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Historical fire regimes from red pines (*Pinus resinosa* Ait.) across the Tension Zone in the Lower Peninsula, Michigan USA

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Abstract

Currently, no multiple century fire scar records have been constructed in the Lower Peninsula of Michigan, USA, a region where historical vegetation ranged from prairies and oak-dominated woodlands in the south to conifer-northern hardwood forests and swamps to the north. The western portion of the Huron-Manistee National Forests is located within this strong vegetation transition (i.e., "Tension Zone") and, based on this study, has well-preserved remnant red pine trees dating back to at least the late 1400s with fire scars dating back to 1523. From fire scar records constructed at four study sites, we documented historical fires as having a wide range of fire intervals and seasonalities. A general timeline of fire activity changes in this region can be described as relatively frequent fire in the pre- and early-European contact eras, variable and generally less fire from this point forward until the period of major logging activities after which fire frequency was significantly increased. Historical fires were associated with drought in the year of fire. Some broad synchronies of fire occurrence existed among sites such as 3 of 4 sites recording fires in years 1717, 1774, and 1829. Interestingly, these years were not exceptionally dry nor among the driest fire years. Future development of fire scar records will likely improve spatio-temporal characterization of regional fire regimes including understanding of human-climate-fire dynamics.

Resumen

Actualmente no existen registros múltiples de cicatrices de fuego de centenarios construidos en la Península baja de Michigan, EEUU, una región donde históricamente la vegetación varió desde praderas y bosques dominados por robles en el sur a coníferas del norte, y bosques de madera dura y pantanos en el norte. La porción oeste del Bosque Nacional Hurón-Manistee, está ubicada dentro de esta fuerte transición vegetacional (i.e. "zona de Tensión") y, basado en este estudio, tiene bien preservados pinos rojos remanentes que datan desde al menos las postrimerías de los años 1400, y que tienen cicatrices de fuego desde el 1523. De los registros de cicatrices de fuego construidos en cuatro sitios de estudio, documentamos fuegos históricos que tenían un amplo rango de intervalos de fuego y estacionalidades. Una escala general de tiempo sobre los cambios en la actividad de fuegos en la región puede describirse como de fuegos relativamente frecuentes en la era de inicios del contacto con la colonización europea, variable y generalmente con menos fuegos desde este punto y hasta el período de mayor actividad de tala de estos bosques, en que la frecuencia de los fuegos se incrementó significativamente. Los fuegos históricos fueron asociados con sequías en el año de ocurrencia del fuego. Algunas sincronías amplias de ocurrencia del fuego existieron entre sitios,

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como que los sitios 3 y 4 registraron fuegos en los años 1717, 1774, y 1829. Interesantemente, esos años no fueron excepcionalmente secos ni se ubicaron entre los años de fuego que fueron los más secos. El desarrollo futuro de registros de cicatrices de fuego mejorará sin dudas la caracterización espacio-temporal de los regímenes de fuego regionales, incluyendo el entendimiento de la dinámica entre el fuego-clima y los seres humanos.

Introduction

Development of fire scar history datasets is an active line of forest and fire ecology research that informs a wide range of natural resource and social science issues. Recent development of the North American Tree-Ring Fire-Scar Network (NAFSN; Margolis et al. 2022), compiled from more than 2500 fire-scar study sites, has revealed the broad utility of these records for understanding fire relationships to climate, humans, forest composition, topography, and other ecosystem characteristics. Compilation of the NAFSN has also revealed major deficiencies in data representation such as relatively little fire scar information across boreal biomes of Canada and large portions of the eastern U.S compared to western North American mountain ranges. Prior to the present research, data for only a limited number of fire-scarred trees for the post-1800 era have been published for the Lower Peninsula (LP) of Michigan, USA (Simard and Blank 1982, Loope and Anderton 1998).

The LP is an approximately 104,000 km^2 region bounded by Lake Michigan and Lake Huron to the west, north, and east. To the south, the LP connects to diverse glacial plains and moraines (Omernick 1987). Across the middle of the LP and extending to other regions of the Lake States region, a strong north-to-south ecological gradient exists due primarily to climate. As such, a vegetation "Tension Zone" exists (Curtis 1959) forming a distinct ecotone (i.e., tens of kilometers in width) and a divide in floristic provinces and multiple species' ranges (McCann 1979; Anderson 2005; Fulford 2005; Nowacki and Thomas-Van Gundy 2022).

Across the Tension Zone, comparisons of settlement-era forests as reconstructed from General Land Office (GLO) surveys and modern forests have revealed that, while broad patterns have remained similar, forests today are different than they were before Euro-American colonization (Elliott 1953; Whitney 1987; Comer et al. 1995). South of the Tension Zone, open canopy ecosystems such as oak woodlands, oak savannas, and prairies were dominant but have since been largely converted to agriculture or transitioned to closed canopy forests (Hanberry and Dey 2019). North of the Tension Zone, mixed conifer-deciduous forests have persisted from historical times, but recently have transitioned to more closed canopy structures with increased importance of mesophytic species (Nowacki and Abrams 2015; Hanberry 2020). These changes are most likely the result of late nineteenth century forest clearing and subsequent twentieth century fire suppression (Hanberry 2020). Many areas were replanted to red pine following widespread forest clearing in the late 1800s.

While it is clear from the presence of fire-dependent ecosystems that fire has long been an important disturbance in the LP, available information on the historical fire regimes of the region is largely limited to inferences. For example, it is widely accepted that fire played an important role in sustaining prairies, savannas, and woodlands and promoting the dominance of fire-adapted species such as red pine, jack pine. Indigenous peoples of the LP were known to have used fire in many facets of life including spiritual and cultural ceremonies (Clifton et al. 1986), but documentation of their influence at larger, landscape scales is lacking. Models based on landtypes, historical vegetation, and fires estimated from GLO surveys have characterized the northern LP (i.e., north of the Tension Zone) as a complex mosaic of frequent to infrequent historical fire regimes (Whitney 1987; Cleland et al. 2004). Areas with historically frequent fire had pyrophilic and fire-dependent vegetation that still exists today. Increases in vegetation density and structural complexity since the advent of fire suppression contribute to high fire risk, including in the wildland-urban interface (Comer et al. 1995; Haight et al. 2004). Some of the largest and deadliest wildfires in the U.S. have occurred in the LP, such as the ~1 million ha Great Michigan Fires of 1871. At present, the potential for high fire risk and high severity fires in historically fire-prone areas remains high (Cleland et al. 2004).

A deeper understanding of historical fire regimes in the LP could help to inform natural resource management and wildfire risk mitigation in this region. While there is a large body of information on historical vegetation characteristics and how they have changed since Euro-American colonization, there have been no long-term fire regime reconstructions developed for the LP. Where centuries-old fire-scarred wood and trees exist, it is possible to develop annual records of fire events based on fire scars that extend back to the early 1500s (Stambaugh et al. 2021), particularly from forests with a component of red pine (*Pinus resinosa*). Our objective was to locate sites across the Manistee National Forest

(MNF) where we could use dendrochronological techniques to reconstruct historical fire occurrence. With these long, annually resolved records of fire, we aimed to quantify fire regime characteristics and explore relationships among fire, climate, humans, and land use change.

Methods

Landscape and study sites

The study region was located within the MNF in the western LP of Michigan (Fig. 1). The MNF landscape (~2200 km^2) is primarily within the Manistee Sandy Outwash Plain Subsection and Interlobate End and Ground Moraines Subsection of the Laurentian Mixed Forest Province (Cleland et al. 2007). Site conditions transition from wet areas associated with swamps, marshes, and rivers to xeric sandy uplands often composed of closed canopy forests with northern hardwoods and conifers. Several major rivers (e.g., Manistee and Pere Marquette) flow westward through the study region towards Lake Michigan and have evidence of human occupation spanning the last 10,000 years (USDA 1976, 1983). Areas of historically frequent fire regimes likely existed to some degree across the region based on natural distributions of open lands and fire-adapted vegetation including trees such as red pine and jack pine (*P. banksiana*). This region of the LP lies at the southern edge of the ranges of both species.

From 2014 through 2021, we searched the MNF for areas where at least 20 remnant fire-scarred red pine trees existed within an approximately 1 km^2 area (Fig. 2). Several areas were identified with red pine snags, downed logs, and stumps from historical logging activities in the mid- to late-1800s (Fig. 2). We located three study sites where adequate samples existed, each separated by approximately 25 km: West Udell Hills (WUH), Olga Lake (OLG), and Wolf Lake (WFL) (Fig. 1). One other site, Shelley Lake (SHL), was also sampled despite a lower abundance of samples because remnant wood exhibited visual qualities of being exceptionally old. At WUH and OLG, the modern forest condition was a mature red pine plantation of early twentieth century origin. The forest composition at WFL was a mixture of red pine plantation and native hardwoods (e.g., northern red oak (*Quercus rubra*)) and conifers (e.g., eastern white pine (*Pinus strobus*)). At SHL, the forest composition was mixed hardwoods and conifers.

Sample collection

Field collections occurred in 2015 (July) and 2021 (April and May). Sites were intensively searched for remnant wood and live trees that exhibited enough tree rings (for cross-dating) and evidence of a recoverable fire-scar record (Fig. 3). We targeted the sampling of red pines due to their known capacity to survive fire injury and persist for long periods as remnants post-mortem due to high resin content. Samples were cut from stumps, standing snags, and logs. Some stumps appeared to have been fully excavated from the ground during past site planting preparation (i.e., chaining, furrowing). We cut approximately 10-cm-thick sections from near the ground level where all fire scars were present on the sample. In some cases, we cut multiple sections to ensure all visible fire scars were captured. Partial or full cross-sections were removed from live trees when allowable. Samples from live, fire-scarred trees covered the last ~100 years, a period unrepresented by remnant wood. At site WFL, in addition to sampling red pines, we also sampled four white oak stumps associated with a recent timber harvest (Fig. 3). All cross-sections were marked to indicate aspect, height above ground, and direction of slope. Tree locations were recorded using a GPS unit.

Laboratory analysis

Surfaces of cross-sections were prepared with progressively finer sandpaper (60–1200 grit) to reveal cellular details of tree rings and fire scars. Tree rings were measured in sequence to 0.01 mm precision using a Velmex TA measuring system (Bloomfield, New York, USA). We used standard dendrochronological methods (Stokes and Smiley 1968; Speer 2010) to crossdate samples and construct absolutely dated master ring-width chronologies by site. Site dating was validated by crossdating with other nearby red pine ring-width series available in the International Tree-Ring Data Bank (ITRDB) (e.g., #MI029, Larson and Rawling 2016). A floating chronology was similarly developed from the four white oak stumps sampled at WFL, which was then absolutely dated using a white oak reference chronology in the ITRDB (#MI016, Wyse and Goebel 2005).

(See figure on next page.)

Fig. 1 Map showing the locations of fire history study sites (black circles and 3-letter labels) collected on the Manistee National Forest (gray dashed boundary) in the Lower Peninsula of Michigan, USA. The colors represent the vegetation cover circa 1800 based on original surveyors tree data and descriptions of the vegetation and land between 1816 and 1856 based on Comer et al. 1995 (Available: https://gis-michigan.opendata.arcgis.com/datasets/Michigan::land-cover-circa-1800/about). Inset map shows the state of Michigan with the Manistee National Forest administrative area in black

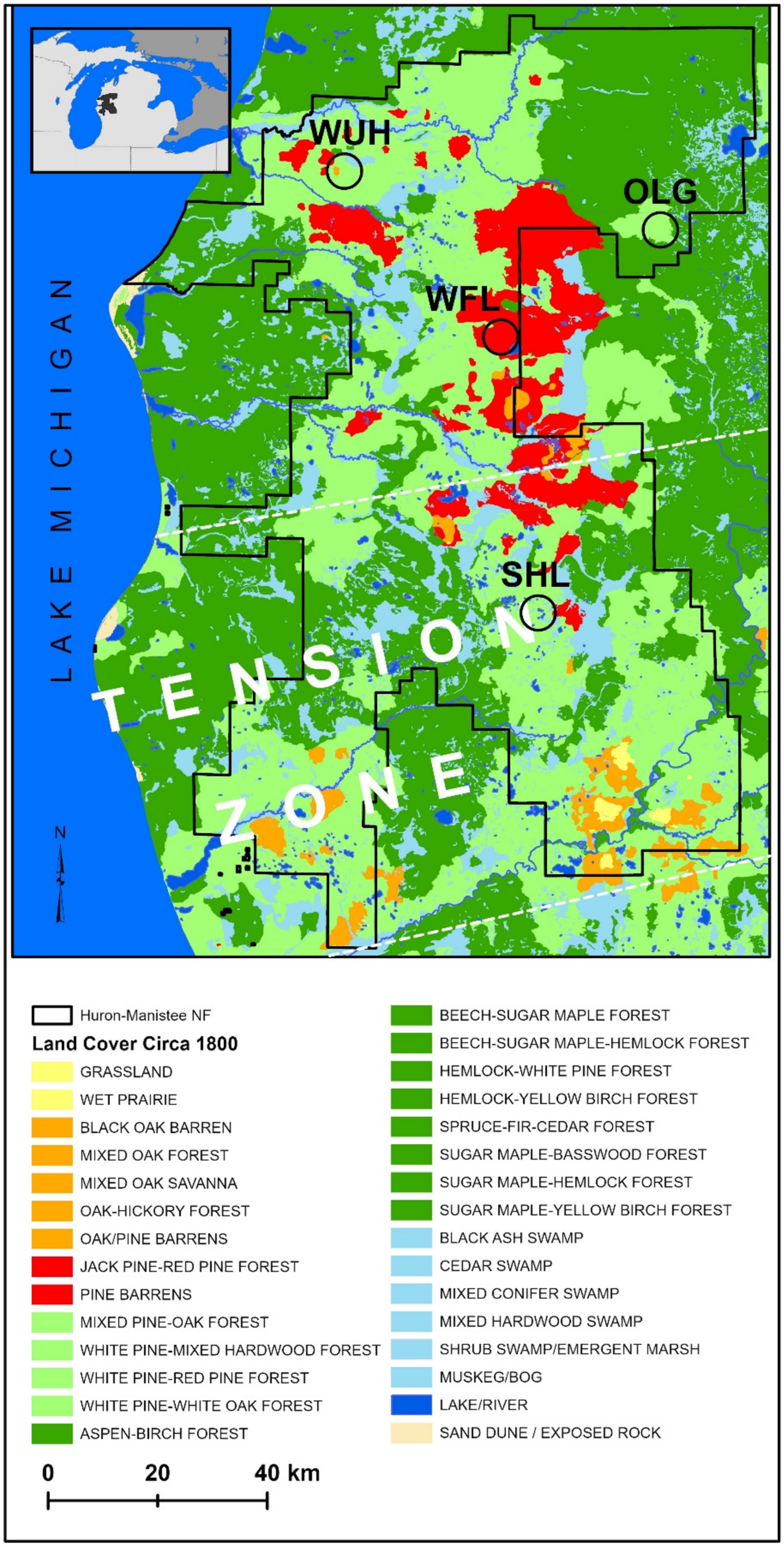

Fig. 1 (See legend on previous page.)

Fig. 2 Top: Photograph from 1938 showing denuded forest lands not restocking on Manistee National Forest in Michigan (text based on the original figure caption; source: U.S. National Archives and Records Administration), repeated fires removed a chance of tree reseeding. Note the presence of both charred and uncut trees (snags) and cut stumps. Bottom left: Sampled red pine (*Pinus resinosa*) remnant tree (stump), WFL120, provided a tree-ring record from 1732 to 1859 with six fire scars identified between 1802 and 1854. Bottom right: Lower portion of a living red pine tree with fire scars and charcoal. This tree regenerated during the peak of logging era. This tree was sampled by removing a partial section from the side that contained pith and all fire scars. This sample had a tree-ring record spanning the time period of 1878-2020 and five fire scars recorded between 1887 and 1921

We identified fire scars on samples based on the presence of callus tissue, charcoal, and traumatic resin canals (Smith and Sutherland 1999), and lack of evidence for mechanically induced injury (e.g., removed wood) that can be caused by agents other than fire (e.g., animal activity, injuries related to human activities such as resin collecting or logging). Fire scars were dated to the year of cambial response to injury and, when possible, we identified the season of occurrence based on scar position within the ring (Kaye and Swetnam 1999). Fire scar seasonality was classified in six positions: dormant, early-earlywood, middle-earlywood, late-earlywood, latewood, or unidentifiable (UFS; when position of fire scar was obscured by decay or other factors).

In a few instances, fire scars were identified in consecutive seasons. Variations in seasonality of injuries can occur in trees due to differences in timing of wood formation. For these instances, we combined consecutive season fire scars into 1 year prior to analyses with seasonality assigned to the majority season. This affected three fire years at two different sites. At WUH, three fire scars with unidentifiable seasonality dated to 1699 were shifted to 1698 for which there were already seven trees with latewood fire scars identified. At SHL, one tree with an unidentifiable seasonality fire scar in 1673 was shifted to 1672, a fire year that had one latewood fire scar recorded on one tree. Also at SHL, one tree with an unidentifiable seasonality fire scar dated to 1792 was shifted to 1791, a fire year that had three trees with latewood fire scars.

Data analysis

Fire regime data were graphed by site using FHAES software v. 2.0.2 (Brewer et al. 2016). Calculations of summary statistics were based on all fire scars recorded (the composite fire chronology). We calculated the percentage of trees scarred during fire years when at least three trees were present in the record. In addition, we merged fire history data from all sites into a single dataset (ALL) to characterize landscape fire regime characteristics. Fire frequency was described using fire return intervals (number of years between subsequent fire events) including calculation of the mean fire interval (MFI) and Weibull median fire interval (WMI). We reported the WMI when a Kolmogorov–Smirnov goodness-of-fit test indicated that the Weibull distribution modeled the interval data better than a normal distribution. Lower and upper and exceedance values for fire intervals (LEI / UEI) were calculated to identify statistically short and long fire intervals, respectively. We calculated fires per decade (FPD) for ALL using a 10-year moving sum.

We used superposed epoch analysis (SEA) to determine whether the occurrence of historical fires was

(See figure on next page.)

Fig. 3 Fire scar history diagrams for the four study sites (left side); Olga Lake (OLG), Wolf Lake (WFL), West Udell Hills (WUH), and Shelly Lake (SHL). Fire scar history diagram on right shows all samples and fires for all sites combined (ALL). On all diagrams, horizontal lines represent the period of tree-ring record for trees. Vertical ticks on horizontal lines indicate fire scars. On the left ends of horizontal lines, slanted and vertical lines indicate inner-most ring and pith years, respectively. On the right side of horizontal lines, slanted or vertical lines indicate outermost ring or bark year, respectively. At the bottom of each diagram is a composite record of all fire event years. Years are colored by seasonality where: yellow = earlywood, orange = latewood, blue = dormant, and no color = undetermined seasonality

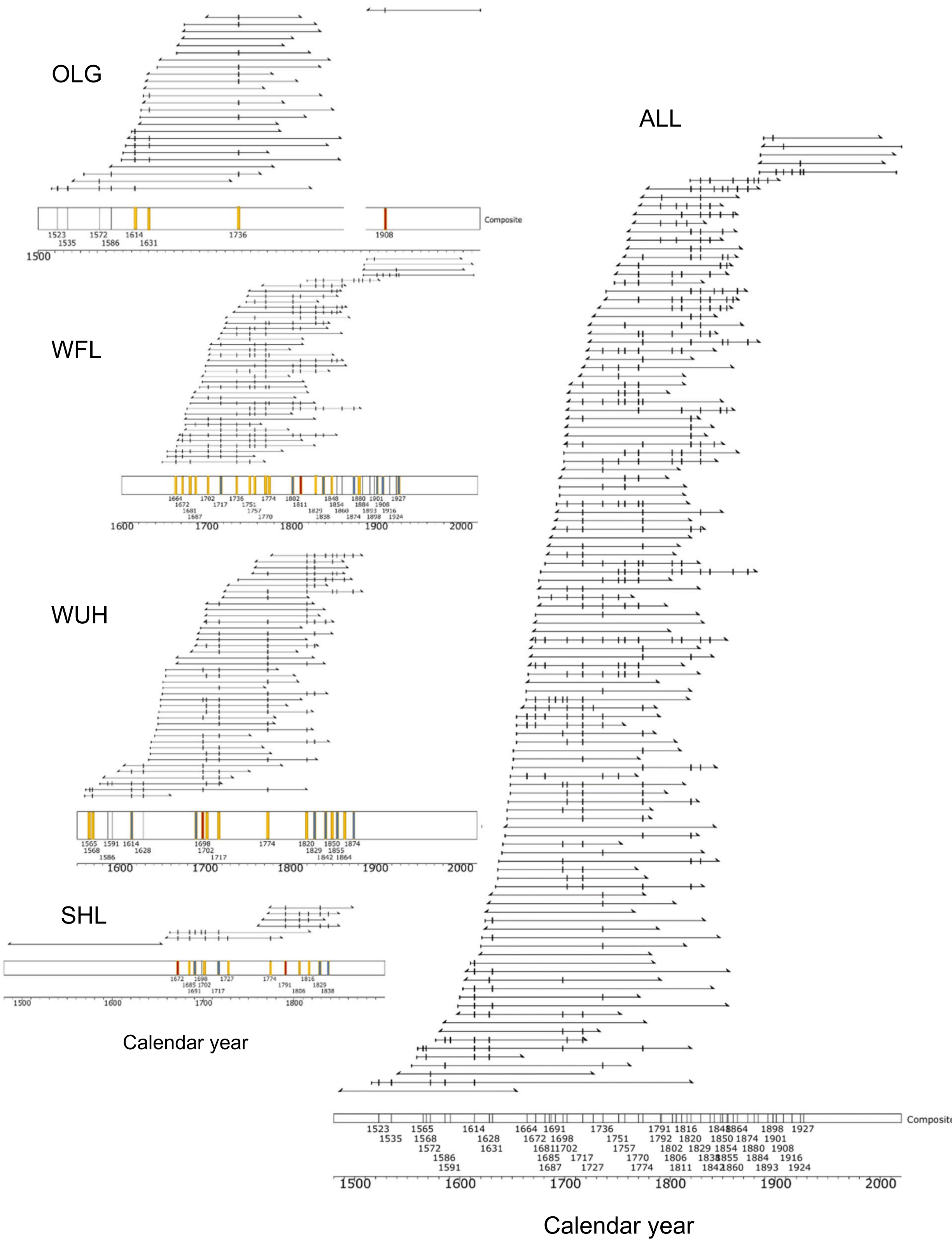

Fig. 3 (See legend on previous page.)

significantly associated with drought years. We tested fire event years at the regional scale (ALL) to maximize fire events considered in the analysis and because fire activity at larger extents is expected to be more influenced by broad-scale drivers (i.e., drought). We ran the SEA for the period when at least 10 trees were represented (1598 to 1865; 33 fire years) and separately for the ten fire events with the highest percentages of trees scarred. Drought data used in the analysis were the reconstructed Palmer Drought Severity Index (Cook et al. 2004) averaged for gridpoints 225 (northern LP) and 226 (southern LP). Drought conditions during of fire event years were tested to see if they were significantly different (drier or wetter) from expected. Drought data were bootstrapped for 1000 simulated events to derive confidence limits. Fire-drought associations were statistically significant when PDSI values exceeded 95% confidence intervals. Using SEA, we also considered potential lagged drought-fire associations for the 6 years preceding to 4 years following fire event years.

Results

Tree-ring and fire-scar records

Across all study sites, samples were collected from 122 trees, with 113 able to be successfully crossdated. Most samples were collected from remnant stumps that, based on outer ring dates, were trees cut between 1870 and 1900. Samples that did not crossdate had either too few rings (e.g., < 50) or highly distorted rings due to fire scar injuries. The tree-ring record spanned the calendar years 1486 to 2020 CE (535 years; Table 1). The fire-scar record for all trees spanned the period of 1523–1927 (405 years; Table 2). The number of fire scars per sample ranged from 0 to 11.

WUH site

At WUH, 41 red pine trees were successfully crossdated providing a tree-ring record spanning the years 1559 to 1885 (Table 1). A total of 118 fire scars were recovered from these trees, representing 17 unique fire years from 1565 to 1874 (Table 2, Fig. 3). Fire return intervals ranged from 3 to 70 years in length, with a site-wide MFI of 19.3 years. The mean percentage of trees scarred in fire years was 53.0% (Table 2). We identified seasonality for the majority of the fire scars and, of these, 27.6% formed in the dormant season, 58.6% in the early-to-mid-growing season, and 13.8% in the late-growing season (Table 3, Fig. 3). Nearly half of fire years had at least one fire scar with a seasonality other than dormant identified (i.e., growing season fire year) (Table 3).

Table 1 Sample and study site characteristics for fire history datasets developed on the Huron-Manistee National Forest

Site code	Samples (*n*)	Tree-ring record (years)	Site area (km^2)	Site center latitude/longitude
WUH	41	1559–1885	1.3	N44.20217° W86.12745°
OLG	26	1516–2020[a]	0.4	N44.14020° W85.63155°
WFL	39	1648–2015	0.7	N44.02623° W85.86011°
SHL	7	1486–1865[b]	0.3	N43.70894° W85.80961°
ALL	113	1486–2020	~1200	Na

Na not applicable

[a] gap in tree-ring record from 1856 to 1887

[b] gap in tree-ring record from 1655 to 1658

Table 2 Historical fire frequency statistics at sites on the Huron-Manistee National Forest, Michigan

Site code	WUH	OLG	WFL	SHL
Fire scar record (cal. years)	1565–1874	1523–1908[a]	1664–1927	1672–1838
Fire years (*n*)	17	8	28	13
Total intervals (*n*)	16	7	27	12
Mean fire interval (years)	19.3	55.0	9.7	13.8
Minimum fire interval (years)	3	12	3	4
Maximum fire interval (years)	70	172	28	47
Weibull median (years)	14.4	39.4	9.1	12.2
Lower exceedance interval (years)	3.2	8.1	3.7	4.1
Upper exceedance interval (years)	39.2	113.1	16.4	25.3
Mean scarred (%)	53.0	50.9	42.0	56.4

[a] Gap in record from 1856 to 1887

Table 3 Historical fire scar seasonality characteristics at study sites on the Huron-Manistee National Forest

Site code	WUH	OLG	WFL	SHL
Fire scars (*n*)	118	28	171	26
Unidentified (%)	26.3	39.3	32.2	19.2
Dormant (%)	27.6	5.9	26.7	33.3
Early-earlywood (%)	31.0	41.2	22.4	23.8
Middle-earlywood (%)	23.0	41.2	22.4	19.0
Late-earlywood (%)	4.6	5.9	20.7	4.8
Latewood (%)	13.8	5.9	7.8	19.0
Years with growing season fire scar (%)	47.1	37.5	53.6	61.5
Years with no seasonality assigned (%)	11.8	50.0	25.0	7.7

OLG site

Twenty-six red pine trees were crossdated at site OLG. The tree-ring record spanned years 1516 to 2020 but included a 21-year gap with no samples from 1856 to 1887 (Table 1). Twenty-eight fire scars were identified on all samples resulting in 8 unique fire years from 1523 to 1908 (Table 2, Fig. 3). Fire return intervals ranged from 12 to 172 years, with a site-wide MFI of 55.0 years. The mean percentage of trees scarred in fire years was 50.9% (Table 2). Seasonality of historical fires was mostly early-to-mid growing season but included small representation of dormant and late-growing season events. The four earliest fire years (during period 1523–1586) did not have any scars with identifiable seasonality due to wood decay. All four of the remaining fire years had at least one scar formed in the growing season (Table 3, Fig. 3).

WFL site

At WFL, we dated 35 red pines and 4 white oaks spanning years 1648 to 2015 (Table 1). A total of 171 fire scars produced 28 unique fire years ranging from 1664 to 1927 (Table 2, Fig. 3). Fire return intervals ranged from 3 to 28 years, with a site-wide MFI of 9.7 years. The mean percentage of trees scarred in fire years was 42.0% (Table 2). We were able to determine seasonality for 67.8% of the fire scars at WFL and, of these, 26.7% were formed in the dormant season, 65.5% were formed in the early-to-mid-growing season, and 7.8% were formed in the late-growing season (Table 3, Fig. 3).

SHL site

Seven fire-scarred red pines were crossdated at SHL with tree-ring records spanning 1486 to 1865 including a gap from 1655 to 1658 (Table 1). A total of 26 fire scars were identified on these samples which represented 13 unique fire years from 1672 to 1838 (Table 2, Fig. 3). Fire return intervals ranged from 4 to 47 years with a site-wide MFI of 13.8 years. The mean percentage of trees scarred in fire years was 56.4% (Table 2). About one-third of the fires occurred in the dormant season, half in the early-to-mid-growing season, and the remaining in the late growing season (Table 3).

Fire regime characteristics

Regional fire activity based on the ALL sites record showed fire occurrence varying through time. Fires were generally less frequent in the earlier part of the record (~1600–1800) and more frequent after about 1800 (Figs. 3 and 4). Prolonged periods (10+ years) with little to no recorded fires occurred in the 1600s, with a notably

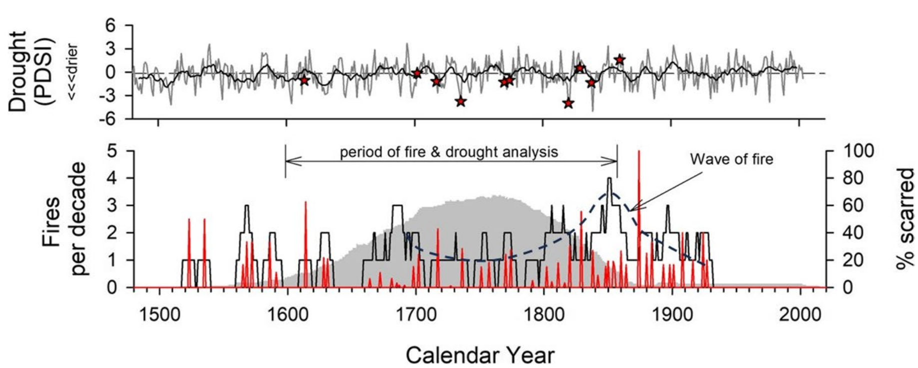

Fig. 4 (Top) Time series plots of drought represented by the average Palmer Drought Severity Index (PDSI). Shown are the annual changes in PDSI (gray line) and changes in the longer-term average (11-yr moving average; black line). Red starts indicate the ten fire events with the highest percentages of trees scarred that were used in the superposed epoch analysis (SEA). (Bottom) Time series plots of fires per decade (FPD; black line) and the percentage of trees scarred in fire years (red line). In the background, gray shading displays the number of trees represented in the record. The period when at least 10 trees are represented and used for SEA tests of drought-fire association is represented by the line bounded by arrows. The "Wave of Fire" (Stambaugh et al. 2018) pattern in fires per decade is portrayed by the dashed line

long fire interval from 1631 to 1664. From the mid-1600s and through the 1700s, sites OLG and WUH had relatively infrequent fires while sites WFL and SHL had more frequent fires. Regional fire activity increased beginning around 1800 and peaked circa 1850. Fires occurred somewhere within the region during most years from 1840 to 1920.

Prior to the 1800s, early-growing season fires were the most common, while during the 1800s a higher proportion of fires occurred during the dormant season (Fig. 3). Most fire years were detected at just one of the four sites, though some years had fires occurring at more than one site. For the period when at least three sites were represented (1664–1874), there were 30 unique fire years, 8 of which were shared between at least two sites. Three fire years (1717, 1774, 1829) were synchronous at three of the four study sites, none of which were exceptionally dry. Of the years when ≥ 10 trees were scarred across the region, the three fire years with the highest percentage of trees scarred were 1614, 1717, and 1829.

Results of the SEA showed that drought conditions during historical fire years were significantly drier than would be expected by chance. This result was found when SEA was conducted for all fire years with at least ten trees recording and separately for only the fire years with the highest percentages of trees scarred. There was no significant association between fire occurrences and the drought conditions in the years preceding them. While a significant association between fire year drought conditions and fire occurrence was found, there was variability through the record—many of the driest years in the record did not have any fires recorded (e.g., 1604, 1839), and some fire years occurred in normal moisture conditions (e.g., 1860). The top three driest years with fire were 1820 (PDSI = −4.0), 1736 (PDSI = −3.8), and 1698 (PDSI = −3.3) and all occurred during the growing season. Eight of the top ten driest fire years occurred during the growing season.

Discussion

Based on the fire history records at these MNF sites, a general timeline of fire activity changes can be described as relatively frequent fire in the pre- and early European contact eras, variable and generally less fire from this point forward until the late eighteenth-century period of major logging activities when fire frequency significantly increased. Finally, very low to no fire activity has occurred during the fire suppression era beginning in the 1930s. None of these study sites have since been managed with prescribed fire, though planning is underway for fire management at MNF.

The observed long-term shifts in fire activity from the 1600s to present are consistent with the "Wave of Fire" (WoF; Stambaugh et al. 2018) (Fig. 4) that exists in historical fire scar records across the eastern U.S. The WoF is a pattern of changing fire frequency that syncs with changes in human populations and land use over the past 400–500 years—from the time of Indigenous inhabitation and through the periods of Indigenous depopulation and cultural disruption, European colonization, and widespread industrialization. The presence of the WoF in the LP demonstrates human influence on fire regimes that corresponds with other regions of the eastern U.S. (Guyette et al. 2002; Stambaugh et al. 2018). This subcontinental-scale pattern, perhaps more extensive, can now be extended to the LP of Michigan from other Lake States regions, including the Upper Peninsula of Michigan (Muzika et al. 2015), northern Wisconsin, and northern Minnesota (Kipfmueller et al. 2021; Stambaugh et al. 2021). The WoF may not exist at all sites (e.g., sites with strong edaphic controls), so increased fire history information at more sites will likely reveal exceptions that relate to specific site characteristics and their human-fire association.

The earliest parts of the fire-scar records at MNF extend to pre-European contact periods for the LP and have the potential to provide important context for Indigenous people and environmental conditions. In the early 1600s, the northwest quadrant of the LP was home to an estimated 4000 Odawa (Ottawa) people, an Algonquin tribe that had likely been in the LP for at least a century prior to European contact (Rubenstein and Ziewacz 2014). During this era, particularly prior to 1630, fire scars revealed that frequent fire existed across all sites with a minimum fire interval ranging from 3 to 12 years across study sites. The shortest fire intervals (3 years) may indicate a lower limit of fire frequency (i.e., the most frequent that systems can burn or were "managed" by Indigenous people). This lower limit also provides insight into what fuels may have existed and what types of ignition sources were occurring (e.g., lightning, human). Short fire return intervals may also provide evidence for understanding specific types of fire use purposes such as burning for blueberries, controlling pests, or reducing woody vegetation encroachment.

Beginning circa 1650 and continuing through the 1700s, pressures on Indigenous people increased as French missionaries, fur traders, and eventually colonizers expanded into the Great Lakes region. Pressure brought upon Indigenous people included or related to new diseases, conflicts, fur trading, and religion (Ross 1938). The fire scar record shows reduced fire activity from the early to late 1700s at individual study sites and generally across the region (ALL), possibly a result of the disruption to Indigenous people and land uses including the use of fire. An exception is at site WFL where fire continued to occur at intervals of 4 to 19 years. Extended periods without fire allow fuels to accumulate and woody plants to establish; several decades without fire in the 1600s/1700s likely led to elevated tree regeneration and survival. Similarly, the fire-free period that has occurred since circa 1930 is unprecedented in at least the last 500 years and also brought about a vigorous pulse of tree regeneration, increased forest density, and forest mesophication (Nowacki and Abrams 2008).

The fire scar records at OLG and WUH sites are unique in that they show potential for both short and long fire return intervals. For example, OLG and WUH fire intervals ranged from 12 to 105 years and 3 to 70 years, respectively. The single MFI values for these sites would likely be misleading for the potential characterization of the fire regime conditions. At OLG, a change in the fire regime appears to have occurred circa 1631. Before this, fire intervals ranged from 12 to 37 years (MFI = 21 years) and afterward only two fire events are detected (MFI > 100 years; note a break in the record occurred in the logging era due to no overlapping trees at the site). Characterizing the forest conditions and fire regimes at sites like this can be challenging as there is likely little physical evidence for fire at the site, but over 390 years ago (pre-1630) there was recurring and relatively frequent fire.

Fire activity increased across most of the study sites circa 1820 to 1830, likely associated with rapidly changing human influences. In 1836, the Washington Treaty of 1836 forced Odawa/Ojibwe/Potawatomi people to cede their lands in the northwestern half of the LP and in 1837 Michigan became a state. Soon after the removal of these Indigenous people, a period of early lumbering in the region began, increasing through the early 1860s when more permanent colonization by Euro-Americans occurred. Lake County, which lies in the center of our study region, recorded the first permanent Euro-American residents in 1863. By 1870, the European descendant population of Lake County was 548 and this population continued to expand over the next two decades along with the logging industry (Powers and Cutler 1912). During the period of increased forest cutting and mechanization, fire frequency also increased. At the regional scale (ALL), fire activity peaked circa 1860, with fire more frequent than at any other time in the record. Based on comparable studies throughout the eastern U.S., it is relatively common for fire frequency to be highest during the intensive and rapidly changing times in Euro-American activity (logging, railroad expansion, agricultural land clearing, rapid increases in population).

Changing forest and fire conditions

The last two centuries have seen a major disruption in the forest environment on the MNF (USDA 1941), but also more broadly across the continent. Major disrupting activities include the removal of Indigenous people, clearing and burning of forests, tree plantation establishment and/or afforestation to closed canopy conditions, and fire suppression. One consequence has been that in many locations major vegetation type conversions have occurred (Elliott 1953). On the MNF, many locations can be found where red pine stumps exist, but where no modern-day red pine occur. Further, many red pine plantations have gone undisturbed by fire or unmanaged providing even-aged and dense, closed-canopy forest structures that were likely less common in historical times with recurring fires. The historical presence of red pine at sites WFL and SHL agree with Michigan's historical vegetation reconstructions from General Land Office Surveys from 1816 and 1855 (Comer et al. 1995). However, vegetation reconstructions from the General Land Office Surveys are in sharp contrast to our remnant red pine trees found at WUH and OLG. At WUH, General Land Office Survey vegetation reconstructions are for white pine-mixed hardwood forests and at OLG, reconstructions are for beech-sugar maple-hemlock forest. Depending on the timing of the surveys, vegetation conditions may have been already highly altered from previous times as evidenced by the fire scar history records.

Based on the recurrence of historical fires and the variability in fire through time, we surmise that these red pine forests were likely rarely closed canopy and instead had variable size, age, and canopy structures. Periods of frequent fire followed by a longer period without fire provides opportunities for red pine cohorts to establish and reach sizes allowing it to survive when relatively frequent burning resumes (Stambaugh et al. 2018, 2019). This process may be evidenced at site WUH where, following frequent burning up to 1628, a 70-year fire free period coincides with establishment of a new cohort of trees. It is likely that the majority of the historical trees (the forest cut in the late-1800s) at WUH resulted from this 1600s fire-free period. It is important to note that these trees were also likely able to persist to mature ages and sizes without conversion to more mesic species due to the resumption of fires through the 1700s and 1800s.

In conclusion, red pine remnant wood shows excellent potential for the preservation of important historical fire regime details across its range. Red pine remnant wood persisting since the late-1400s at SHL site, though unique, is not unprecedented (Mann et al. 1994, Muzika et al. 2015; Kipfmueller et al. 2021; Stambaugh et al. 2021). Recently, targeted searching for extremely old wood in Pennsylvania resulted in the development of a tree-ring record extending into the 1300s (Marschall et al. 2022). Based on this finding and our field experience of searching and finding remnant wood in this region, it is likely that many more potential study locations exist which could extend further back in time, expand the spatial characterization of eastern North American fire regimes, and thereby improve understanding of historical forest stand dynamics (e.g., tree regeneration, forest density) and fire regimes (e.g., historical fire sizes, landscape delineation of firesheds) including how they may have changed with cultural and climate conditions.

The data presented here provide important physical evidence of site-level fire regime changes since the sixteenth century in an area of the Tension Zone. Long-term changes in fire frequency appear to have corresponded with broad changes in human cultures, populations, and land use particularly since EuroAmerican colonization and increased industrialization. Fire scars and burning associated with time periods of Indigenous peoples warrant further attention and may provide improved understanding of historical land and fire uses. Further, increased knowledge of regional fire regime dynamics has important applications to future fire management including both wildland fire mitigation and prescribed fire management.

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Authors' contributions

MCS: original study design, data collection, statistical analyses, and manuscript preparation and editing. JMM: data collection and curation, laboratory analysis, manuscript editing. ERA: laboratory analysis, manuscript preparation, and editing. RPG: original study design, data collection and curation, and laboratory analysis. DCD: original study design, data collection, and manuscript editing.

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Availability of data and materials

The datasets used or analyzed during the current study will be made available upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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