations of red pine is possible with only one high-intensity wildfire (Mosseler 1992).

In the face of these threats, quantitative fire history information can be used to guide management decisions that increase the chances for sustaining these ecologically important natural communities. While red pine may persist in the absence of fire on individual dry and rocky sites where competing vegetation is at a minimum, other sites may require the intentional use of fire to sustain the species. Historically, a fire regime of infrequent, patchy, low-intensity fires and occasional higher-intensity fires

created and sustained natural red pine communities in the Adirondacks. Today, ignitions are suppressed and landscapes are more fragmented, meaning that intentional fire or mechanical treatments that emulate the effects of fire are likely required to ensure red pine regeneration and perpetuation. While the future of these communities is uncertain in a changing climate, management for regeneration and reduced vulnerability to catastrophic loss may be the best path for preservation of natural red pine communities in the Adirondacks.

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