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Red pine (*Pinus resinosa* Ait.) fire history and management implications in the Mississippi River headwaters, Minnesota, USA

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ABSTRACT

We used dendrochronological methods and remnant fire-scarred red pines (*Pinus resinosa* Ait.) to reconstruct historical fire regime characteristics and relate these findings to past climate, human land use changes, and vegetation for a landscape in northern Minnesota, USA. A total of 314 fire scars were dated, representing 56 unique fire events from 1565 to 1967. In the period prior to fire exclusion (1535–1935), fire intervals ranged from 1 to 40 years across the landscape and the mean fire interval was 6.6 years. The majority of fire scars (74%) occurred in the dormant season. Climate analyses showed that conditions two years before fire events were significantly wet and, in the year of fires, conditions were significantly dry. Overall, our study reveals complex interactions among climate, humans, and physiographic factors and how these have varied through time. For fire and forest management of red pine specifically, the results point to the use of silvicultural systems with high levels of retention, including non-stand replacing disturbances.

1. Introduction

Across the northern Great Lakes region, historical and widespread logging, wildfires, land conversion, and fire suppression have led to modern forest conditions that are often greatly departed from pre-settlement conditions (Frelich, 1995; Schulte et al., 2007; Paulson et al., 2016). As a consequence, fire-adapted species that were once dominant are now reduced in abundance (Thomas-Van Gundy and Nowacki, 2016). In particular, red pine (*Pinus resinosa* Ait.), which covered an estimated 3 million hectares in this region, has been reduced by as much as 87% of its original distribution (Gilmore and Palik, 2006). Red pine is a fire-dependent species (Van Wagner, 1970) with stands thought to require a combination of periodic surface fires and less frequent crown fires for successful establishment and perpetuation (Gilmore and Palik, 2006; Stambaugh et al., 2019; Palik et al., 2020). In the absence of periodic fires, forests become spatially homogenous, succeed to shade-tolerant species, and red pine regeneration (seedlings) and recruitment (midstory saplings) fail to occur (Schulte et al., 2007; Rauchfuss and Ziegler, 2011; Fraver and Palik, 2012). Across the region, forest management goals, particularly on public and conservation ownerships, often seek to return the ecological processes in remaining red pine forests to sustain the species and promote landscape diversity and resilience.

Understanding of the factors that control the occurrence of natural red pine forests in the Upper Lake States has evolved over time. Seminal research in the 1970s established the importance of infrequent (~100–200 years), severe fires for the renewal of these forests, often coincident with severe drought and following widespread blowdown events (e.g., Heinselman, 1973; Frissell, 1973; Schulte and Mladenoff, 2005). In recent history, large, high-severity fires occurred in this region during the early period of European settlement and development of the timber industry (e.g., Peshtigo fire of 1871, Hinckley fire of 1894, Cloquet fire of 1918). More recent studies have led to an emerging understanding of the importance of frequent, low-severity fires that scar trees (Guyette and Dey, 1995; Kipfmueller et al., 2017). In some areas, fire scar records extending back to the 1500s show that low severity fires had potential to be frequent at the landscape scale (e.g., Muzika et al., 2015), but more records would improve the spatial and temporal understanding of historical fire regimes, particularly by severity types (e.g., low, mixed, high).

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Multiple fire history studies in the region have revealed that fire frequency before European settlement varied widely and was related to site conditions (e.g., geology, fuel characteristics, fragmentation) and Native American populations (e.g., Loope, 1991; Drobyshev et al., 2008; Guyette et al., 2016; Kipfmueller et al., 2017). Region-wide disruption in fire regimes occurred during major cultural and societal changes in the mid-1700s and logging activities in the mid- to late-1800s. Gaps in our understanding remain with regard to regional climate-fire drivers which may further clarify the historical importance of human versus lightning ignitions. As forest management objectives increasingly seek to restore fire as a disturbance process for multiple resource benefits, even more nuanced understanding of historical fire regimes (e.g., fire seasonality, severity, frequency) and resulting vegetation conditions (e.g., types, structures, forest stand dynamics) is needed for guidance.

Reconstructions of historical fire using fire scars on trees provide insight into the role of fire and fire regimes that shaped and maintained ecosystems, particularly prior to widespread Euro-American influence (Swetnam et al., 1999; Harley et al., 2018). There has been only limited research using this approach to better understand historical fire regimes of red pine-dominated ecosystems in the northern Great Lakes region. With this need in mind, we used fire scar dating methods to reconstruct fire regimes centered on a northern Minnesota, USA study landscape that includes the Leech Lake Band of Ojibwe Reservation and the Chippewa National Forest. Across this landscape, remnant fire-scarred trees (e.g., snags, stumps), particularly red pines, can be found dating back multiple centuries. Our objectives were to use dendrochronological methods to date historical fire scarring events, use fire event data to characterize fire regimes, and relate these findings to climate, human land use changes, and vegetation. With these data and results, we discuss fire and forest management strategies and approaches to restore and sustain red pine forests that are consistent with the historical fire regimes that promoted them.

2. Methods

2.1. Study landscape

The study landscape lies within the Chippewa Plains ecological subsection of the Northern Minnesota Drift and Lake Plains section, in the Laurentian Mixed Forest province (Cleland et al., 1997). Currently, vegetation cover types in this landscape consist of woody wetlands, and deciduous, mixed, and evergreen forests (Dewitz, 2019) (Fig. 1).

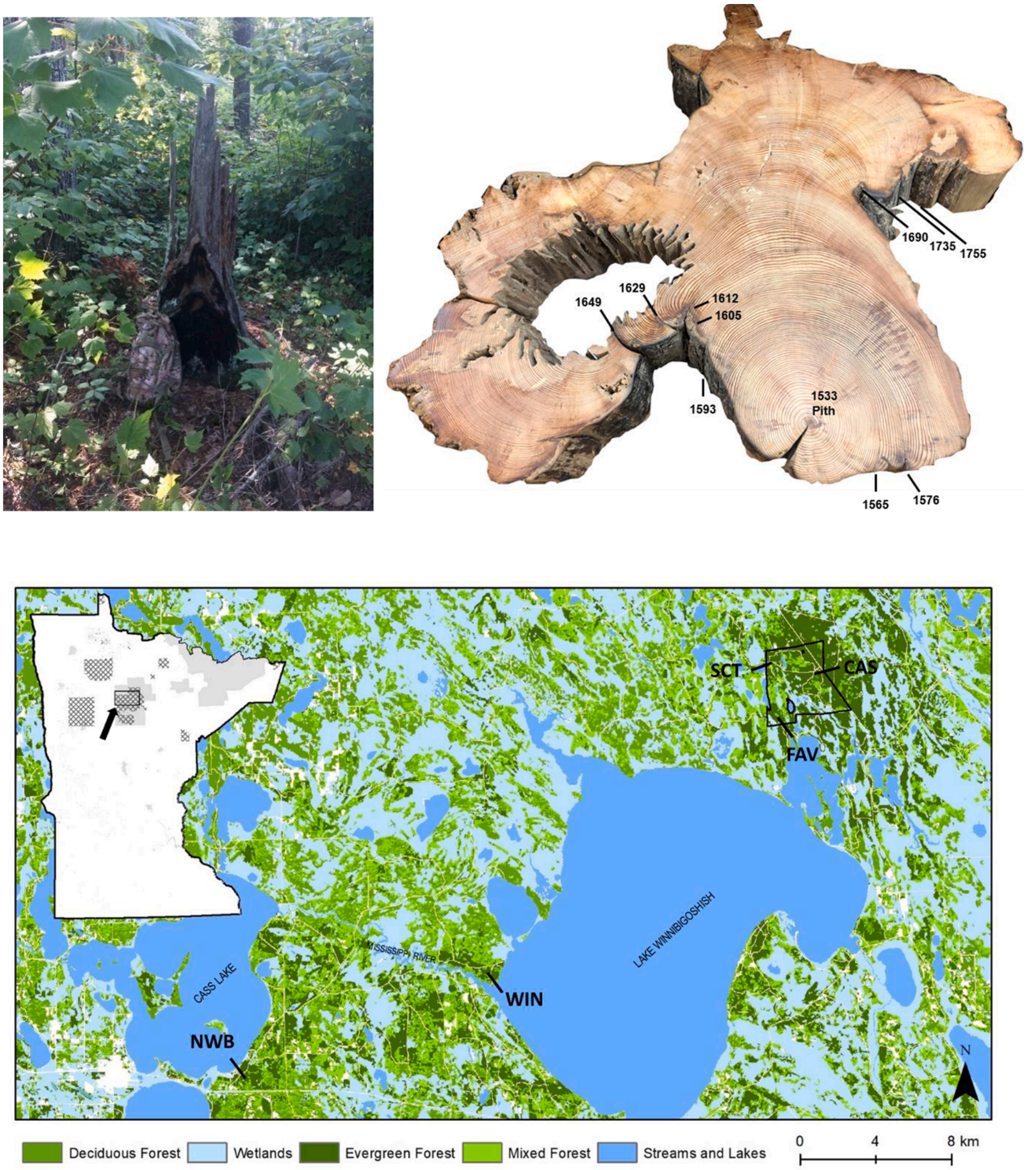

Fig. 1. Top left) Remnant fire-scarred red pine (*Pinus resinosa*) tree from Norway Beach (NWB) study site contrasts with current conditions of fuel accumulation and succession to fire sensitive tree species. Top right) Cross-section of fire-scarred red pine (*Pinus resinosa*) from SCT cluster showing dates of pith and fire scars. Bottom) Map of land cover types across the Minnesota study landscape with sample sites and clusters indicated by three letter codes. Inset map shows location of study landscape within Minnesota (outlined rectangle indicated by arrow) where federal lands (grey shade) of the Chippewa National Forest and tribal lands (crosshatched) of the Leech Lake Reservation overlap. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Streams and lakes are interspersed within the Mississippi River Headwaters watershed. The climate is humid continental, with warm summers and long, cold winters. Average monthly temperatures range from −14.3C (Jan.) to 19.8C (July), and average annual precipitation is 68.0 cm, with monthly normals ranging from 1.5 cm (Feb.) to 10.2 cm (July) (Cass Lake station, 1981–2010 climate normal; Arguez et al., 2012). Snow cover is a major impediment to fall- to- early spring season fire occurrence and, on average, this region has > 83 days of snow cover > 2.5 cm depth (period: 1961–1990; NCDC, 1999).

2.2. Humans and land use history

The Mississippi River Headwaters region has been occupied by humans for at least 8000 years. Multiple cultures have been identified through excavated artifacts, including the Brainerd, Laurel, Blackduck, and Sandy Lake cultures (Johnson, 1979; Le Vasseur, 2000). In the 17th century and for some time prior, the Leech Lake region was inhabited primarily by the Santee Dakota (Blegen, 1975) and possibly other native groups (e.g., Assiniboine, Cree, Ojibwe). Beginning in the mid-17th century, French fur traders and explorers were present in the region, though in relatively small numbers. The Ojibwe tribe also arrived, migrating westward in response to increasing European incursion in their northeastern homelands and also in search of a prophesized land where food grew on water, in reference to wild rice (*Zizania* spp.) (Jenks, 1901). These groups coexisted peacefully for several decades, but by 1750 intertribal conflict had resulted in the Dakota moving southward and the Ojibwe occupying the northern half of Minnesota (Blegen, 1975). British fur traders and explorers were active around Leech Lake by the 1780s. Multiple North West Company trading posts were located in the area around the turn of the 19th century (Johnson, 1979).

White settlement of Minnesota began at St. Paul in 1838, but the area surrounding Leech Lake remained inhabited by the Ojibwe at that time. Despite several negotiations and treaties, by 1855 the Ojibwe and Dakota had ceded most of their traditional lands in Minnesota to the US government and the Leech Lake Reservation was established. While lumbering gradually increased in other parts of Minnesota through the mid-19th century, the lands of the Leech Lake Reservation were inaccessible to loggers. This changed with the Dawes Act (1887) and the Nelson Act (1889), which began a new era of large-scale lumbering, railroad expansion, and increased white settlement. Lumbering operations resulted in widespread cut-over lands and several disastrous wildfires (Bachmann, 1969). Portions of the area around Cass Lake and Lake Winnibigoshish were considered for national park designation circa 1900 (Pearson and Gales, 2004). The Minnesota National Forests (now Chippewa National Forest) was established in 1908 and overlaps extensively with the Leech Lake Reservation lands (Fig. 1). Fire control efforts began in the late 19th century but were not fully effective until approximately 1935 (USDA Forest Service, 1986). Nearly a century of fire exclusion has resulted in highly altered fire regimes and vegetation which further emphasizes the need to understand the historical drivers and ecology of fire and vegetation (Scheller et al., 2005).

2.3. Sample collection

From 2015 to 2017, we surveyed the study landscape and identified areas with multiple fire-scarred living trees, stumps, logs, and standing snags at locations that extended west to east from Cass Lake to the Cutfoot Experimental Forest (Fig. 1). We cut full and partial basal cross-sections from the boles of live trees within each area using a chainsaw. We assigned cross-sections sample numbers and marked them to retain information of orientation and height cut above ground. A GPS unit was used to record locations to 3-m accuracy. Areas where 15 or more fire-scarred samples were distributed across $\geq$ 0.5 km^2 were considered “sites” and these were located at two locations: Norway Beach (NWB) and within the Cutfoot Experimental Forest (CAS). We considered areas with smaller sample sizes and extents “clusters” and these were located at three locations: on the western side of Lake Winnibigoshish (WIN) and within the Cutfoot Experimental Forest (FAV, SCT) (Fig. 1). Higher sampling replication and spatial coverage at sites provide greater confidence that fire events were captured by scars on trees; however, thresholds for adequate sample sizes are difficult to determine as the rate of sample scarring is highly variable (i.e., some trees may record few fire events while others may record a majority).

At NWB, topography is level with a mature overstory of red pine and a dense understory of white pine (*Pinus strobus* L.) and mixed hardwoods (e.g., *Betula papyrifera* Marshall, *Acer rubrum* L.). This site has been impacted by tornados twice in the last few decades causing partial to complete canopy removal and tip-up mounding in localized areas. By comparison, topography at WIN, CAS, FAV, and SCT is flat to gently sloping with locally steep relief. FAV is adjacent to Sunken Lake, a previously studied old-growth red pine – white pine site undergoing transition to northern hardwoods similar to many old-growth sites across Minnesota (Fraver and Palik, 2012).

2.4. Laboratory methods

Cross-sections were dried and then progressively polished using belt and orbital sanders (80 to 1200 grit sanding paper) to reveal cellular detail of tree rings and fire scars. Tree-ring widths were measured in sequence to 0.01 mm precision using a binocular microscope and a Velmex TA measuring system (Bloomfield, New York, USA). Ring-width series were plotted and visually crossdated using standard dendrochronological techniques (Stokes and Smiley, 1968) and verified statistically using the COFECHA computer program (Holmes et al., 1986). Fire scars were identified based on the presence of callus tissue, traumatic resin canals, and cambial injuries (Smith and Sutherland, 1999). Fire scar injuries were assigned to the year of cambial response to injury and, where possible, seasonality was recorded based on the position of the fire scar within the ring (Kaye and Swetnam, 1999). Growing season fire scars occur within the annual ring growth period while dormant season scars occur at growth ring boundaries. Where seasonality was not determinable due to decay and other factors, we recorded fire scars as unknown seasonality.

2.5. Data analyses

We used FHAES (v. 2.0.2) fire history analysis software (Brewer et al., 2016) to construct fire event chronologies, calculate fire interval statistics, and summarize fire scar seasonality for three levels: records of individual fire history sites (i.e., NWB, CAS), combined records within the extent of the Cutfoot Experimental Forest (i.e., CAS, FAV, SCT), and all records across the landscape. Fire frequency was described using fire interval ranges, mean fire intervals (MFIs, average number of years between fire events), and Weibull median fire intervals (WMIs). WMIs were only reported when a Kolmogorov–Smirnov goodness-of-fit test indicated that the Weibull distribution modeled the interval data better than a normal distribution. Upper and lower exceedance probabilities of the fire interval distribution (i.e., lower and upper exceedance intervals (LEI, UEI)) were calculated to identify extremely short and long intervals. Percentages of trees scarred in each fire event were summarized to provide an approximation of fire severity at the stand level.

Superposed Epoch Analysis (SEA) was conducted using FHAES to examine possible associations between regional drought conditions and fire occurrence. Reconstructed summer season Palmer Drought Severity Indices (PDSI, grid point 188, 95.0°W 47.5°N) (Cook et al., 2004) were compared to all fire event years by location, fire event years shared among sites, growing versus dormant season, and fire event years stratified by time periods and percentage of trees scarred to thoroughly explore any climate-fire associations. For the SEA, PDSI data were bootstrapped for 1,000 simulated events to derive confidence limits that were then used to test whether drought conditions associated with fire event years were significantly wetter or dryer than expected. To account for potential lagged effects of drought on fire occurrences, SEA tests included the six years preceding and four years succeeding fire events.

3. Results

3.1. Sample depth

For all trees, the full tree-ring chronology included 61 crossdated trees and spanned the period 1533 to 2016 (483 yrs, Table 1). A total of 314 fire scars were dated, representing 56 unique fire events from 1565 to 1967 (n = 403 years; Table 2, Fig. 2). One sample from SCT (SCT001) extended much farther back in time than any other samples, with a pith date of 1533. This sample recorded three fire events in the 16th century (1565, 1576, 1593) that were included in the fire history and SEA analyses despite being the only sample recording in this period.

Though sample numbers were lower at clusters (Table 1), these data proved valuable to the fire history record as they extended the time period and spatial extent. In addition to extending the chronology farther back in time by >60 years, three samples from SCT and WIN recorded 14 fire events that were not previously recorded at NWB and CAS.

3.2. Fire intervals

In the period prior to fire exclusion (1535–1935), fire intervals ranged from 1 to 40 years across the landscape and the MFI was 6.6 years (Table 2). When considering samples from just the Cutfoot Experimental Forest, the MFI was 11.1 years. At the individual fire history sites, MFIs were shorter at NWB (7.5 yrs, range 1–17) than at CAS (12.2 yrs, range 1–39). Fire frequency varied through time at both sites, with fire intervals generally longer before about 1750 and shorter after until circa 1921 (Fig. 3). Long periods of infrequent fire occurred from 1650 to 1729 (79 yrs), 1736–1755 (19 yrs), and 1864–1889 (25 yrs). Only one fire occurred after the beginning of effective fire suppression practices circa 1935 (1967 at CAS).

The mean percentage of trees scarred for the period 1605–1935 (not including the SCT001 16th century fire scars) across the entire study area was 22.3%, but ranged as high as 51.3% (CAS) at the individual sites (Table 2). Eight fire years had an average percentage of trees scarred of 50% or greater, six of which occurred after 1750 (Fig. 3). Ten fire years (18.2%) were recorded at more than one of the spatially disjunct sampling locations (Cutfoot Experimental Forest, NWB, WIN); all shared fire years occurred after 1750 (Fig. 3). Four of these were shared between NWB and WIN, and six were shared between NWB and the Cutfoot Experimental Forest; no fire years on the WIN sample were shared years with any of the Cutfoot Experimental Forest. Between the NWB and CAS sites, five fire years were recorded at both, all of which had PDSI values less than −1.0 (incipient dry). The single driest year of the record was 1863 (PDSI = -4.19, extreme drought) and this was one of the fire years shared between NWB and CAS.

Table 2
Fire year and interval summary statistics and scar seasonality for all years prior to 1936 (beginning of the modern era of fire suppression/exclusion).

	Landscape	Cutfoot Experimental Forest	CAS	NWB
Time span (years)	1535–1935	1535–1935	1631–1935	1660–1935
Fire years (n)	55	32	19	23
MFI	6.6	11.1	12.2	7.5
SD	8.2	9.6	10.8	4.6
Range	1 to 40	1 to 40	1 to 39	1 to 17
WMI	4.5	8.6	9.6	6.7
LEI	0.8	2.1	2.4	2.5
UEI	13.8	21.9	24.0	13.0
% Scarred	22.3	38.0	51.3	39.5
Scars (n)	313	176	117	127
% Ident	64.2	65.9	68.4	60.6
%D	74.1	64.7	62.5	85.7
%E	1.0	1.7	2.5	0.0
%M	2.5	3.5	3.8	1.3
%L	6.5	3.5	2.5	11.7
%A	15.9	26.7	28.8	1.3

3.3. Fire seasonality

Of the 314 fire scars, 64% (n = 201) were seasonally identifiable. Across all locations, the majority of these scars (74%, n = 149 of 201) occurred in the dormant season (Table 2). Growing season scars were more common at CAS (n = 28 of 80 seasonally determined scars) than NWB (n = 11 of 77 determined scars). Eight of 55 (15%) fire years before 1935 occurred in the growing season: 1605, 1629, 1689, 1734, 1830, 1861, 1863, and 1909.

3.4. Climate-fire relationships

SEA revealed significant associations between fire events and drought (Fig. 3). SEA results of all fire events across the landscape and at the scale of the Cutfoot Experimental Forest showed summer season PDSI to be significantly wetter than normal two years before (lag −2) fire events and significantly drier than normal in the year of fire (lag +0) (Fig. 4a). An analysis of just growing season fire years showed that these years were significantly drier than normal for the year of fire (lag +0) and for the two years following the fire (Fig. 4d). A pattern of longer-term drought conditions changing from wet to dry around fire events is potentially evidenced in SEA plots. This pattern was consistently found in nearly every analysis conducted (e.g., events filtered by site, time period, % trees scarred, shared fire years, growing season fire years) (e.g., Fig. 4b, d). A conspicuous difference was seen, however, when analysis was limited to fires in the pre-1650 time period (Fig. 4c), where wetter than normal conditions prior to the fire event were not prominent.

Table 1
Summary statistics for fire history study sites/clusters and records in the Minnesota study landscape. Percent unique is the percentages of fire event years unique to the site/cluster.

	Landscape				
	Cutfoot Experimental Forest				
Site/cluster code	CAS	FAV	SCT	NWB	WIN
Area (km^2)	1.6	0.15	0.3	0.8	na
Trees (n)	31	10	2	17	1
Record (yrs)	386	297	347	353	119
Period	1630–2016	1595–1892	1533–1880	1659–2012	1744–1863
Fire years (n)	20	15	18	23	10
% Unique	25	6.7	44.4	56.5	60
MFI (yrs; pre-1935)	12.2	17.9	17.1	7.5	11.7

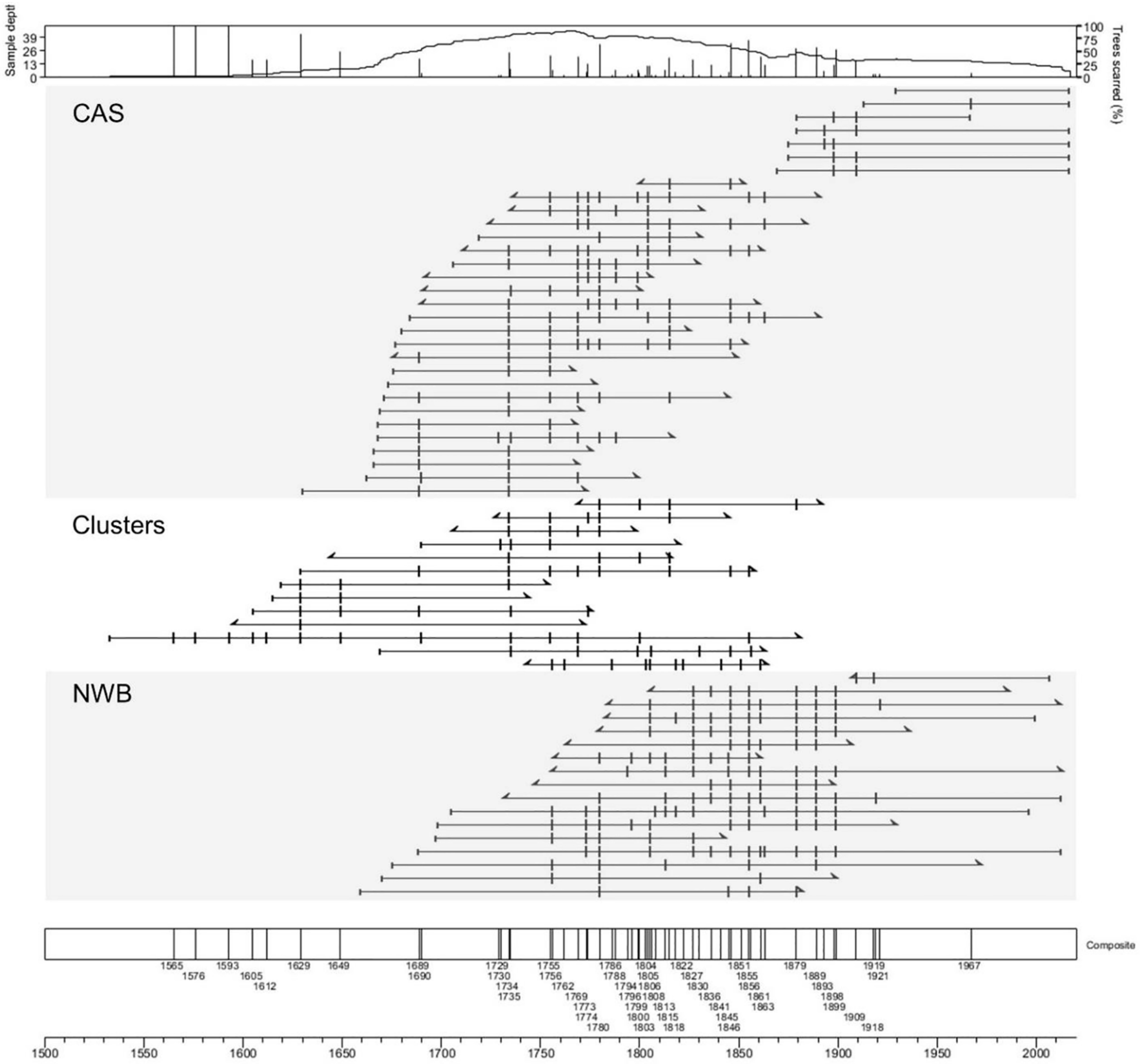

Fig. 2. Fire history diagrams for study sites (CAS and NWB) all other samples collected in clusters. Horizontal lines represent the period of tree-ring record for 61 crossdated samples spanning the period 1533–2016 (483 yrs). Vertical ticks on horizontal lines indicate fire scars (n = 314). Slanted and vertical lines on the left ends of horizontal lines indicate inner-most ring and pith years, respectively. Similarly, on the right side of horizontal lines, slanted or vertical lines indicate outermost ring or bark year. At the bottom is a composite record of all fire event years for the study landscape.

4. Discussion

The results of this study provide new multi-century fire event records that suggest historical fire regimes in the study region were characterized by relatively frequent, non-stand replacing fire events that occurred predominantly in the dormant season. The fire records also suggest that drought and humans have both been important factors influencing historical fire activity. Transitions from wet to dry conditions commonly corresponded with fire activity, especially for drought years. At the same time, longer-term changes in fire frequency suggest human controls and regime changes associated with major cultural changes (e.g., circa 1750 and 1935). These data support an emerging characterization of historical fire regimes of red pine forests in the Upper Lake States that includes mixed severity fires, with a combination of infrequent large-scale, high severity fires largely driven by climate (e.g., lightning ignited, dry conditions) and more frequent, low severity surface fires largely driven by human ignitions (e.g., Loope, 1991; Anderton, 1999; Muzika et al., 2015; Johnson and Kipfmueller, 2016; Kipfmueller et al., 2017). This is in contrast to previous paradigms in this region which were based on the idea that historical fire regimes were more dominated by large-scale stand-replacing fires (Heinselman, 1996) like in boreal regions.

Fires at our study sites were historically more frequent than would be expected from just lightning ignitions. Modern fire occurrence data (1970–2002) for the Chippewa National Forest shows approximately 1 lightning fire/400,000 ha/year (Kay, 2007). These red pine sites are perhaps more pyrogenic than the majority of the surrounding landscape (e.g., wetlands, mixed/deciduous forests), and ample fuels exist for fire spread. Despite this, we found no evidence of stand-replacing fire events and we surmise that fires were generally small as 61% of fire events were not shared between sampling locations, echoing the findings of Kipfmueller et al. (2017) at Voyageurs National Park in northern Minnesota.

The frequency of fires at our individual study sites and across the landscape is comparable to what has been found by other fire history studies in the region. The study area-wide MFI of 6.6 years is slightly shorter than the 8.8 yr MFI documented at nearby Itasca State Park (~67 km southwest; Frissell, 1973), and longer than the 3.8 yr MFI found for the landscape of Lac La Croix, MN (~190 km NE; Johnson and Kipfmueller, 2016). These differences may be a consequence of sample size and spatial coverage or site conditions such as geology and soil type. Interestingly, the Lac La Croix landscape is highly fragmented by open water and islands. For a more direct comparison, individual site MFIs in this study (i.e., CAS, NWB) were very similar to the MFIs identified for

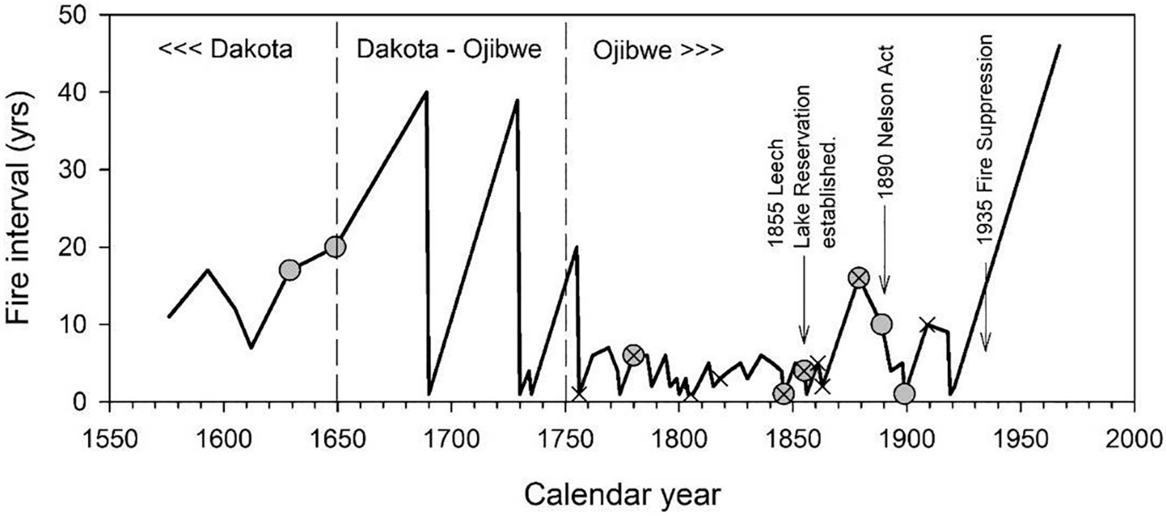

Fig. 3. Decadal averaged fire intervals from 1570s to 1960s based on fire scar records across the study landscape. Filled circles represent shared fire years across multiple sites while x's represent years when > 50% were scarred. Dashed lines separate time periods by Native American cultural groups. Cultural periods and events of the landscape are indicated by text and arrows.

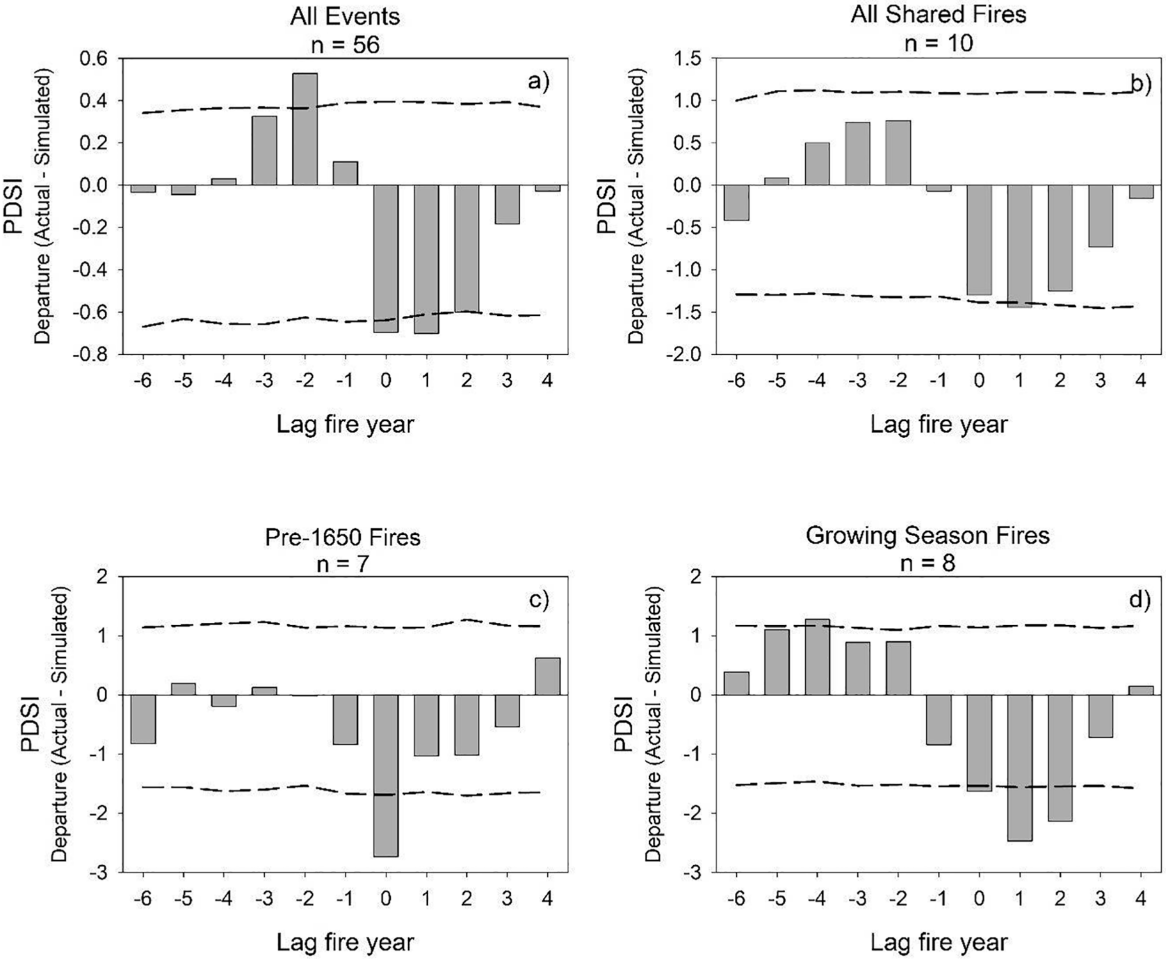

Fig. 4. Superposed epoch analysis (SEA) of drought conditions before, during, and after fire events for (a) all event years in the study landscape, b) fire years shared by two or more sites, c) fire years prior to 1650, and d) growing season fire years. Drought data represent summer season Palmer Drought Severity Index. Vertical bars represent deviation from expected conditions based on 1,000 simulations. The 95% confidence limits are indicated by the dashed line.

the three 'mainland' sites at Lac La Croix (range MFI 14.2–16.6 yrs).

Fire frequency increased through the 18th-century with a marked change circa 1750. Other sites in the Lake States region also showed marked increases in fire frequency at this time and were attributed to changing human influences (Guyette et al., 2016). The most frequent burning occurred from about 1790 to 1820. Surprisingly, we did not see dramatic increases in fire activity during the period of European settlement (late 19th century) as some studies have found (e.g., Drobyshev et al., 2008) possibly due to the unique local history of Leech Lake as a reservation.

Drought was historically an important condition for fire occurrences. Although this result may not be surprising, thus far, analyses of historical drought-fire relationships in the Great Lakes region have yielded mixed results, with some studies showing its significance (Kipfmueller et al., 2017; Martin, 2019; Meunier and Shea, 2020) and others not (Johnson and Kipfmueller, 2016). The association between drought and fire occurrence can be masked by local effects such as human ignitions/exclusion or site factors that buffer fire occurrence and climate influences. Further, seasonal to annual drought metrics likely do not capture shorter periods such as abbreviated dry periods or weather conducive to ignition and fire spread in otherwise wet months to years. Similar to this study, Martin (2019) found conditions in the year of fires being significantly drier than expected when considering data from a large landscape, but not for individual sites. Our findings are also similar to Meunier and Shea (2020) in northern Wisconsin where severe to extreme drought appeared to be important in explaining large fire years, but overall, most fire years occurred in years that were just moderately dry. Our results of fire frequency increasing circa 1750 and remaining relatively frequent through the 19th century may be indicative of Ojibwe cultural fire practices (Fig. 3). These results are also somewhat similar to Johnson and Kipfmueller (2016), which concluded that changes in fire frequency at Lac La Croix, MN were more related to human (Ojibwe) ignitions than drought conditions.

Scale of observation is likely key to uncovering the climatic factors driving historical fire regimes of the region, emphasizing the value of continued and expanded work documenting historical fire events through fire scars. Further, seasonality of fire scars may provide information to interpret the importance of climate on fire occurrence. Some growing season fire years were detected in this study and were significantly related to dry conditions in the fire year, consistent with characteristics of summer season - dry condition - lightning ignited fires in this area (Johnson and Kipfmueller, 2016). However, we found that the majority of fires occurred in the dormant season, possibly indicating a strong relationship with human ignition factors.

The SEA findings of significantly wetter than normal conditions two years preceding fire events and significantly dry conditions during fire years suggests that fuel accumulation and drought conditions were important to historical fire events. These findings are somewhat surprising since they are more commonly found in fuel production-limited environments such as arid to semi-arid regions (Brown et al., 2008; O'Donnell et al., 2011). In Minnesota, these findings may suggest that fuels were historically comprised of a larger proportion of fine fuels than exist today. Repeated burning at 10-year intervals over several centuries likely produced a fuel bed more dominated by herbaceous vegetation and shrubs than currently exists. The past 70 or more years without fire is the longest interval of the last five centuries and has likely resulted in transitions from grass-herbaceous to timber-litter fuel types and heavy woody fuel accumulations.

Differences in this fire history between pre-1750 and post-1750 (more frequent fire, higher %scar, more shared fire years after 1750) corroborate the findings of Kipfmueller et al. (2017) at Voyageurs National Park 130 km to the north of our study area, and similarly, do not appear to be explained by any changes in climate conditions. In addition, there were long periods without fire that did not correlate with prolonged wet conditions. These anomalous long periods without fire are likely related to the complex social, biological, and ecological consequences of European colonization on Native Americans and societies (including depopulation, Cameron et al., 2015). For example, the fire-free period from 1865 to 1889 may reflect the forced movement of the local Ojibwe population to reservation lands and decreased land use autonomy.

More recent evidence for cultural influences on fire regimes exists in the cessation of fires before fire suppression techniques were effective. Detection of fires in this landscape abruptly halt after about 1921, before the time when fire control activities were fully effective (USDA Forest Service, 1986). This may indicate that fire cessation was more related to changes in Ojibwe land use than organized fire suppression. The decades following the Nelson Act of 1889 were a time of extreme exploitation of the Ojibwe and the Leech Lake Reservation lands. The Nelson Act also stripped tribal members of their previously held rights to hunt and fish according to their own traditions. Dramatic decline in fire activity attributable to changes in traditional indigenous land use rather than climate or fire suppression has also been observed at other Upper Great Lakes study sites (Larson et al., 2020; Loope and Anderton, 1998).

4.1. Implications

Scientists and managers in the Lake States region have gradually come to appreciate that the historical fire regime for red pine-dominated ecosystems is more complicated and variable than the long-perceived model of frequent stand-maintaining surface fires punctuated by infrequent stand-replacement fires. While such a disturbance dynamic likely occurred in some places and times, accumulating scientific evidence, including the current study, points to a fire regime that likely included mixed-severity effects, with fires ranging from surface to crown fires within and among stands, and with more severe, true stand-replacement events likely linked to severe to extreme regional drought.

An important consideration for management emerging from this research is that fires which killed overstory trees were not always (perhaps not often) entire stand replacement events, but rather were likely patchy and variable with more frequent surface fires that varied in severity occasionally killing overstory trees to create openings of various sizes. It is in the openings that new cohorts of red pine established, resulting in two or more (uneven) cohort age structures (Fraver and Palik, 2012; Meunier et al., 2019). This uneven-age stand structure and process associated with fire contrasts to the long-standing plantation forestry silvicultural model for red pine that emphasizes even-aged stands that are clearcut and replanted to red pine at high densities, with the belief that this dynamic emulates the natural disturbance and development model for red pine ecosystems.

Even with this growing understanding, the details of fire as a disturbance in red pine, and how it can inform management, are not well known, but the current research provides this detail. First, our results point to a high frequency of fire, with a landscape fire interval several years shorter than what has previously been reported for red pine in the ecoregion (i.e., Northern Minnesota Drift and Lake Plains section). Second, fires in the study area were predominantly occurring in the dormant season. These two findings strongly suggest an important human element to ignition and burning in the study landscape, specifically frequent burning by indigenous peoples. This latter result likely has important implications to prescribed fire management, particularly in understanding the importance of humans for maintaining fire regimes and the implications and effects of burning outside of the dominant (dormant) historical season.

Results of this study suggest use of silvicultural systems with high levels of structural retention, including smaller-scale, non-stand replacing silvicultural disturbances (e.g., Fraver and Palik, 2012; Palik et al., 2020). The use of multiple prescribed fires in combination with other silvicultural practices, such as the irregular shelterwood method or high-retention harvests, may be used to produce, for example, an expanding forest canopy gap dynamic that prepares a good seedbed for red pine, reduces competing vegetation, and provides openings for red pine recruitment into the overstory. Use of such an approach may be useful where restoration of composition and natural structural complexity is a goal in red pine systems. The historical variability in fire occurrence in the study landscape, likely due to local and landscape factors such as topography and humans, and larger-scale influences like drought and cultural period/group, suggests that the sequencing of silvicultural practices is important and should vary over time and space. Further, this fire sequence variability could allow for control of competing vegetation and maintaining suitable seedbeds with periods of frequent fire in some areas, while also providing for sufficiently long fire-free periods to allow for red pine regeneration and survival (Stambaugh et al., 2019).

Our study points to the complexity of interactions among fire, climate, and humans and how this varied through time. Having a more fully developed and scientifically supported understanding that is site-specific, such as provided with the results of this study, provides increased perspective and allows for the best possible management decisions, given the state of our understanding. Over the last five centuries, fire regimes show potential for highly varied conditions ranging from frequent, localized, low severity to infrequent, extensive, and high severity.

5. Conclusion

It can be difficult to determine the relative importance of climate versus humans in the historical fire regime. Expanding the fire scar network across the region is increasing understanding of the broader scale drivers of historical fire regimes. These data provide new support for the idea that, while climate has been an important forcing factor for periodic large-scale fires in this region, historical human ignitions were also likely important to the frequent mixed-severity fire regime including its landscape heterogeneity. The understanding of historical fire regimes, relationships with humans and climate, combined with an understanding of the ecological requirements of red pine and its adaptations to fire need to be integrated in designing silvicultural prescriptions. Humans historically used fire to manage the land for their benefit and well-being, and humans today need to realize the critical role of fire in these landscapes and integrate its use into land management to achieve goals and objectives in resource and conservation management.

CRediT authorship contribution statement

Michael C. Stambaugh: Conceptualization, Funding acquisition, Project administration, Data curation, Formal analysis, Writing - original draft. **Erin R. Abadir:** Formal analysis, Writing - original draft. **Joseph M. Marschall:** Data curation, Formal analysis, Writing - review & editing. **Richard P. Guyette:** Conceptualization, Funding acquisition, Project administration, Data curation, Formal analysis. **Brian Palik:** Writing - original draft, Writing - review & editing. **Daniel C. Dey:** Conceptualization, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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