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Climate forcing of regional fire years in the upper Great Lakes Region, USA

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ABSTRACT

Background. Drivers of fire regimes vary among spatial scales, and fire history reconstructions are often limited to stand scales, making it difficult to partition effects of regional climate forcing versus individual site histories. **Aims.** To evaluate regional-scale historical fire regimes over 350 years, we analysed an extensive fire-scar network, spanning 240 km across the upper Great Lakes Region in North America. **Methods.** We estimated fire frequency, identified regionally widespread fire years (based on the fraction of fire-scarred tree samples, fire extent index (FEI), and synchronicity of fire years), and evaluated fire seasonality and climate–fire relationships. **Key results.** Historically, fire frequency and seasonality were variable within and among Great Lakes' ecoregions. Climate forcing at regional scales resulted in synchronised fires, primarily during the late growing season, which were ubiquitous across the upper Great Lakes Region. Regionally significant fire years included 1689, 1752, 1754, 1791, and 1891. **Conclusions.** We found significant climate forcing of region-wide fire regimes in the upper Great Lakes Region. **Implications.** Historically, reoccurring fires in the upper Great Lakes Region were instrumental for shaping and maintaining forest resilience. The climate conditions that helped promote widespread fire years historically may be consistent with anticipated climate–fire interactions due to climate change.

Keywords: climate–fire interactions, dendroecology, ecoregions, fire history, Lake Superior, Michigan, natural disturbance regimes, Pinus resinosa Ait., Upper Peninsula.

Introduction

Ecological resilience is a central objective in forest management, as increasing climate variability and altered disturbance regimes affect forests in novel ways (Churchill *et al.* 2013). Fire regimes are generally characterised by variability in intensity, frequency, extent, and seasonality of multiple fires over space and time (McLauchlan *et al.* 2020). Changes in fire regimes can serve as catalysts of ecological change (Turner *et al.* 2003; North and Keeton 2008) as they impact regeneration and growing conditions in post-fire environments. Key processes in fire regimes include critical thresholds of climate, natural and human-induced ignition frequencies, land cover relationships to fire, and human–land use changes (Gillson *et al.* 2019). Understanding and predicting changes in landscapes historically driven by fire requires information about factors that govern fire regimes over a range of temporal and spatial scales. These include regional scales dominated by climatic controls (i.e. top-down exogenous drivers) and more local scales at which topography, vegetation heterogeneity, and human management operate (i.e. bottom-up endogenous drivers; Heyerdahl *et al.* 2001; Gillson *et al.* 2019).

To identify drivers, fire regimes must be examined at the same spatial scales at which they operate (Urban *et al.* 1987; Levin 1992; Heyerdahl *et al.* 2001). Although drivers of fire regimes can be global, such as climate change, responses to drivers vary considerably at local scales (Sommerfeld *et al.* 2018). Scale of analysis profoundly affects inferences on drivers most critical for fire activity. Patterns of fire occurring synchronously across broad spatial scales, for example, can capture broad-scale drivers, whereas asynchrony reflects local influences (Heyerdahl *et al.* 2001; Falk *et al.* 2011; Yocom Kent *et al.* 2017). A 'super-fire-regime' describes characteristics of fire within a biome, integrating all possible variations in climate, fuel properties, and human influences (Whitlock *et al.* 2010). Biomes form and persist over centuries to millennia in response to long-term climate changes, and reconstructing 'super-fire-regimes' can aid in anticipating responses to future variability (Whitlock *et al.* 2010).

Historical context can help to interpret past and potential climate change influences on disturbance processes but is reliant on robust historical baselines (Meunier 2022). Fire–climate associations for modern fires may by insufficient for understanding drivers for projected fire regimes. Human-induced disequilibrium (e.g. fire exclusion via landscape fragmentation, grazing, and fire suppression) has weakened relationships among fire, vegetation, and climate (Marlon *et al.* 2012; Higuera *et al.* 2015; Meunier 2022). Comparisons of climate variables (i.e. temperature, precipitation, moisture deficit, and evapotranspiration) between historical (fire scar) and modern (North America Fire Atlas data) records, for example, find larger climate–space discrepancies in the northern forests of the upper Great Lakes Region than in any other North American ecoregion (Margolis *et al.* 2022). Similarly, contemporary fires in the upper Great Lakes Region have occurred almost entirely in spring (Cardille and Ventura 2001). However, spring is projected to become wetter, whereas late growing seasons will be more variable and with frequent drought periods (Kling *et al.* 2003). Historical data in the upper Great Lakes Region suggest that fires occurred across all seasons (Guyette *et al.* 2016; Sutheimer *et al.* 2021).

Fire regimes are often climate-limited (i.e. weather and atmospheric conditions are seldom sufficiently dry for combustion to occur), fuel-limited (i.e. frequent fire consumes fuels or aridity limits fuel abundance), or occasionally both (Agee 1996; Krawchuk and Moritz 2011; Hessburg *et al.* 2019). In many areas, forest types, and associated fire regimes, are generally predictable based on elevational gradients of precipitation and temperature. In the upper Great Lakes Region, diverse forest systems and strong spatial heterogeneity exist irrespective of large elevational gradients. This diversity is a result of the Great Lakes modulating local and regional climate across the region, coupled with physiographic heterogeneity created during postglacial erosion, and variability in soil formation relative to glacial deposit type (Albert 1995; Zhang *et al.* 2000). Evaluating disturbance regime drivers across such heterogeneous landscapes is intrinsically difficult (Reuter *et al.* 2010). However, the integration of fire histories across forests of diverse types in close spatial proximity can help to reveal interactions among local- and regional-scale patterns and processes that control fire regimes (Schulte and Mladenoff 2005; Falk *et al.* 2011; Swetnam *et al.* 2016).

Fire scars, which are fine-resolution proxy records of fires via cambial injuries on growth rings of individual trees, provide accurate stand- or site-level records of low- to moderate-severity fires (Swetnam *et al.* 1999; Falk *et al.* 2011). When compiling local records into regional fire-scar networks, there are new opportunities to understand regulation of ecosystem properties (Falk *et al.* 2011; Drobyshev *et al.* 2016; Margolis *et al.* 2022). In the upper Great Lakes Region of the US there has been a wealth of recent fire scar-based fire histories (Margolis *et al.* 2022) and burgeoning understanding of the importance of recurring, low-severity fires across various ecosystems (Drobyshev *et al.* 2008*a*; Muzika *et al.* 2015; Meunier *et al.* 2019). Additionally, the upper Great Lakes Region is a boreal–temperate forest transition zone (where many species are at the edges of their ranges; Brandt 2009) and a region expected to be disproportionately affected by climate change (Duveneck *et al.* 2014). However, fire histories have largely been local-to-landscape scale (1–10s km^2) with little attempt to examine data regionally, thus limiting their utility for understanding broader-scale climate–fire interactions (Drobyshev *et al.* 2012, 2015).

We examine here a wealth of recent fire histories developed on diverse landscapes across the upper Great Lakes Region to better understand regional drivers of fire regimes, focusing on frequency, extent, and seasonality of multiple fires over space and time generally – and widespread fire years specifically – in a region projected to be markedly affected by climate change (Kling *et al.* 2003; Pryor 2013). We analysed an extensive fire-scar data network representing diverse forest types to: (1) evaluate similarities and differences of fire frequencies among ecoregions; (2) detect regionally widespread fire years among study areas; and (3) evaluate climate forcing and seasonality of widespread fire years.

Methods

Study area

We conducted this study across the Upper Peninsula of Michigan (UP; latitudinal extent of 45.25° to 46.75° and longitudinal extent of −89.75° to −84.25°) within the upper Great Lakes Region of North America (Fig. 1; Kling *et al.* 2003). The UP is strongly influenced by the Great Lakes, which contain 21% of total global freshwater volume (Jabbari *et al.* 2021). The UP includes highly diverse physiography and vegetation (Fig. 1, Table 1) due to the Wisconsin glaciation, which ended approximately 9500 years ago, with postglacial erosion and soil formation on glacial deposits contributing to modern physiology (Peterson 1986; Albert 1995). Climate across the UP is continental and spatially highly variable, with increased lake-effect precipitation and moderation of temperature extremes nearest the Great Lakes (Table 1). Average number

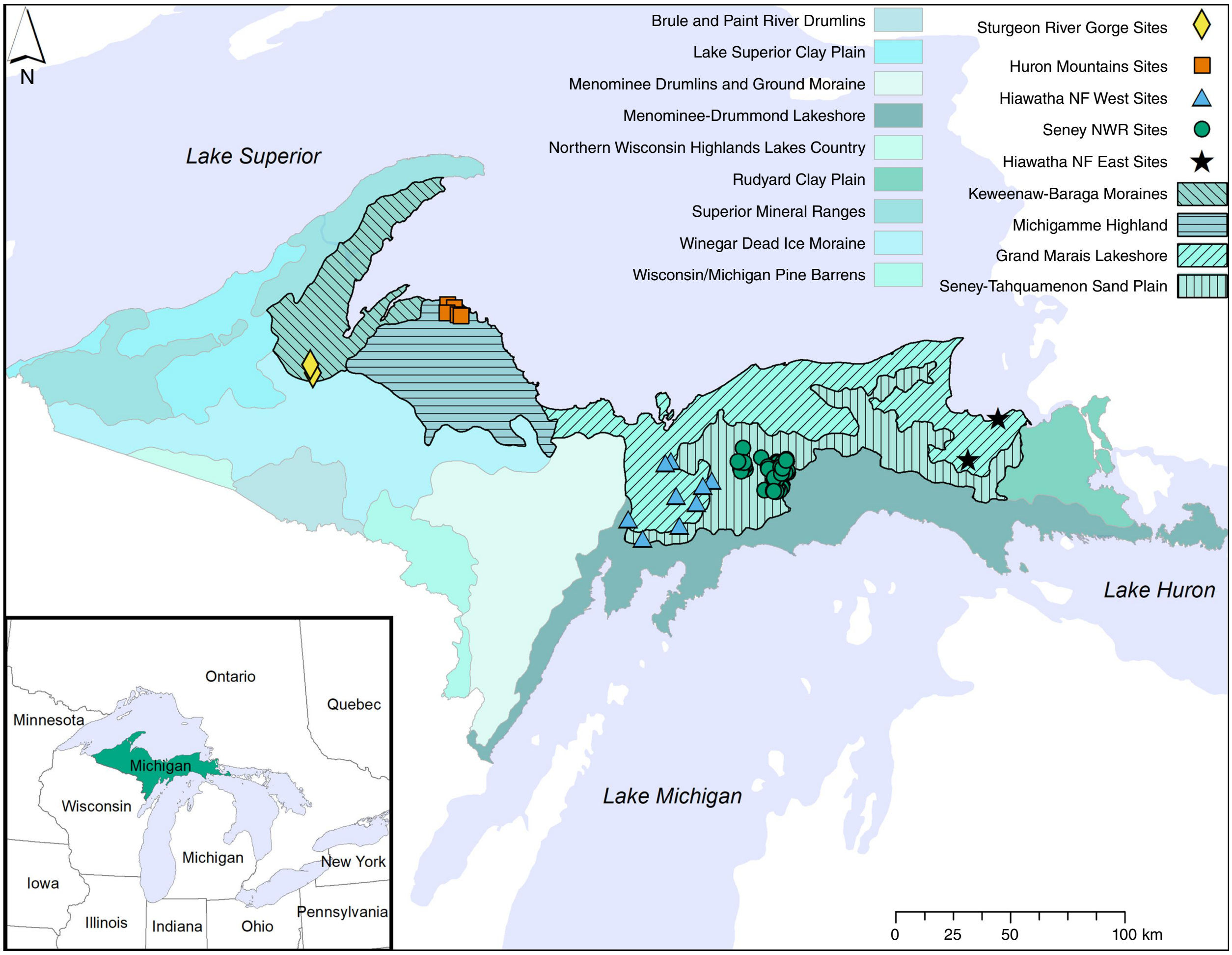

Fig. 1. Location of study areas spanning multiple ecoregions of the Upper Peninsula of Michigan, USA, with inset of upper Great Lakes region. Yellow diamonds are sites ($n = 2$) with crossdated fire history for Sturgeon River Gorge study area, orange squares are sites ($n = 5$) with crossdated fire history for Huron Mountains study area, blue triangles are sites ($n = 9$) with crossdated fire history for Hiawatha National Forest West study area, green circles are sites ($n = 50$) with crossdated fire history for Seney National Wildlife Refuge study area, and black stars are sites ($n = 2$) with crossdated fire history for Hiawatha National Forest East study area.

of growing season days/year ranges from 75 to 230, average rainfall from 76 to 91 cm, and average snowfall from 254 to 500 cm (Table 1; Albert 1995).

Our study sites include northern hardwood forests, which are abundant in the western UP and predominant in the Huron Mountains and Sturgeon River Gorge study areas (Table 1, Fig. 2*a*, *b*). Mixed-pine forests with *Pinus resinosa* Ait. (red pine), *Pinus strobus* L. (white pine) and *Pinus banksiana* Lamb. (jack pine) are abundant in the eastern UP and predominant in the Hiawatha National Forest East and Hiawatha National Forest West study areas (Table 1, Fig. 2*c*, *d*). Throughout the central and eastern portions of the UP, peatlands are extensive in the poorly drained lacustrine deposits, with sandy well-drained ridges, islands, and dunes supporting mixed-pine forests (Table 1, Fig. 2*e*, *f*). Seney National Wildlife Refuge (hereafter Seney), Hiawatha National Forest West, and Hiawatha National Forest East all contain peatland complexes intermixed with mixed-pine forests.

Data collection and preparation

We analysed previously published fire-scar records from the Huron Mountains (Muzika *et al.* 2015) and Seney National Wildlife Refuge (Drobyshev *et al.* 2008*a*, 2008*b*, 2012) in addition to fire-scar records we collected in the Sturgeon River Gorge, Hiawatha National Forest East, and Hiawatha National Forest West (Fig. 1). For these new study areas, we used the same collection methods as for the published records so datasets were compatible and could be combined without bias. We collected cross sections with chainsaws predominantly from remnant red pine stumps (i.e. trees harvested ~1850–1920), and occasionally white pine or jack pine stumps. We sampled fire-scarred stumps with >50 growth rings. We non-destructively sampled select living trees and snags with evidence of fire scars by removing partial sections (Arno and Sneck 1977).

Table 1. Characteristics of ecoregions sampled across Upper Peninsula of Michigan.

Ecoregion	Study area	Forest type	Physiography	Climate
Keweenaw-Baraga Moraines	Sturgeon River Gorge	Northern hardwood forest {*Acer saccharum* Marshall (sugar maple), *Acer rubrum* L. (red maple), *Betula alleghaniensis* Britton (yellow birch), *Populus grandidentata* Michx. (bigtooth aspen), *Populus tremuloides* Michx. (quaking aspen)}; *Pinus resinosa* Ait. (red pine), *Pinus strobus* L. (white pine), *Tsuga canadensis* (L.) Carrière (eastern hemlock)) abundant historically on ridges but declining	Broad ridges with well-drained sandy soils 150–500 ft high; gullies on steep slopes of moraines; poorly drained sandy lake plain near Lake Superior but not extensive	Growing season: Relatively cool, 110–130 days near Lake Superior Precipitation: Average rainfall 76–81 cm; average snowfall 356–508 cm
Michigamme Highlands	Huron Mountains	Northern hardwood forest with *Quercus rubra* L. (red oak), red pine, and white pine occurring on excessively drained soils and exposed bedrock, localised *Pinus banksiana* Lamb. (jack pine) barrens	Steep sandy till deposits and large outwash plains; Exposed ridges of granite or sandstone bedrock 500–800 ft high occur in Huron Mountains	Growing season: 75–150 days, longest along Lake Superior Precipitation: Average rainfall 81–91 cm; average snowfall 330 cm along Lake Superior to 508 cm inland
Grand Marais Lakeshore	Hiawatha National Forest East Hiawatha National Forest West (six sites)	Red pine and jack pine ridges and dunes along Lake Superior; Interior uplands with red pine and jack pine with scattered northern hardwoods and eastern hemlock-white pine forests; Peatlands with *Picea mariana* (Mill.) Britton, Sterns & Poggenb. (black spruce), *Thuja occidentalis* L. (arborvitae), *Larix laricina* (Du Roi) K. Koch (tamarack) and sandy ridges with white and red pine within peatlands	Well-drained sandy ridges and dunes along Lake Superior; Extensive peatlands in poorly drained lacustrine deposits; bogs with deep peat in western kettles	Growing season: 100 days inland to 140 days along Lake Superior Precipitation: Average rainfall 81–86 cm; average snowfall 254 cm to 457 cm along Lake Superior
Seney-Tahquamenon Sand Plain	Seney National Wildlife Refuge Hiawatha National Forest West (three sites)	Mixed conifer swamp, muskeg/bog, and patterned peatlands dominated by tamarack and black spruce on poorly drained sand lake plain; Mixed pine forests (red pine, jack pine, and white pine) on sandy ridges and dunes	Poorly drained sand lake plain with large expanses of wetlands; Well drained glacial outwash and lacustrine deposits support transverse dune complexes	Growing season: <100 days in central frost pocket of the ecoregion to 230 days along edges Precipitation: Average rainfall 81–86 cm; average snowfall 203–305 cm nearest Lake Superior

We modified the characteristics from Albert (1995). Climate data used by Albert (1995) was collected from 125 weather stations in Michigan from 1950 to 1981.

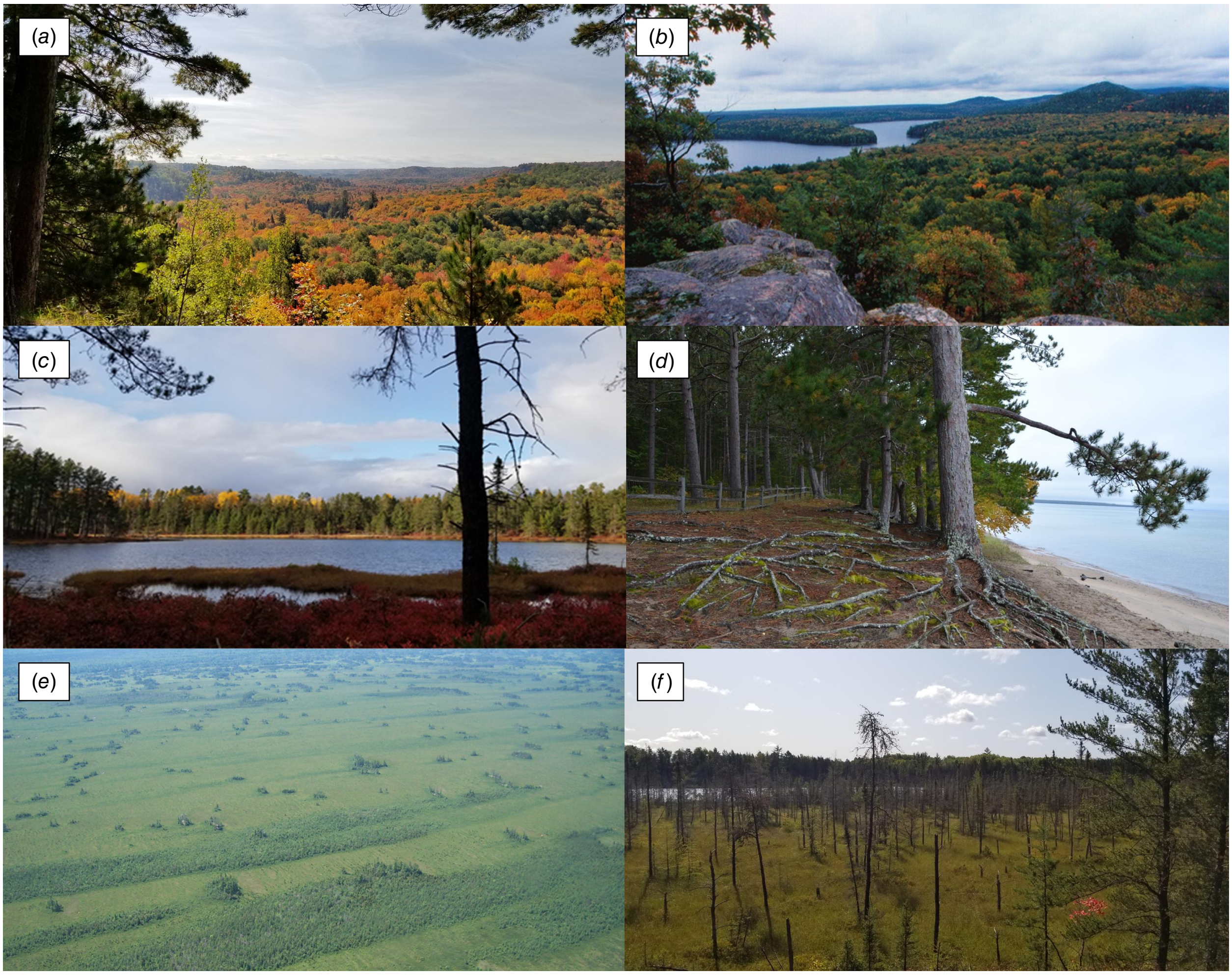

Fig. 2. Study areas across Upper Peninsula of Michigan, USA, depicting ecoregion vegetation types and landforms. (*a*) Sturgeon River Gorge in Keweenaw-Baraga Moraines ecoregion, northern hardwoods within gorge with mixed-pine forest atop ridges. Image by C.M. Sutheimer. (*b*) Pine Lake surrounded by Huron Mountains with red oak and red pine on exposed bedrock outcrops and northern hardwood forest typical of Michigamme Highland ecoregion. Image by D. Richler. (*c*) Mixed-pine forest with scattered hardwoods on two sandy ridges extending alongside a shallow lake in Hiawatha National Forest West characteristic of interior Grand Marais Lakeshore ecoregion. Image by C.M. Sutheimer. (*d*) Red pines on sandy dune along Lake Superior in Hiawatha National Forest East typical of shorelines in the Grand Marais Lakeshore ecoregion. Image by C.M. Sutheimer. (e) Strangmoor Bog, a patterned fen in Seney National Wildlife Refuge, characteristic of extensive peatlands with mixed-pine ridges and islands of the Seney-Tahquamenon Sand Plain ecoregion. Image by E. Brosnan. (*f*) Transverse dune complex adjacent to Upper Lost Lake in Hiawatha National Forest West with mixed-pine ridges and peatlands, characteristic of the Seney-Tahquamenon Sand Plain ecoregion. Image by C.M. Sutheimer.

We dried and surfaced samples with increasingly finer-grit sand paper to reveal cellular structure of annual rings, and digitally scanned each sample to measure annual ring widths (Speer 2010). In the laboratory, we used a microscope to crossdate samples using standard dendrochronological techniques, assigned exact calendar dates to all fire scars, and determined fire season when possible (Grissino Mayer and Swetnam 2000; Speer 2010) based on fire-scar position within annual rings. We correlated ring-width patterns to other fire-scar records for the region (Wendland and Swain Henselman 2002; Stambaugh and Guyette 2013; Stambaugh *et al.* 2013) using Cybis CDendro version 9.3.1 (Larsson 2018).

Data analysis: fire frequency

We analysed fire scar data using Fire History Analysis and Exploration System (FHAES version 2.0.2) and the burnr package in R version 4.0.2 (Brewer *et al.* 2015; Malevich *et al.* 2018). We used percentage-scarred filters to identify fire years of increasing extent within each study area (Swetnam and Baisan 2003), assuming that higher percentage

Table 2. Fire history in study areas across the Upper Peninsula of Michigan.

Study area	No. sites	No. samples	Area sampled (km^2)	No. years w/fire	MFRI[A]	MFRI 10%[B]	MFRI 25%[C]	Years[D]
Sturgeon River Gorge	2	24	2	30	17	17	27	1659–2020
Huron Mountains[E]	5	77	15	46	14	18	23	1510–2005
Hiawatha NF West	9	114	656	156	5	10	29	1574–2019
Seney NWR[F]	50	255	277	203	3	21	45	1596–2006
Hiawatha NF East	2	77	64	93	7	9	17	1548–2018

Fire history information from year of first fire event to year each study area was sampled, organised by longitude (west to east).
[A]MFRI is mean fire return interval (years) for fire years when ≥2 samples scarred.
[B]MFRI 10% is mean fire return interval (years) for fire years when ≥2 samples and 10% of samples were scarred.
[C]MFRI 25% is mean fire return interval (years) for fire years when ≥2 samples and 25% of samples were scarred.
[D]Composite range of years for individual site fire-scar records within study area.
[E]Data from Muzika *et al.* (2015).
[F]Data from Drobyshev *et al.* (2008*a*, 2008*b*, 2012).

of fire-scarred samples for a fire year corresponded to more widespread fires (Farris *et al.* 2010). We included fire years that scarred at least two samples within a study area to capture ecologically meaningful but smaller fires (e.g. affecting more than a single lightning-struck tree; Heyerdahl *et al.* 2008), moderately sized fire years where fires scarred ≥10% of samples within a study area, and large fire years where fires scarred ≥25% (Farris *et al.* 2013). Spatially distributed fire-scarred samples help to estimate area burned during single fire years and to identify more extensive fires that burned large portions of a given study area (Falk *et al.* 2007; Farris *et al.* 2010, 2013). We compiled fire years for each filtering method within each of our study areas (multiple sampling sites in each of the five study areas; Table 2) to estimate mean fire return intervals (Falk *et al.* 2007). We assessed variability and distribution of mean fire return intervals for each filtered set of fire years at each study area to characterise changes in fire frequencies within and among study areas from 1650 to 2000.

Data analysis: widespread fire years

Delineating large, widespread fire years is difficult and results can differ among methods, so we identified widespread fire years across the region through (1) peaks in percentage of fire-scarred tree samples (Farris *et al.* 2010, 2013), (2) fire extent index (FEI, Guyette *et al.* 2016), and (3) synchrony of fire years within study areas and among study areas (Arizpe *et al.* 2020). We restricted the beginning year of our analyses to when there was an overlap in fire-scar records for all study areas. We used 1650 as the beginning year for analyses because fires were not detected in the Sturgeon River Gorge prior to 1650 (Fig. 3). We compiled all fire-scarred samples across the region and identified the years when the most samples were scarred. FEI estimates relative spatial extent of individual years; larger FEI values correspond to more widespread fires. We calculated FEI(x) following Guyette *et al.* (2016) as the product of the number of study areas recording fire in year $x(n)$ and the percentage of all trees recording fire scars in year $x(s)$.

$$\mathrm{FEI}(x) = ns$$

We defined widespread fire years as years that were synchronous within (≥25% of samples were fire-scarred) and among study areas (≥two study areas). We defined regionally widespread fire years as the most widespread fire years that also had the largest FEI values. We did not include percentage of fire-scarred samples to identify regionally widespread fire years because it was already incorporated through FEI.

Although fire scars cannot capture the spatial variability in fire severity and actual area burned during individual fires, fire-scar synchrony among spatially distributed study areas provides a relative index of total area burned (Morrison and Swanson 1990; Swetnam 1993; Taylor and Skinner 1998). Evidence shows that widespread fire years correspond to region-wide burning (Guyette *et al.* 2006; Farris *et al.* 2010; Drobyshev *et al.* 2015; Swetnam *et al.* 2016). We did not weight detected percentage of fire-scarred trees by study area size or number of samples in a study area because temporal and spatial variability of fire-scar records are influenced by different local-scale drivers of fire regimes, specifically of fire frequency and extent of multiple fires, in individual study areas (Falk *et al.* 2007; Dewar *et al.* 2021)

Data analysis: climate–fire relationships

We summarised intra-annual positions of fire scars among study areas and among regionally widespread fire years to infer the seasonality of past fires (Swetnam and Baisan 1996). Fires that scar trees during earlywood cell formation occur in the early growing season (i.e. late May, June, and July), fires that scar trees during latewood cell formation occur in the late growing season (i.e. August and early September), and fires that scar trees between two fully

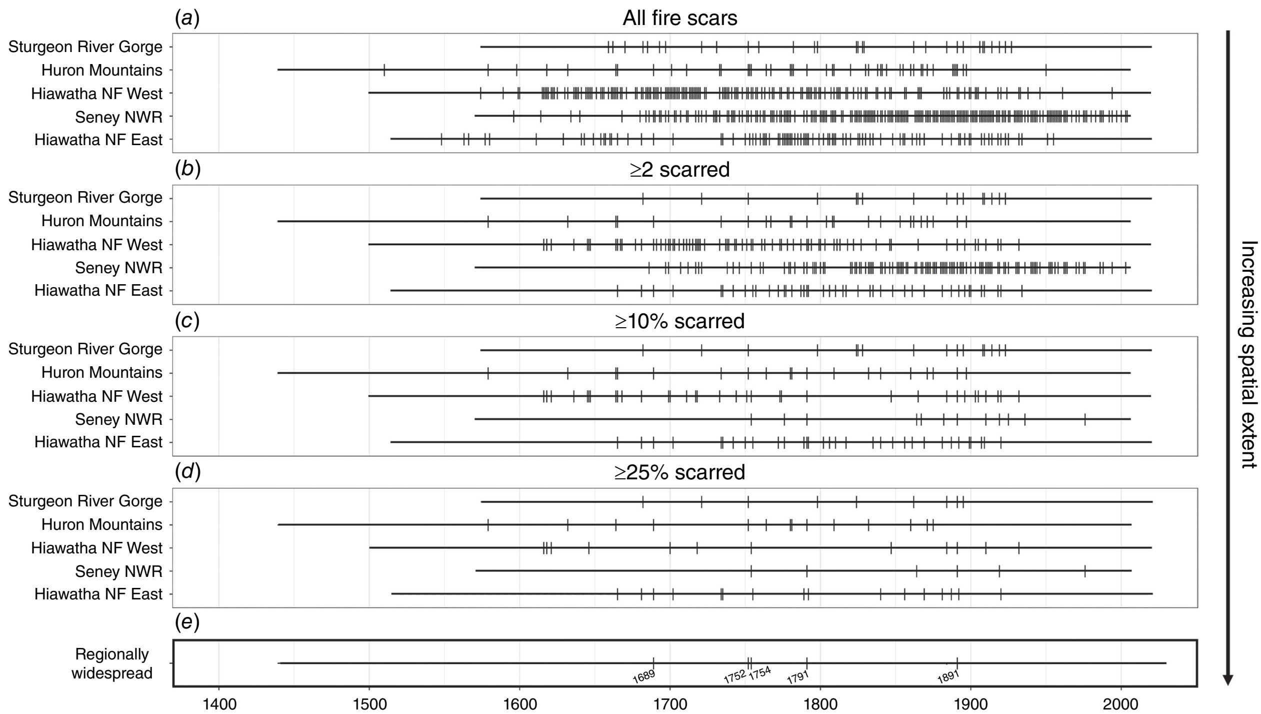

Fig. 3. Composite fire-scar records of five study areas in Upper Peninsula of Michigan, USA, with study areas arranged from west to east and blocked top to bottom by increasing spatial extent of composited fire years. Horizontal lines represent composited fire-scar records for each study area, with fire years (vertical ticks) filtered by relative spatial extent. (*a*) All fire scars detected. (*b*) Fire years when ≥2 samples were scarred and correspond to less extensive fire years. (*c*) Fire years when ≥2 samples and 10% of samples were scarred and correspond to moderate fire years. (*d*) Compiled fire years when ≥2 samples and 25% of samples were scarred and correspond to large fire years. (*e*) Regionally widespread fire years that had the largest FEI values and fire years that were synchronous within (≥25% of samples were fire-scarred) and among study areas (≥two study areas).

formed rings occur during cessation of cellular growth when the tree is in dormancy (i.e. late September through May; Baisan and Swetnam 1990; Speer 2010). We used predominance of fire-scar positions and variability in fire scar seasonality to identify intra-annual patterns of climate forcing of fires at broad spatial scales.

We used growing season (June–August) Palmer Modified Drought Index (PMDI) to assess relationships between historical climate and widespread fire years. PMDI integrates drought reconstructions from tree-ring networks, independent from fire-scar networks, with instrumental data, to construct a grid of points at a spatial resolution of 2.5° throughout North America (Cook *et al.* 2010). Palmer Drought indices are influenced by precipitation, air temperature, and soil moisture, with negative values representing dry periods and positive values representing wet periods (Palmer 1965). We obtained PMDI values from the Living Blended Drought Atlas (Cook *et al.* 2010). We averaged growing-season PMDI values from 17 2.5° resolution grid cells within the 42 000 km^2 of the UP to reconstruct annual growing season (June–August) drought for each year within the analysis period, 1650–2000.

We superimposed widespread fire years from our fire-scar network over regional PMDI to compare the occurrence of fire years with broad-scale patterns in drought over time. We evaluated climate–fire relationships using superposed epoch analysis (SEA; Swetnam and Betancourt 1990; Grissino Mayer and Swetnam 2000; Swetnam and Baisan 2003) in the R *burnr* package version 4.0.2 (Malevich *et al.* 2018) to compare regional PMDI across the UP during, for 3 years before, and for 3 years after fire years. We detected widespread fire years using largest percent of trees scarred, largest FEI, and greatest synchrony of years among the five study areas across the UP. We used 1000 non-parametric simulations for bootstrapped confidence intervals to assess the statistical significance (P-value < 0.05) of departure from mean annual growing season (June–August) PMDI for widespread fire years and ± 2 years of those fire years (Grissino Mayer and Swetnam 2000; Malevich *et al.* 2018).

Results

Fire frequency

We analysed fire frequency, calculating mean fire return intervals for each of our filters (≥ 2, $\geq 10\%$, and $\geq 25\%$ fire-scarred samples) from 1650 to 2000 because that period had the greatest temporal overlap among the five study areas (Fig. 3*b–d*). We detected that in total, 285 unique fire years and occurrences of fire years were variable among study areas, with fewest fire years (n = 30) detected in Sturgeon River Gorge and most fire years (n = 197) detected in Seney National Wildlife Refuge (Fig. 3*a*). Occurrences of fire years were also variable across time, with the most fire years (n = 47) detected from 1850 to 1900, and the fewest (n = 30) from 1950 to 2000 (Fig. 3*a*) when using 50-year intervals. Occurrences of fire years were also variable across time, with the most fire years detected (n = 47) from 1850 to 1900 and the fewest fire years detected (n = 30) from 1950 to 2000 (Fig. 3*a*) when using 50-year intervals. Across the five study areas, mean fire return intervals for fire years recorded on ≥2 samples within each study area ranged from 3 to 17 years, on ≥ 10% fire-scarred samples from 9 to 21 years, and on ≥25% fire-scarred samples from 17 to 45 years (Table 2). Fire years with more scarred samples within study areas generally had longer mean fire return intervals except in the Sturgeon River Gorge, where mean fire return interval was the same for fire years when ≥2 samples were scarred and for fire years when ≥10% of samples were scarred (Table 2). Seney National Wildlife Refuge (Seney) had both the shortest mean fire return interval when including less extensive fire years, and the longest mean fire return interval for larger fire years (25% filter; Table 2).

Less extensive fire years (≥2 fire-scarred samples) and moderate fire years (≥10% of samples) were more frequent in study areas with shorter mean fire return intervals in the central and eastern UP (Seney and both Hiawatha NF East and West) than in the western UP (Sturgeon River Gorge and Huron Mountains; Fig. 4). Overall, we detected fewer fire years in the western UP (Sturgeon River Gorge Wilderness and Huron Mountains; Fig. 3). However, the similar mean fire return intervals among differing spatial extents indicates most fire years detected in the western UP were moderate and large fire years (Table 2). The greatest range in fire return intervals for all study areas occurred for larger fire years (≥25% fire-scarred samples), with the longest overall fire return interval (93 years) in the Hiawatha NF West (Fig. 4). An apparent trend in the first half of the 19th century was that there were more frequent, less extensive fire years (≥2 fire-scarred samples) and an absence of larger fire years (≥25% fire-scarred samples) in the central UP (Hiawatha NF West and Seney study areas) and eastern UP (Hiawatha NF East). Fire frequency across the entire region decreased after 1900, with fewer fire years at all spatial extents and after 1950, fires were only detected in Seney (e.g. 1976; Fig. 3).

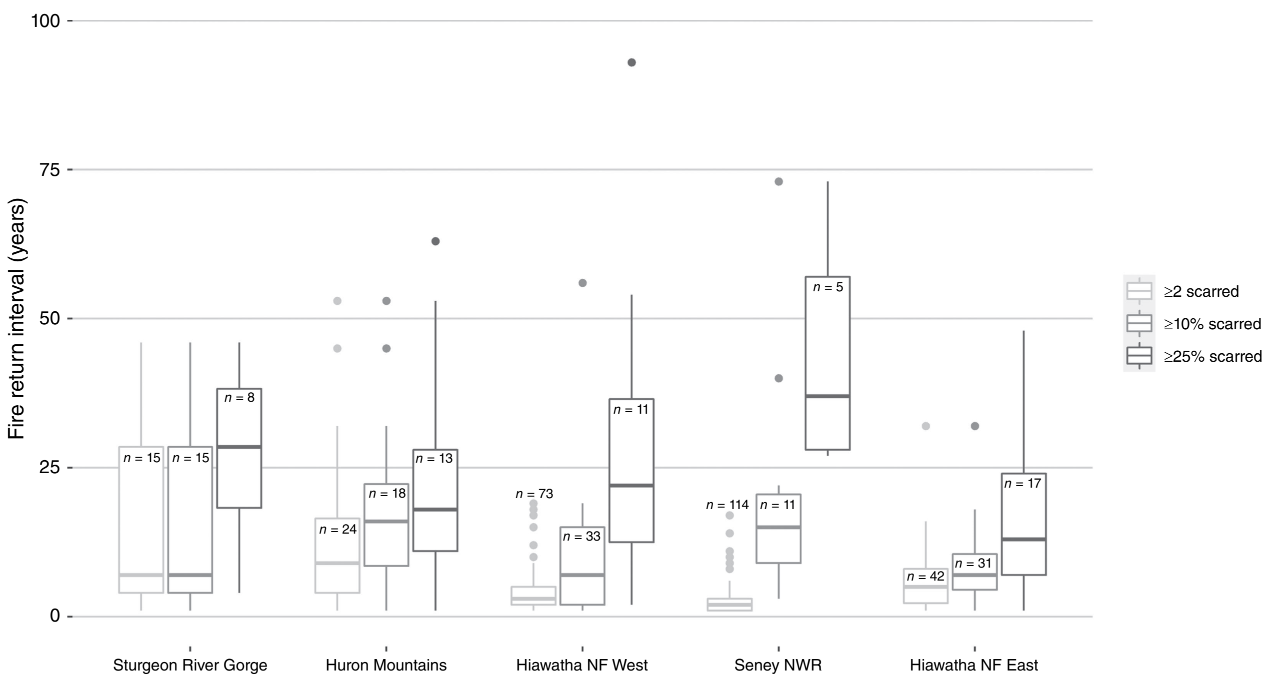

Fig. 4. The variability of fire return intervals (years) for small, moderate, and large fire years within each of five study areas across the Upper Peninsula of Michigan, USA. The horizontal lines within each boxplot represent median fire return interval. Each box bounds the second and third quartiles of fire return intervals of a particular size range. The whiskers represent the lowest and highest fire return intervals within 1.5 times the interquartile range, with outliers marked by filled circles. Number of fire return intervals (n) is labelled for each box. Light grey boxplots indicate fire years when ≥2 samples were scarred, medium grey indicates fire years when ≥2 samples and 10% of samples were scarred, and black indicates fire years when ≥2 samples and 25% of samples were scarred.

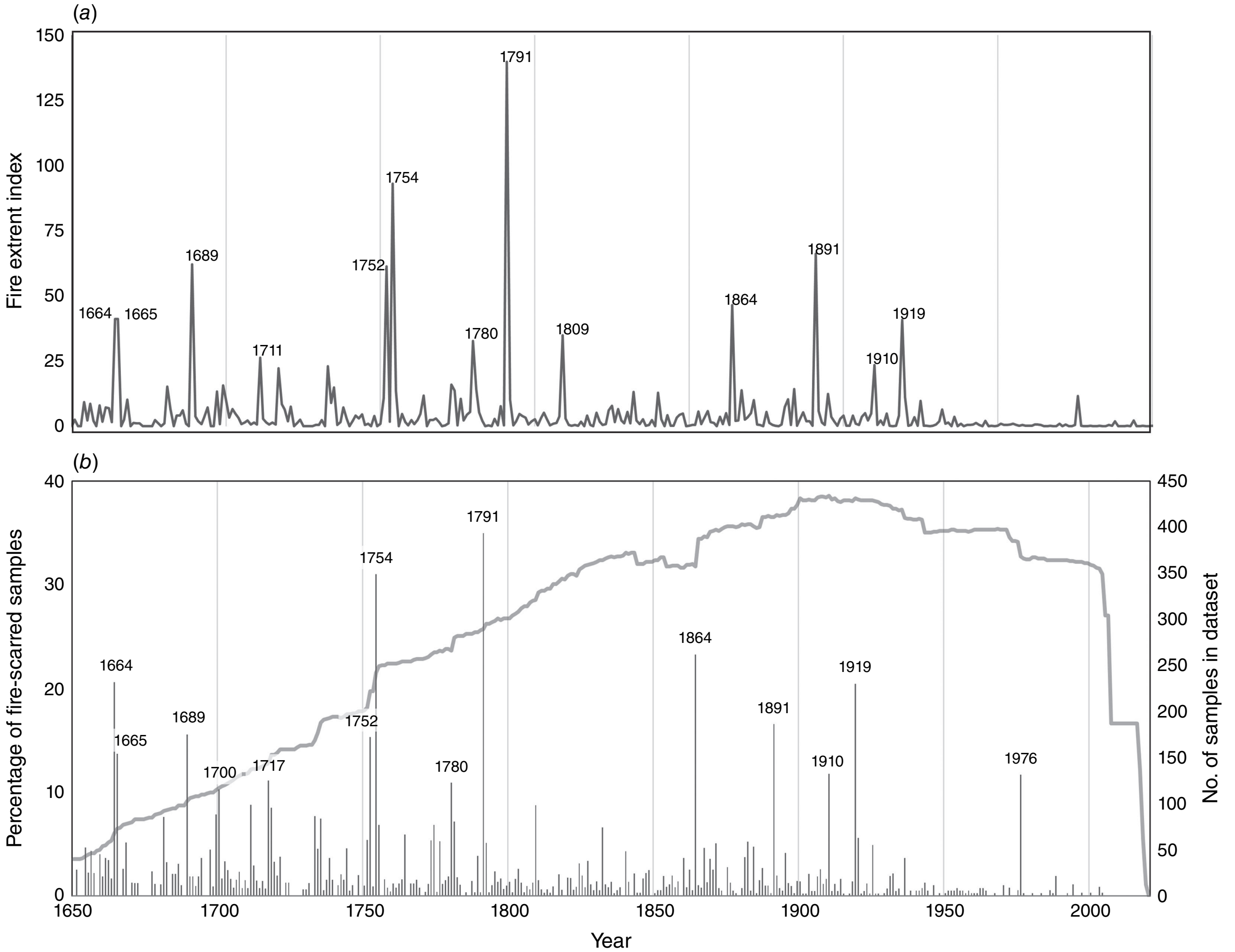

Fig. 5. Widespread fire years from 1650 to 2000. (*a*) Widespread fire years are indicated by largest values of fire extent index. Fire extent index for each year is the product of the number of study areas recording a fire in each year and the percentage of fire-scarred samples in each year. (*b*) Widespread fire years indicated by greatest percentage of fire-scarred samples, relative to all samples recording in that year. The left axis indicates the percentage of samples scarred by fire in each year and the right axis indicates sample depth (total number of samples in the dataset in each year) as a continuous line.

Widespread fire years

We detected 16 widespread fire years across the UP from 1650 to 2000 using total percentage-scarred samples, fire extent index, and synchrony within and among study areas. Each widespread fire year detected by percentage of scarring ($n = 14$) scarred more than 10% of all samples (Fig. 5*a*). There were eleven fire years with fire extent index values >20 (Fig. 5*b*). Widespread fire years were most frequent from 1750 to 1800 ($n = 4$) and least frequent from 1800 to 1850 ($n = 1$), 1900–1950 ($n = 1$), and 1950–2000 ($n = 1$). Mean fire return interval for widespread fire years ($n = 16$) was 21 years.

We identified 1689, 1752, 1754, 1791, and 1891 as regionally widespread fire years because fire years were synchronous both within (≥25% fire-scarred samples) and among study areas (at least two study areas), and these years also had the largest FEI values (Figs 3*d*, 5*a*, 6). Between 1664 and 1976, regionally widespread fire years occurred in the UP approximately every 24 years (Fig. 5*a*, *b*). 1791 and 1891 were the most extensive fire years, each with >18% of all samples scarred (Figs 3, 6). 1689 was extensive across the region, but lower percentages of samples contained fire scars (Fig. 6). 1752 was an extensive fire year and scarred high percentages of samples, especially in the western UP (57% of Sturgeon River Gorge and 39% of Huron Mountains samples; Fig. 2). 1754 was the least spatially extensive of the regionally widespread fire years but scarred high percentages of samples in the central UP (50% of Hiawatha NF West and 34% of Seney samples; Fig. 6).

Climate–fire relationships

Generally, fire seasonality varied among study areas, with variable percentages of fire scars occurring in dormant (0.9–47.6%), earlywood (0.8–31.0%), and latewood (0.0–40.2%) positions among study areas (Table 3). Within study

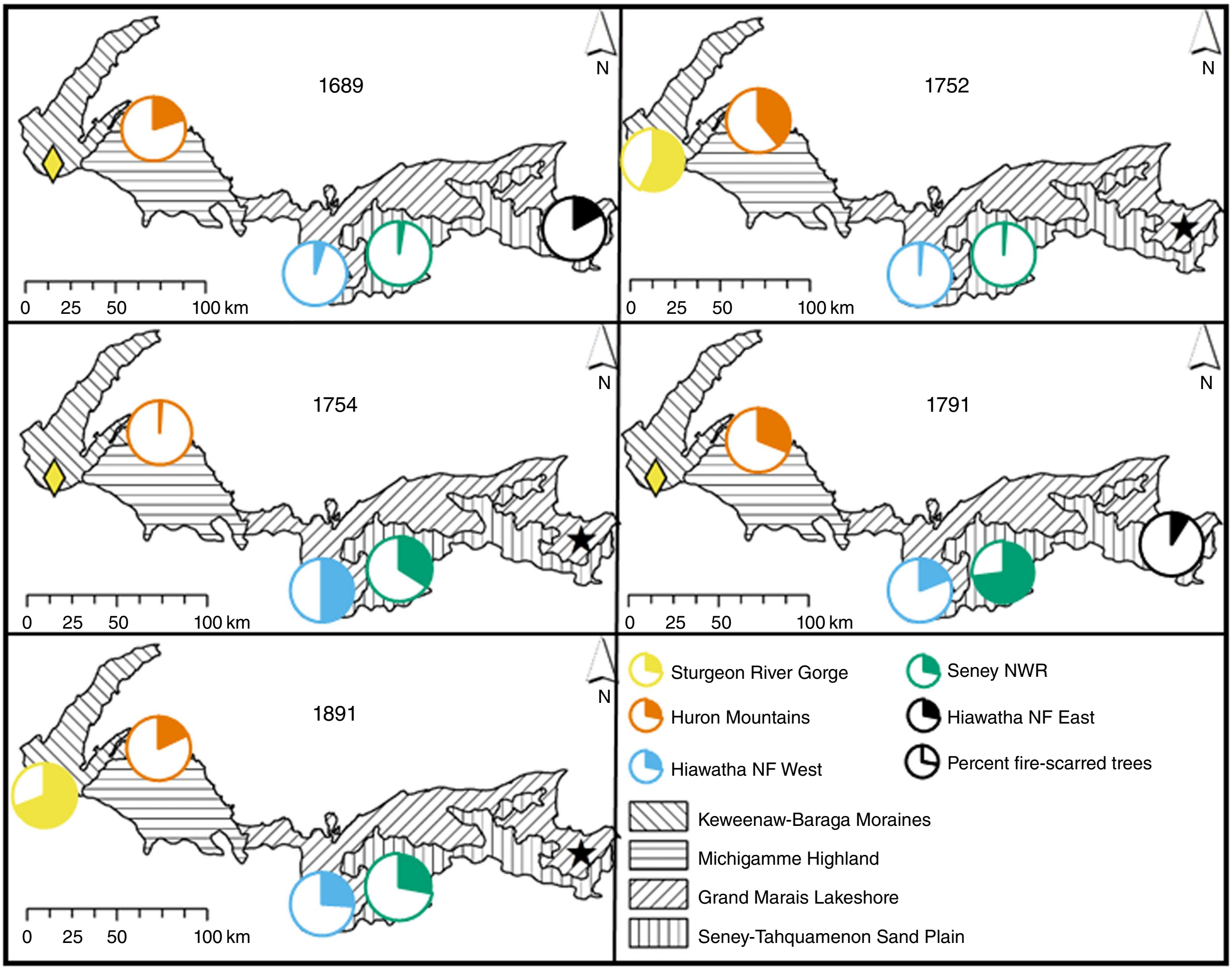

Fig. 6. Spatial extent of regionally widespread fire years across the Upper Peninsula of Michigan, USA. Each panel corresponds to a single year, and separate pie charts positioned at the centre of each study area indicate fire-scarred samples as a percentage of all samples recording in the associated year. A star or diamond indicates that study area did not record a particular fire year.

Table 3. Fire scar seasonality in study areas across the Upper Peninsula of Michigan.

Study area	Dormant (%)	Earlywood (%)	Latewood (%)	Unknown (%)
Sturgeon River Gorge	47.6	19.5	0.0	32.9
Huron Mountains[A]	10.7	31.0	40.2	18.0
Hiawatha NF West	15.7	10.2	28.9	45.3
Seney NWR[B]	0.9	16.1	35.7	47.3
Hiawatha NF East	37.0	0.8	12.1	50.2

Percentages were determined out of total number of fire scars at each study area: Sturgeon River Gorge ($n = 82$), Huron Mountains ($n = 261$), Hiawatha NF West ($n = 433$), Seney NWR ($n = 919$), and Hiawatha NF East ($n = 257$). Dormant fire scars occur between the latewood and earlywood ring margins and were assigned to the following earlywood year. Earlywood fire scars occur at any position (early, middle, or late) in the earlywood portion of the tree ring. Latewood fire scars occur at latewood positions in the tree ring. Unknown corresponds to fire scars for which ring position could not be determined.
[A]Data from Muzika *et al.* (2015).
[B]Data from Drobyshev *et al.* (2008*a*, 2008*b*, 2012).

areas, latewood fire scars were predominant in the Huron Mountains (40.2%), Hiawatha NF West (28.9%), and Seney (35.7%), indicating fire scars formed during late growing-season fires likely in August and early September. Dormant fire scars were predominant in Sturgeon River Gorge (47.6%) and Hiawatha National Forest East (37.0%; Table 3),

Table 4. Fire scar seasonality summarised by regionally widespread fire years for the upper Great Lakes Region.

Year	Dormant (%)	Earlywood (%)	Latewood (%)	Unknown (%)
1689	0.0	6.3	62.5	31.3
1752	11.8	64.7	0.0	23.5
1754	4.0	13.3	48.0	34.7
1791	0.0	5.0	74.3	20.8
1891	11.8	7.4	48.5	32.4

Percentages were determined out of total number of fire scars for each fire year across all samples: 1689 ($n = 16$), 1752 ($n = 34$), 1754 ($n = 75$), 1791 ($n = 101$), and 1891 ($n = 68$). Dormant fire scars occur between the latewood and earlywood ring margins and were assigned to the following earlywood year. Earlywood fire scars occur at any position (early, middle, or late) in the earlywood portion of the tree ring. Latewood fire scars occur at latewood positions in the tree ring. Unknown corresponds to fire scars for which ring position could not be determined.

indicating fires occurred after onset of dormancy (i.e. late autumn) or prior to new wood formation (i.e. early spring) of the next year. However, although seasonality varied among study areas, this was not the case for the majority of the regionally widespread fire years (1689, 1754, 1791, and 1891), where 48.0–74.3% of fire scars were in the latewood position for all years (i.e. late growing season in August or early September; Table 4).

We used superposed epoch analysis to detect significant departures in average Palmer Modified Drought Index (PMDI; Cook *et al.* 2010) before, during and after widespread fire years ($n = 16$) to investigate climate–fire relationships. Widespread fire years were associated with significant negative departures in average PMDI ($P < 0.05$), which indicated regional drought conditions during the growing season (June–August; Fig. 7*a*). No other departures in average PMDI before or after widespread fire years were significant, suggesting that regional seasonal drought was important for widespread fire years, but multi-year drought conditions were not (Fig. 7). All but three widespread fire years across the UP occurred during droughts (Fig. 7; Palmer 1965). Eight of the most widespread fire years occurred in years with moderate or severe regional droughts ($-2 \geq \text{PMDI} > -4$) and one year, 1910, occurred during an extreme regional drought ($\text{PMDI} < -4$; Fig. 7*a*; Palmer 1965).

Discussion

Linking regional and local fire histories to global processes, such as climate, can offer insights about future fire regimes (Turner *et al.* 1989). Despite high heterogeneity among ecoregions we studied, which ranged from dry, fire-prone outwash sand plains to highly dissected glacial moraines and large, persistently saturated peatlands (Table 1, Fig. 2), fires were historically frequent across all areas (MFRI = 3–45 years; Table 2). We observed strong similarities among fire regimes (e.g. Figs 3, 4), and widespread, climatically driven fire years were common over the past 350 years (Figs 5, 7). We identified the five most regionally widespread fire years in the UP: 1689, 1752, 1754, 1791, and 1891. These regionally widespread five fire years in addition to other widespread fire years that we detected (e.g. 1664, 1665, 1864, 1780, and 1910) were important fire years across North America (Heinselman 1973; McMurry *et al.* 2007; Guyette *et al.* 2016; Meunier and Shea 2020; Meunier 2022). Widespread fire years can modify climate–vegetation relationships (Bergeron *et al.* 2004), are relevant for wildfire preparedness, and can influence ecosystem resilience under an increasingly variable climate.

Widespread fire years corresponded overwhelmingly to drier years ($\text{PMDI} < 0$). However, most fire years were near normal (i.e. $\text{PMDI} = -0.49$ to 0.49) or mild to moderate drought years ($-1.00 > \text{PMDI} > -2.99$; Fig. 7). Many fire years that burned under moderate conditions have been interpreted as evidence of local, anthropogenic controls (Muzika *et al.* 2015; Guyette *et al.* 2016). However, moderately dry conditions can be sufficient for widespread fires even in saturated peatlands (Sutheimer *et al.* 2021). Anthropogenic fires can be synchronous across large areas, and deciphering contributions of various drivers of fires can be difficult, though increasing drought signals (lower Palmer Drought Index, PDI, values) have been correlated with increasingly widespread fire years (Meunier and Shea 2020). Notably, PDI is most effective in determining long-term drought (several months) but less sensitive to short-term drought (Alley 1984). Recent wildfires include the 26 000-ha Seney Fire in 1976 (captured in our historical tree-ring records and in Drobyshev *et al.* 2008*a*), and the 37 507-ha Pagami Creek fire in Minnesota in 2011. Both fires occurred in moderately dry conditions and were summer, lightning-ignited fires in wetlands that burned for weeks prior to rapid, wind-driven growth (Anderson 1982; United States Forest Service 2012).

Fires are spatially heterogeneous, and fire scars cannot fully capture spatial variability in fire severity or continuity of burning, making it difficult to estimate fire sizes. However, spatially distributed fire-scar data are useful to understand regional and even continental-scale fire years (Morgan *et al.* 2001) because fire-scar data tend to record fires in relative proportion to the area burned, and synchronous scarring among multiple sites indicates widespread fires burning (Farris *et al.* 2010). Widespread fires have

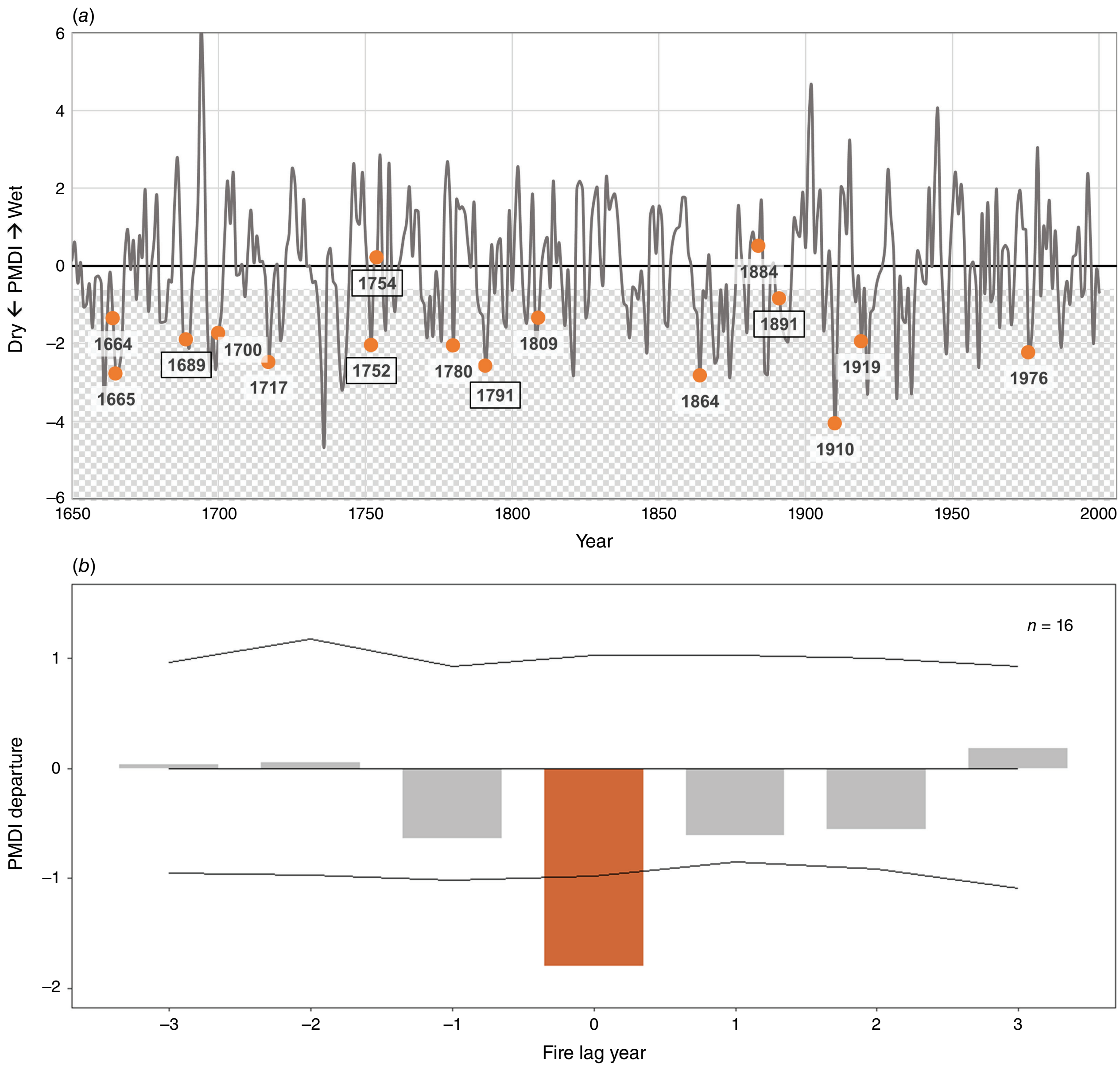

Fig. 7. Relating widespread fire years across upper Great Lakes Region to growing season (June–August) Palmer Modified Drought Index (PMDI; Cook *et al.* 2010), 1650–2000. (*a*) Time series of PMDI with widespread fire years among all study areas of the Upper Peninsula of Michigan. Orange circles indicate the most widespread fire years ($n = 16$) during the analysis period, determined as years with greatest fire extent index values, greatest percentage of samples scarred by fire, and fire years synchronous among study areas. Solid line corresponds to regional PMDI for 17 grid points within the UP during the analysis period. Hashing corresponds to drought conditions (PMDI ≤ -0.49; Palmer 1965), and regionally widespread fire years are outlined. (*b*) Superposed epoch analysis (SEA) comparing widespread fire years with average PMDI across the upper Great Lakes Region 2 years prior, and 2 years after the 16 widespread fires indicated in (*a*). Horizontal solid lines indicate the 95% confidence interval in annual variability in growing season PMDI. Orange-shaded bar indicates lag year in which there was a significant departure ($P < 0.05$) from average growing PMDI. n = number of widespread fire years used in SEA.

disproportionate effects on area burned (Stocks *et al.* 2002), including in the upper Great Lakes Region (Heinselman 1973), where the top 3% of historical fires burned 97% of the landscape (Frelich 2002). Although the largest contemporary fires (e.g. Pagami Creek Fire in 2011, Seney Fire in 1976) in the upper Great Lakes Region are the largest since record keeping began around 1911, they are likely not representative of fires before the cutover period in the upper Great Lakes Region, which burned hundreds of thousands of hectares (Meunier and Shea 2020).

Comparing fire regime characteristics (frequency, extent, and seasonality) among landscapes with similar climate, variable topographic complexity, and differing forest composition can disentangle relative influences of climate versus landscape controls (Falk et al. 2011), and is a powerful way to understand factors determining and constraining fire patterns (Morgan et al. 2001). Red pine, for example, is one of the few fire-resistant tree species in the North American Laurentian mixed forest region and southern fringe of the North American boreal forest region (Bergeron and Brisson 1990; Rudolf 1990; Flannigan and Bergeron 1998). Within this range, red pine fire return intervals vary greatly from 3 to 5 (Bergeron and Gagnon 1987) to >300 years (Heinselman 1973; Drobyshev et al. 2008a). This variability underscores the need for understanding drivers controlling fire dynamics at regional scales (Drobyshev et al. 2008b). Synchrony of fires across diverse and heterogeneous study areas (Figs 1, 6), along with significant departures in regional drought conditions during widespread fire years (Fig. 7), suggest that regionally widespread fire years in the upper Great Lakes Region were predominantly climate driven over the past 350 years.

Analysing fire frequency and fire extent over broad areas provides insights into variability in regional fire regimes. For example, there were only a few widespread fire years in common between the Huron Mountains and Seney NWR (e.g. 1754, 1791, 1891) (Drobyshev et al. 2008a, 2008b, 2012), which was suggested as evidence for the dominance of anthropogenic, rather than climatic, drivers (Muzika et al. 2015). However, in our expanded dataset, 1754 and 1791 were among the most widespread fire years across the entire UP (Fig. 5), albeit with variable proportion of scarring within and among sites (Fig. 6). The year 1891 was another large climatically driven fire year; both across the UP (Fig. 5) and Great Lakes Region (Meunier 2022), with a high rate of scarring within and among locations (Figs 6, 7). Interestingly, two regionally widespread fire years (1752, 1754) occurred just 2 years apart (Fig. 6). Study areas differed between these 2 years, with a high percentage of trees scarred in 1752 followed by a low percentage of trees scarred in 1754 in the Huron Mountains in the eastern UP, and in the central UP in Hiawatha West and Seney NWR there were lower percentages of scarring in 1752 and higher percentages of scarring in 1754 (Fig. 6). These differences may be attributable to factors including variability in local climatic conditions across the UP (Handler et al. 2014; Clark et al. 2016) and interactions of climate and vegetation (Gajewski 1987; Parisien et al. 2014).

At regional scales, seasonality of fire occurrence varies in relation to interactions of weather and climate. In Canada, prairies and southern boreal plains have highest fire weather indices in early growing season (April and May), whereas the boreal forest, taiga, and Laurentian mixed forest have highest fire weather indices in late growing season (June and July; White et al. 2011). Across the upper Great Lakes Region, seasonal changes in precipitation and wind directly influence fire activity, which peaks when dried fine fuels are abundant and during periods of increased wind after 2 weeks or more of dry conditions (National Wildfire Coordinating Group 2014). Seasonality of all historical fires detected in the UP was variable both within and among sites (Table 3), though widespread fire years over the last 350 years were primarily detected as growing-season fires (earlywood + latewood fire scar positions; Table 1). By contrast, most contemporary fires in the upper Great Lakes Region are small (<400 ha) and occur in spring (Cardille and Ventura 2001; Carlson et al. 2021). However, larger contemporary fires in the upper Great Lakes Region have also been lightning-ignited summer fires (e.g. August 2007 Sleeper Lake Fire in Michigan burned 7487 ha, August 2011 Pagami Creek fire in Minnesota burned 37 231 ha, and August 2021 Greenwood Fire in Minnesota 10 844 ha). This is also consistent with wildfire trends in the US, where from 2002 to 2012, for example, lightning-ignited fires, which are relatively uncommon (14% of all ignitions), were responsible for most area burned (62%; Brusentsev and Vroman 2016).

Local factors controlling fire events, specifically weather fronts and wind changes, contribute to the complexity of fire regimes at broader scales such that they must be considered in addition to regional drought and climate (Little et al. 2016). In California, for example, extreme fire seasons along the southern coast track Santa Ana winds (Wells and McKinsey 1995) rather than temperature, precipitation, or peak lightning season (Westerling et al. 2004; van Wagtendonk and Cayan 2008). Wind is an important disturbance mechanism in the upper Great Lakes Region (Schulte and Mladenoff 2005) and the main driver of large fires in temperate mesic forests with climate-restricted fire regimes (Evers et al. 2022). In transitional mixed wood and boreal conifer forests of northwestern Quebec, for example, fires tend to grow large with a passage of cold fronts and associated wind shifts (Brotak and Reifsnyder 1977; Flannigan and Wotton 2001; Bergeron et al. 2004). Substantial increases in surface-water temperatures and associated increases in wind speeds are predicted due to climate change across the upper Great Lakes Region (Jabbari et al. 2021), and Michigan was already the third windiest state in the US in 2021 (Global Wind Atlas 3.0 2021).

In the upper Great Lakes Region, fire histories have been analysed primarily at local or landscape scales (1–10s km^2 respectively), and have focused on anthropogenic drivers (e.g. human ignition sources, Euro-American settlement land use changes) rather than biophysical drivers (e.g. climatic, edaphic, and vegetation patterns) (Muzika et al. 2015; Guyette et al. 2016; Johnson and Kipfmueller 2016; Kipfmueller et al. 2017, 2021). Analysing anthropogenic and biophysical drivers of fire regimes across multiple scales is a fundamental objective of fire ecology (Lui and Wimberly 2015), and can reveal interactions among both drivers at regional scales. One example observed in fire-scar records across the upper Great Lakes Region is the substantial effect of fire suppression. After 1950, apart from Seney NWR, we detected no fire years within any study areas (Fig. 3*b*–*d*). This pattern of decreasing fire frequency and fire extent has been observed and attributed to fire suppression across the Great Lakes Region (Cleland *et al.* 2004; Nowacki and Abrams 2008; Paulson *et al.* 2016; Meunier 2022), North America (Taylor *et al.* 2016; Chavardès *et al.* 2018), and globally (Şahan *et al.* 2022). With organised fire suppression efforts starting in the mid-19th century, extensive changes in forests are found throughout North America (Pyne 2001; Nowacki and Abrams 2008).

A century of fire suppression caused fundamental shifts in the forests and fire regimes of the upper Great Lakes Region (Nowacki and Abrams 2008; Paulson *et al.* 2016; Meunier 2022), but it is not evident how these changes will interact with future climate (Flannigan *et al.* 2009; Duveneck and Scheller 2015). Climate variability has been high during the 20th century across the upper Great Lakes Region compared with previous centuries (Warner *et al.* 2021). Total annual precipitation has increased and is projected to continue to increase throughout the 21st century, but future projections predict variability among seasons, with decreasing precipitation and warming temperatures in the late-growing season (Kling *et al.* 2003; Easterling *et al*. 2017; Wehner *et al*. 2017). Changes in seasonal precipitation and warming could contribute to decreases in soil moisture during the late-growing season, contributing to increased fire activity – especially in the driest areas of the upper Great Lakes Region (Kling *et al.* 2003). In the upper Great Lakes Region, daily precipitation variability from mean annual precipitation can have a stronger effect on fire activity than changes in total annual precipitation (Lafon and Quiring 2012), and the impacts of drought on fire activity are dependent not only on drought severity but also drought seasonality (Pryor 2013). Although there is general agreement among projected trends of precipitation and warming for the upper Great Lakes region, projected trends in drought and fire frequency are not as apparent (Drever *et al.* 2009; Handler *et al.* 2014; Vose *et al.* 2016).

Effective intervention requires an understanding of the processes that maintain resilient landscapes (Stephens *et al.* 2013; Levine *et al.* 2017; Meunier and Shea 2020). Our results suggest weather and climate were drivers of large-scale fires across disparate forest types across the upper Great Lakes Region over several centuries. Importantly, the fires we detected were primarily low- to moderate-severity fires (as evidenced by trees surviving fires). Historically, reoccurring fire years were instrumental for shaping and maintaining resilient landscapes. However, the disruption of historical fire regimes resulted in major shifts in forest composition and fire regimes, including the loss of fire-resistant species (such as red pine) and reduced landscape diversity (Drever *et al.* 2008; Nowacki and Abrams 2008; Handler *et al.* 2014). To maintain historical diversity of forest communities and resilience throughout the upper the Great Lakes Region, processes that foster the regeneration of disturbance-adapted species (e.g. harvesting and/or fire use) are needed (Drever *et al.* 2009; Vose *et al.* 2016). Adaptive management will need to consider climate trends while also addressing altered forests and fire regimes due to fire suppression, agricultural expansion, and logging since the Euro–American Settlement period (Drever *et al.* 2009; Vose *et al.* 2016; Angel *et al.* 2018). The question remains – what types of fires and forests will comprise future landscapes of the upper Great Lakes Region?

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Data availability. Some of the data that support this study are available in the International Multiproxy Paleofire Database at https://www.ncei.noaa.gov/products/paleoclimatology/fire-history. The remainder of the data that support this study can be shared upon reasonable request to the corresponding author.

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