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To cite this article: Erica R Bigio *et al* 2022 *Environ. Res. Lett.* **17** 054043

IOP Publishing Environ. Res. Lett. 17 (2022) 054043 https://doi.org/10.1088/1748-9326/ac6964

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
12 December 2021

REVISED
13 April 2022

ACCEPTED FOR PUBLICATION
22 April 2022

PUBLISHED
9 May 2022

LETTER

The influence of land-use activities and regional drought on historical fire regimes of Buryatia, Siberia

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Keywords: wildland fire, dendrochronology, Siberia, fire history, fire–climate, tree rings, frequent fire

Supplementary material for this article is available online

Abstract

Every year, millions of hectares burn across Siberia, driven by a combination of warming temperatures, regional drought and human-caused ignitions. Dendrochronology provides a long-term context to evaluate recent trends in fire activity and interpret the relative influence of humans and climate drivers on fire regimes. We developed a 400 year record of fire-scarred trees from 17 sites in pine-dominated forests located southeast of Lake Baikal. Site-level mean fire return intervals (MFIs) ranged from 4 to 27 years for all fires and 8 to 35 years for widespread fires within sites. Sites with the lowest MFI values were located within 1 km of agricultural fields in grassland valleys, suggesting that agricultural burning influenced MFIs at nearby sites. Fire frequency varied over the record, with significantly high values around 1790, from 1865 to 1880, 1948 to 1955 and 1995 to 2005. The increased fire activity corresponded with migration waves to the region and major socio-economic change connected with the establishment and breakdown of the Soviet Union. At broader scales, superposed epoch analysis showed that synchronous fire years were associated with regional drought and precipitation deficits. Wet conditions for 2–3 years prior to the event year were also significant, suggesting that increased moisture promoted growth of understory fine fuels to support more extensive fires across the study area. Although fire frequencies increased during the 20th century, fire–climate relationships weakened, suggesting increased human-caused ignitions may override regional climate drivers. Our dataset presents a continuous record of frequent surface fires over the past 400 years, providing a valuable opportunity to compare dendrochronology-based reconstructions with satellite and documentary records.

1. Introduction

Every year, extensive wildfires burn across the boreal forests of Siberia, damaging ecosystems and contributing to global carbon emissions (Soja *et al* 2007, Krylov *et al* 2014, Ponomarev *et al* 2019, Kharuk *et al* 2021, Tomshin and Solovyev 2021). There is much variability in the extent, severity and seasonal timing of fire activity in different regions of Siberia (Jupp *et al* 2006, Soja *et al* 2007, Kukavskaya *et al* 2013b, Tomshin and Solovyev 2021). In southern Siberia, fire frequency has increased since the 1990s, influenced by an association with increasing late-winter temperature and spring drought (Kukavskaya *et al* 2016, Kim *et al* 2020). Furthermore, increasing fire frequency and severity has led to recruitment failure, type conversions and losses in terrestrial carbon sequestration (Cai *et al* 2013, Barrett *et al* 2020). With future warming, fire activity is expected to increase (Shuman *et al* 2017), further enhancing positive feedbacks to the climate system.

In addition to climate drivers, human activities have contributed to more frequent fires in recent decades, especially in southern Siberia (Jupp *et al* 2006, Kukavskaya *et al* 2016). Human-caused ignitions relate to a combination of arson, accidental ignitions, and escaped agricultural fires since the early 1990s (Kovacs *et al* 2004, Jupp *et al* 2006, Ivanova *et al* 2010, Kukavskaya *et al* 2016). Such ignitions have increased during the post-Soviet era, when land-use activities shifted (e.g. increased illegal logging, and agricultural burning) and resources for fire suppression were dramatically reduced (Pyne 1996, Ivanova *et al* 2010, Goldammer *et al* 2013, Kukavskaya *et al* 2013a, Dara *et al* 2019). During extreme drought years, human-caused ignitions may amplify the climate-driven fire risk, leading to more extensive area burned. For example, during the 2002 and 2003 extreme drought years, up to 78% of the burned area was associated with anthropogenic influences (Kovacs *et al* 2004, Achard *et al* 2008).

The coincidence of socio-economic change and a warming climate in recent decades makes it difficult to separate the influences of human activities and climate drivers on fire regimes in southern Siberia. Yet, disentangling these factors is necessary for accurate predictions of future vegetation patterns, fire activity and associated carbon emissions (Bowman *et al* 2011, Shuman *et al* 2017). If these drivers can be accounted for, especially at regional scales, there is potential for improved fire management and resource conservation (Kitenberga *et al* 2019, Ryzhkova *et al* 2020). Although some paleo-ecological and modern fire studies are published for southern Siberia (Swetnam 1996, Ivanova *et al* 2010, Kukavskaya *et al* 2016, Wang *et al* 2021), very little is known about fire regimes prior to the 1960s, and to what extent climate variability and land-use activities have influenced fire activity over the past several centuries.

Satellite records, covering the past 20–30 years, have identified specific climate drivers for increased area burned, such as late-winter temperatures, early snowmelt and spring precipitation anomalies (Kukavskaya *et al* 2016, Kim *et al* 2020). Some datasets identify human drivers through spatial associations between elevated fire frequency and roads, villages or railroads (Kovacs *et al* 2004, Kukavskaya *et al* 2016). Documentary records, extending to the 1960s, also indicate dry climate conditions combined with major socio-economic changes have contributed to the upward trend in fire activity since the 1990s (Korovin 1996, Ivanova *et al* 2010, Kukavskaya *et al* 2016). Longer records of fire history are necessary for contextualizing recent trends in fire activity and for evaluating relative drivers for southern Siberia.

Tree-ring methods provide this long-term perspective of fire regimes at landscape to regional scales. Fire-scarred trees preserve a record of surface fires, often covering up to several centuries of annual and seasonal fire occurrence (Falk *et al* 2011). Forests along the forest-steppe ecotone of southern Siberia have abundant fire-scarred trees, yet only a few tree-ring based fire history records have been developed from these regions (Swetnam 1996, Ivanova *et al* 2010, Saladyga *et al* 2013, Hessl *et al* 2016, Wang *et al* 2021). These studies show that frequent surface fires burned over the past three centuries, though with variations in fire return interval at individual sites, often related to human activities. At regional scales, drought can synchronize fire activity across a larger network of sites (Hessl *et al* 2016). In contrast to western North America and northern Europe (Swetnam and Baisan 1996, Wallenius 2011, Taylor *et al* 2016), frequent fire regimes continue through the 20th century, enabling integration with satellite data for evaluation of current trends.

We present a multi-century record of fire activity for the Republic of Buryatia, located southeast of Lake Baikal. We use our dataset to evaluate the relative influences of climate and humans on spatial and temporal patterns in fire activity. Given that humans can exert control at local scales, we expect there will be spatial variation in fire frequency among sites throughout the region. We hypothesize that fire return intervals will be shorter (higher fire frequencies) in sites closer to human settlements, roads and agricultural fields. In a similar way, we expect that higher fire frequencies will coincide with periods of population growth, civil unrest and socio-economic change. We expect that extensive and synchronous fire activity across our study area correspond with regional drought.

2. Methods

2.1. Study area

The Republic of Buryatia is located to the south of Lake Baikal in central Siberia (figure 1). The study area is within the forest-steppe ecotone of the southern Boreal forest, where stands of Scots pine (*Pinus sylvestris*) and Siberian larch (*Larix sibirica*) grow above grassland valleys. Scots pine grows on drier valley sites and larch dominates on mesic slopes close to Lake Baikal. Central Siberia has a continental climate with very cold and dry winters. Average annual rainfall is 27 cm (10.5 inches), and 65% of precipitation falls as rain in June, July and August (www.climexp.knmi.nl, www.meteo.ru). The local fire regime includes low severity surface fire, with ~80% of fires occurring in March, April and May before the onset of summer rains, when fires spread easily during dry and windy conditions (Farukh *et al* 2009, Kukavskaya *et al* 2016, Kim *et al* 2020). The remainder of fire activity is typically during September–October following the decline in summer rains (Korovin 1996, Kukavskaya *et al* 2013b, Krylov *et al* 2014).

Figure 1. Map of sites of fire-scarred trees, overlaid with forest cover (Hansen *et al* 2013) and other features (Selenga River, railway lines, political boundaries). Lower left panel: view towards the Selenga River Valley from the SUB site. Lower middle panel: living fire-scarred trees exhibiting open wound with multiple fire scars. Lower right panel: partial cross section from living fire-scarred tree.

We sampled fire-scarred trees at 17 sites throughout the province (table 1, figure 1). A prior dendroclimatic study identified pine-dominated stands with older living trees (Andreev *et al* 1999, 2001). These sites were located on well-drained soils and adjacent to grassland valleys at the lower limit of the Scots pine distribution (figure 1). We revisited these sites, where we searched an area of 20–40 ha for well-preserved fire scars on living trees, remnant stumps and logs to capture the most complete record of fire activity (Farris *et al* 2013). We sampled approximately 5–30 trees at each site. Three sites were collected from local sawmills, where the wood was sourced from nearby forests, as confirmed with local foresters and sawmill operators.

One group of sites (‘western sites’) was located along the Selenga River valley. In this region, the forests were younger and more fragmented, grasslands were more extensive, and sites were located adjacent to valleys with roads, agricultural fields and small towns. The understory of continuous grass cover was relatively dense at mesic sites. A second group of sites (‘eastern sites’) was located along the Uda River valley towards the village of Khorinsk, where grasslands were limited and forests were more extensive and older. The understory of these sites had sparse grass and needle cover (figure 1).

2.2. Laboratory methods

We processed all samples according to standard dendrochronological methods (Speer 2010), including polishing surfaces with progressively finer grit sand paper until annual rings, cellular structures, and fire scars were clearly visible under magnification. We crossdated samples and assigned a year and season to each scar based on the position of the

Table 1. Summary of sites collected with geographic information and forest composition.

Western sites		Latitude	Longitude	Elevation (m)	Forest composition	No. of sampled trees
KLU	Klyuchi village	51.68	107.17	728	Pine	5
SAW	Chinese Sawmill	51.63	106.89	625	Pine	14
UBI	Ubiennaya crossing	51.18	106.55	811	Pine	9
ENH	Enhor village	50.98	106.58	736	Pine	13
KYB	Kyachta boundary	50.74	106.50	870	Pine	11
SUB	Subuktui	50.60	106.63	716	Pine	12
OKI	Okino Klyuchi	50.68	107.07	742	Pine	11
BIL	Bilyutai sawmill	50.77	107.10	576	Pine	10
SAG	Sagan-nuur Lake	51.26	108.05	904	Pine	11
TUG	Tugnui village	51.28	108.42	853	Mixed	15
Eastern sites						
ZAI	Zaigraevo	51.91	108.27	696	Pine	19
TAL	Verkhiye Tal'tsy	52.11	108.92	757	Pine	28
TAR	Tarbagatai	52.10	109.16	657	Pine	20
KUL	Kulsky Stanok	52.14	109.67	695	Pine	25
KHO	Khorinsk Sawmill	52.15	109.79	663	Mixed	9
ONI	Oninoborsk	52.26	109.99	789	Pine	28
ASH	Ashanga sawmill	52.33	110.21	729	Pine	9

scar within the ring (Stokes and Smiley 1968, Baisan and Swetnam 1990). Crossdating was verified by two dendrochronologists. The majority of fire scars were positioned in the early-earlywood ring position, consistent with other fire history studies from the forest-steppe ecotone (Korovin 1996, Ivanova *et al* 2010, Hessl *et al* 2016). We assigned dormant scars to the following calendar year (i.e. spring dormant). The frequency of early fire scars in our samples is consistent with spring fires being common in the modern record (Farukh *et al* 2009, Kukavskaya *et al* 2016). Fall fires are less common (Hessl *et al* 2016, Kukavskaya *et al* 2016), and we only assigned dormant scars to the prior year if the scar coincided with a prior-year latewood scar from same site.

2.3. Fire regime reconstruction

We entered all fire year and seasonality data into the Fire History Exploration and Analysis software (FHAES, V2.0.2) (Brewer *et al* 2017), and used a combination of FHAES, Excel, and *burnr* in *R* (burnr V0.5.0; Malevich *et al* 2018, R v4.0.3, R Core Team 2020) for analyses. We used these programs to create fire history chronology graphics for each site and composite graphics for the study area.

We calculated the mean fire return interval (MFI) within a period of analysis for each site, starting when two trees are recording fire. Trees begin 'recording' following the first fire to create an open wound. Initial scarring causes the loss of protective bark and resin flow to the wound area, and thus, increases the probability of re-scarring during later fires. Many sites experienced single-tree fires prior to the period of analysis, before sample depth was sufficient to calculate the MFI. At each site, the MFI was calculated for two different filters: (a) fires of any size ('all fires') recorded by one or more trees, and (b) fires that scarred 25% of recording trees with a minimum of two scars ('25% filter'). The 25% filter identifies more spatially extensive fires across individual sites. The filtered fire years were selected for subsequent analysis of fire synchrony among sites and fire–climate relationships, as described below. Synchronous fire events are determined when two or more spatially isolated sites record fire in the same year.

2.4. Spatial and temporal variations in fire return interval

We tested for differences in MFIs between regions (western vs. eastern sites) and between time periods (pre- and post-1900) using the Mann–Whitney test of medians. To identify land-use activities that may have contributed to differences in MFI among sites and regions, we measured the distance from each site to the nearest cultural features (roads, agricultural areas, settlements) using Google Earth Pro©. We noted whether the site was located in a small, fragmented forest patch or within more extensive and intact forest. This analysis was supplemented by our field observations, where we documented culturally-modified trees, rock mounds that indicate past structures, and understory vegetation within each site.

We generated two separate time series to quantify the variability of fire occurrence at different spatial scales. The first series includes all fires events across all trees and sites (all fires). The second time series included only synchronous fire events (25% scarred) that were recorded at two or more sites in the same year. We transformed each series to standard normal 'z' values ($z = (x - \text{mean})/\text{standard deviation}$), and then we determined periods of significant fire frequency increases when the number of fire events per decade exceeded $z = 1.64$ (significance level of $p < 0.05$, i.e. exceeding the 95% confidence level). We compared significant periods of fire frequency with key historical events and population growth in the region. Key historical events include migration patterns throughout the 18th–20th centuries, end of serfdom (1861), construction of the Trans-Siberian Railway (~1900), along with socio-economic changes during and following Soviet Era (1917–1991).

2.5. Fire–climate analysis

The selection of synchronous fire events among multiple sites helps to determine the regional climate influences on fire activity. Our sites are widely dispersed, often separated by roads, rivers, and extensive grasslands with agricultural fields, making continuous fire spread between most sites highly unlikely. Therefore, when multiple site burn in the same year, it suggests that external climate is driving abundance and continuity of surface fuels, while leading to dry fuels and extensive fire spread during drought years.

We used two climate reconstructions to compare with synchronous fire years in statistical tests of fire–climate relationships: (a) a regional drought reconstruction and (b) a local water-year precipitation reconstruction. For the drought reconstruction, we used an average of 48 grid points located within 100 km of our study sites from the Monsoon Asia Drought Atlas (MADA, V2) (Cook *et al* 2010). The MADA is a gridded (0.5 degree) tree-ring reconstruction of June–August self-calibrating Palmer Drought Severity (scPDSI) that incorporates precipitation and temperature to estimate soil moisture based on local station data (Wells *et al* 2004). We excluded points within 50 km of the Lake Baikal to avoid the influence of lake effect weather. The local water-year precipitation reconstruction (prior August to current August) used meteorological station data from Ulan-Ude for 1922–1988. The reconstruction was developed from tree-ring width chronologies from a prior dendroclimatic study within our study area (Andreev *et al* 1999, 2001). The chronologies for the precipitation reconstruction are independent of our fire history reconstruction and of the chronologies used for the drought reconstruction.

To provide a statistical test of fire–climate relationships, we conducted superposed epoch analysis (SEA) for several groups of fire years using the drought and precipitation reconstructions. A common application in tree-ring fire history studies (Swetnam and Baisan 1996, Yocom Kent *et al* 2017, Guiterman *et al* 2019, Wang *et al* 2021), the SEA procedure averages the climatic time series for the fire event years in each test of both negative and positive lag years. Bootstrap resampling is then performed on an equal number of randomly drawn years within the time period of the events. The bootstrapping is performed 1000 times to compute a robust average of potential event and lag years. The event and lag year averages are subtracted from the mean of the bootstrap values as a departure of the climate time series for the fire event years. Significance of the departure values is assessed against the 95% confidence intervals obtained from the bootstrap procedure. The SEA was performed with the *burnr* function *sea,* using a seven-year window, including 4 years prior and 2 years following the event year. We conducted SEA for the filtered fire years (25% scarred) when a minimum of two and three sites burned in the same year. We divided the synchronous fire years (two-site minimum) into two groups: pre-1900 years and post-1900 years to identify changes in fire–climate relationships over time.

3. Results

Our fire history reconstruction includes 205 crossdated trees from 17 sites (figure 2). The oldest fire scars dated to the 1300s in the eastern sites of ONI and TAL (table 2, SI figure 2 available online at stacks.iop.org/ERL/17/054043/mmedia). Between 1508 and 2010, there were 116 years, when fires burned extensively within sites (25% scarred), though the majority (70%) of these fires were only recorded at a single site. The remaining years ($n = 33$) burned synchronously at two or more sites. The primary season of burning was in the spring, as indicated by a majority of scars in the dormant and early-earlywood portion of rings (84%) (SI table 2).

3.1. Spatial and temporal variations in fire regimes

The MFI for each site ranged from 4 to 27 years for all fires, and from 8 to 35 years for more extensive fires within sites (25% scarred) (table 2). Three sites (TUG, UBI, SUB) experienced very frequent fire (MFI $<$ 10 years), whereas, the other sites ranged from 10 to 57 years (all fires). The western sites had lower MFI values than the eastern sites for the whole record ($p < 0.01$, SI figure 3). Prior to 1900, the western sites did not differ significantly from the eastern sites ($p = 0.2$). After 1900, MFI lengthened for the eastern sites, and were significantly longer than the

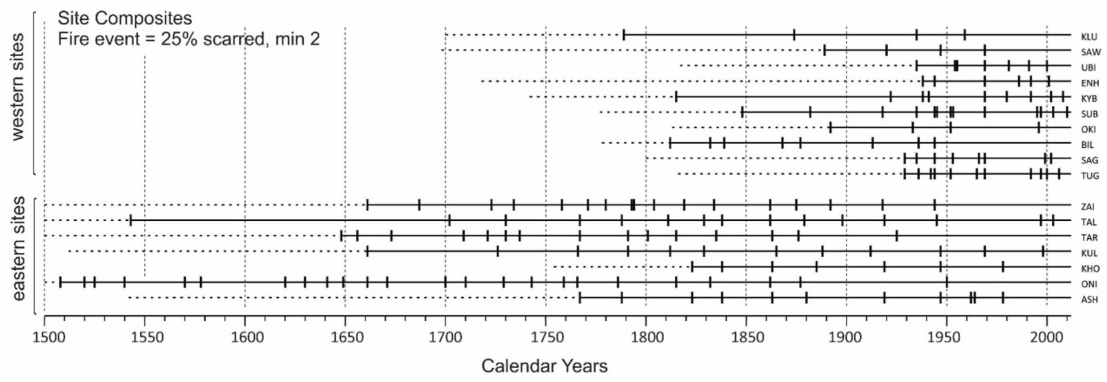

Figure 2. Fire-scar chronologies for each site. Site composites include filtered fire events (vertical tick marks) recorded on 25% of trees with a minimum of two trees scarred. Dashed lines represent the full length of the dated tree-ring samples and solid lines indicate the period of analysis, when at least two trees are recording fire. Fire history chronologies are cut off at 1500 to provide more detail when sample depth increases after 1650.

Table 2. Summary of results for each site. The period of analysis begins when two trees begin recording fires at each site. The MFI is calculated during the period of analysis for all fires and filtered fire events (25% scarred). Sites are grouped by region.

Site code				Mean fire return interval—MFI (range)	
Western sites	No. dated trees	First fire scar	Period of analysis	All fires	25% Scarred (min 2 scars)
KLU	3	1752	1789–1959	57 (24–85)	57 (24–85)
SAW	11	1735	1889–1969	27 (22–31)	27 (22–31)
UBI	9	1847	1935–2000	7 (1–15)	11 (1–19)
ENH	11	1844	1923–2001	10 (1–25)	13 (6–25)
KYB	9	1815	1815–2008	13 (2–42)	24 (3–107)
SUB	11	1848	1848–2010	9 (1–34)	14 (1–36)
BIL	8	1812	1812–1944	17 (7–29)	19 (7–36)
OKI	9	1879	1892–1998	21 (2–44)	35 (19–44)
SAG	8	1852	1929–2002	10 (3–30)	10 (3–30)
TUG	10	1835	1929–2006	4 (1–22)	8 (2–23)
Eastern sites					
ZAI	19	1661	1661–2000	13 (1–30)	18 (1–36)
TAL	23	1347	1501–2003	22 (1–62)	33 (6–159)
TAR	18	1368	1635–2003	16 (1–78)	20 (7–49)
KUL	18	1562	1661–1998	15 (2–37)	31 (17–65)
KHO	7	1790	1823–1978	9 (1–27)	26 (15–34)
ONI	23	1389	1466–1950	12 (1–73)	20 (5–73)
ASH	8	1575	1788–1978	17 (2–34)	21 (2–39)

western sites ($p < 0.001$) (SI figure 3). These temporal variations in fire frequency can be observed in the time series of the percent of sites scarred for each region (figures 3(A) and (B)). When fire intervals are compiled for the whole study area, MFI values were significantly shorter after 1900 ($p < 0.05$), indicating that fire frequency was overall higher during the 20th century.

The fire frequency plots (# fires/decade) highlight the temporal variations in fire activity for the study area (figures 3(C) and (D)). For all fires, the fire frequency exceeded the 95% confidence level for decades centered on 1789 and 1792, and then again from 1865 to 1880 (figure 3(C)). During the 20th century, fire frequency increased during the 1930 and 1940s, and exceeded the 95% confidence level from 1948 to 1955. Fire frequency declined until 1979, though was not significantly low, before rising again in the 1990s. Fire frequency again exceeded the 95% confidence level from 1995 until 2005. The lowest fire frequency of the record occurred shortly after 1900, when no fires were recorded from 1899 to 1911.

Synchronous fire events represent years of more extensive fire across the study area, indicating climate as a dominant driver of fire activity. Synchronous fire activity briefly exceeds the 95% confidence level of 2.7 fires per decade in 1827, 1833 and from 1916 to 1919. The synchronous fire record exceeds the 95% confidence level for an extended period of time from 1933 to 1952, and then again from 1995 to the end of the record. Based on a visual comparison of the time series in figure 3, fire frequency and synchrony are primarily influenced by the eastern sites prior to 1900, after which time fires burn less frequently in the eastern region. Whereas, in the western sites, fire frequency increases after 1900, and these sites contribute

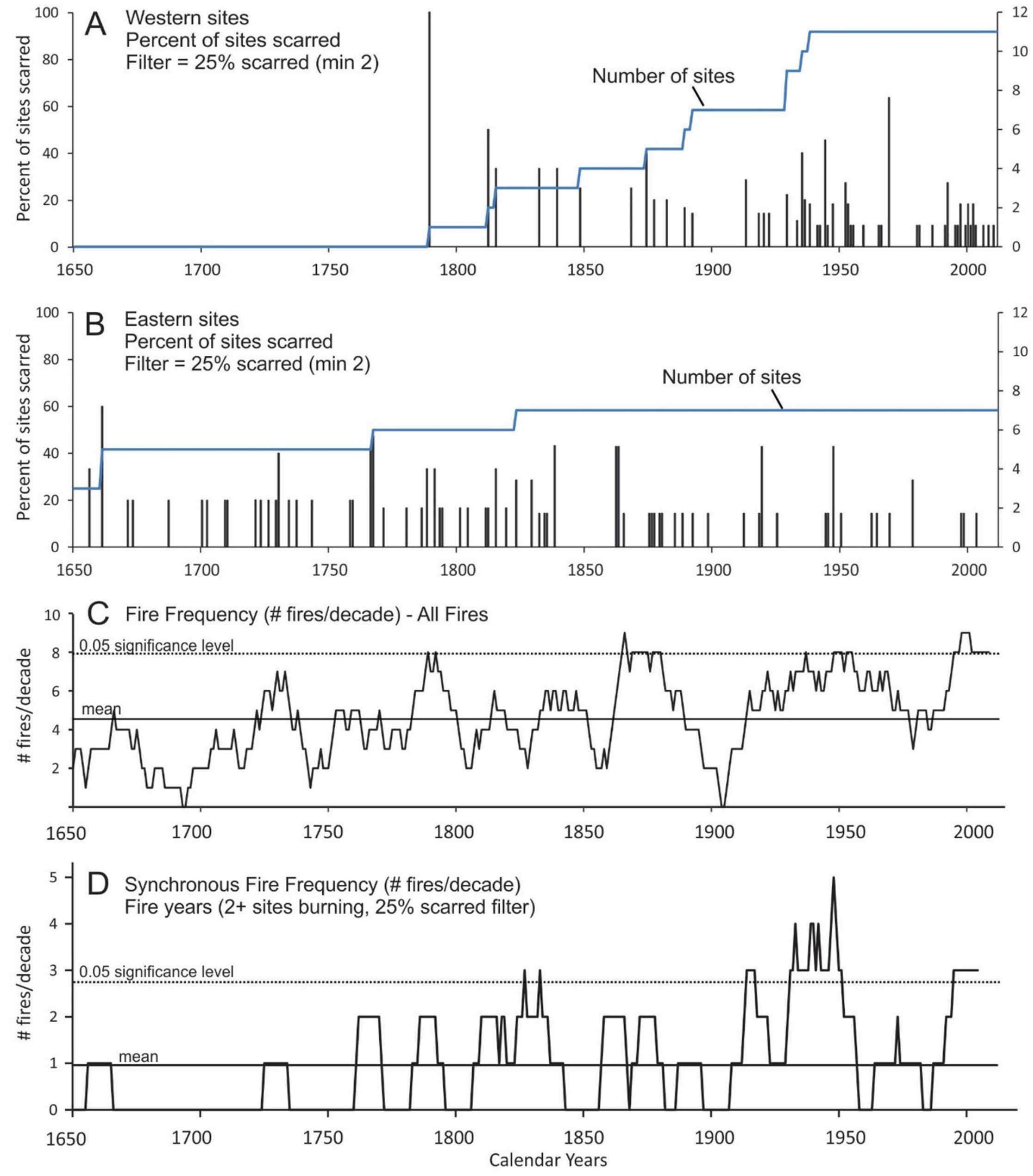

Figure 3. Spatial and temporal variability in fire activity. Panels (A) and (B) represent the percent of sites scarred by filtered fires (25% scarred) for the western and eastern groups. Panel (C) shows the running fire frequency of all fires (# fires/decade). Panel (D) shows the frequency (# fires/decade) of filtered fires that were synchronous at two more sites. In panels (C) and (D), the mean fire frequency and $p < 0.05$ significance levels are shown.

more to periods of elevated fire frequency during the 20th century (figures 3(A), (B) and SI figure 3).

3.2. Distance to cultural features

In the majority of sites, the distance to agricultural fields was shorter than other cultural features (roads, settlements), even in the eastern region with more limited grasslands (SI table 1). The sites with the shortest MFI values (TUG, UBI, SUB) were located less than 1 km from distinctive agricultural fields. Two sites (ENH, OKI) were adjacent to extensive grasslands, though agricultural fields were not distinctive. One site (KYB, 12 years) was located near a pass on a primary road at a political boundary, representing a common stopping point for travelers. Two sites with the longest MFI values (OKI, TAL) had culturally-modified trees and other signs of settlement, that may have limited fire spread or ignitions. We did not observe any correspondence between MFI values and distance to roads or settlements (SI table 1).

3.3. Fire–climate relationships

Based on a visual comparison of fire events and climate reconstructions, synchronous fire years (2 + sites burned) occurred primarily in moderate and dry years (figure 4). A 65% of synchronous fire years (2 + sites burned) occurred in years of

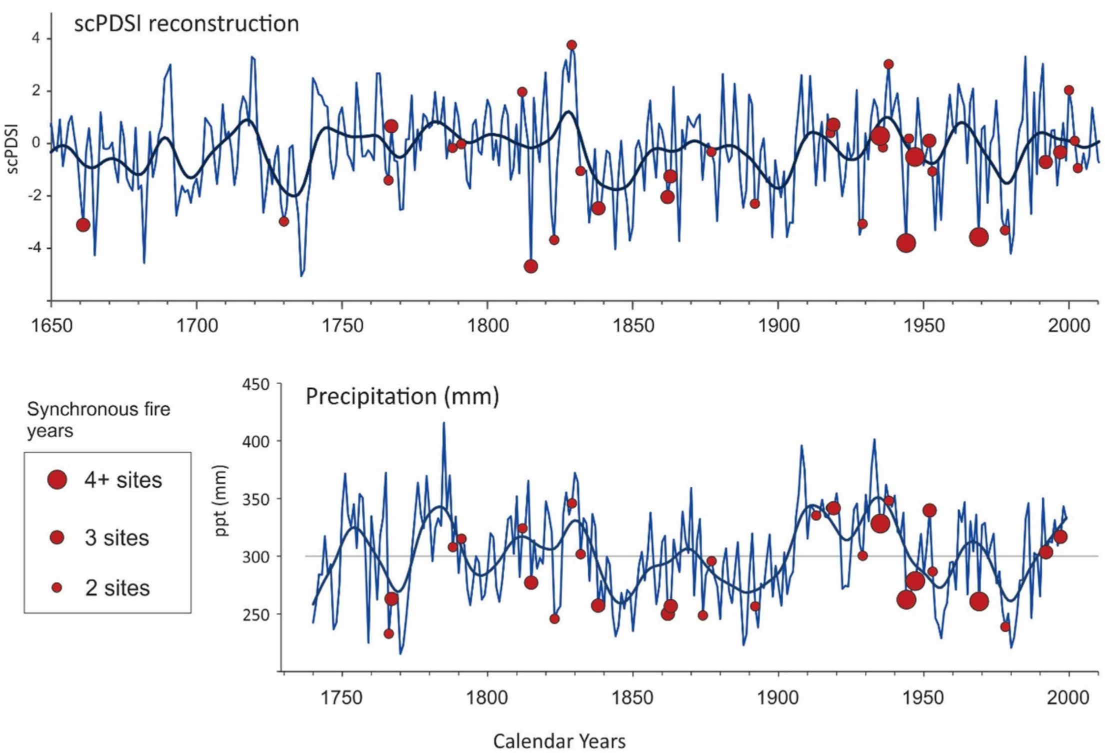

Figure 4. Synchronous fire events plotted with the scPDSI reconstruction (1650–2005) (Cook *et al* 2010) and water-year precipitation reconstruction (1750–1997) (Andreev *et al* 2001). Synchronous fire is defined by the number of sites that record more extensive fire (25% scarred) in the same year.

below average moisture (scPDSI < -0.1). For years of greater fire synchrony (3 + sites burned), 73% occurred when scPDSI values were below average. In a similar way, 65% of synchronous fire years (3 + sites) coincided with years of below average precipitation (figure 4).

The SEA provided a statistical test of the associations between synchronous fire events and the two climate reconstructions. For a minimum two sites ($n = 33$) burned, scPDSI was significantly negative ($p < 0.05$) in the fire year and within average conditions in the prior year (figure 5(A)). Synchronous fire years were significantly associated ($p < 0.05$) with increased moisture 2–4 years prior to the fire year (figure 5(A)). For years with greater fire synchrony, when a minimum of three sites burned ($n = 12$), there was a significant relationship with drought in the event year ($p < 0.05$). However, relatively wet conditions prior to the fire years were not significant. The association of precipitation with synchronous fire years was negative during the event year, though the relationship was not significant for either group of fire years (min two and min three sites burned). However, precipitation was positively and significantly associated ($p < 0.05$) for 1–3 years prior to the event year, depending on the degree of synchrony (figure 5(B)).

To evaluate temporal shifts in fire–climate relationships, we separated the synchronous fire years (minimum two sites) into pre- and post-1900 groups. The pre-1900 group ($n = 16$) showed a significant departure ($p < 0.05$) of scPDSI in the fire year and average conditions during the prior year. However, significant positive ($p < 0.05$) values were recorded 2 and 3 years prior to the event. The post-1900 era ($n = 17$) showed a weaker relationship between fire and drought during the 20th century. Climate during the fire year was moderately dry, but not significant. The association with precipitation was only significant ($p < 0.05$) for positive departures at 2 years prior to the event during the pre-1900 period and for 3 and 4 years prior to the event in the post-1900 period.

4. Discussion

Our record shows that frequent surface fires burned over past 400 years along the forest-steppe ecotone of southern-central Siberia. Our sites represent fire regimes for pine-dominated stands adjacent to grassland valleys, where there is potential for human activities to influence fire activity. Here, we consider whether variations in fire return interval among sites were influenced by agriculture and pastoralism in nearby valleys. Through time, variations in fire frequency across the study area were likely influenced by population growth and socio-economic change in the region. At broader scales, synchronous fire activity was significantly associated with drought conditions prior to 1900. Whereas, after 1900, weaker fire–climate relationships may relate to an overriding

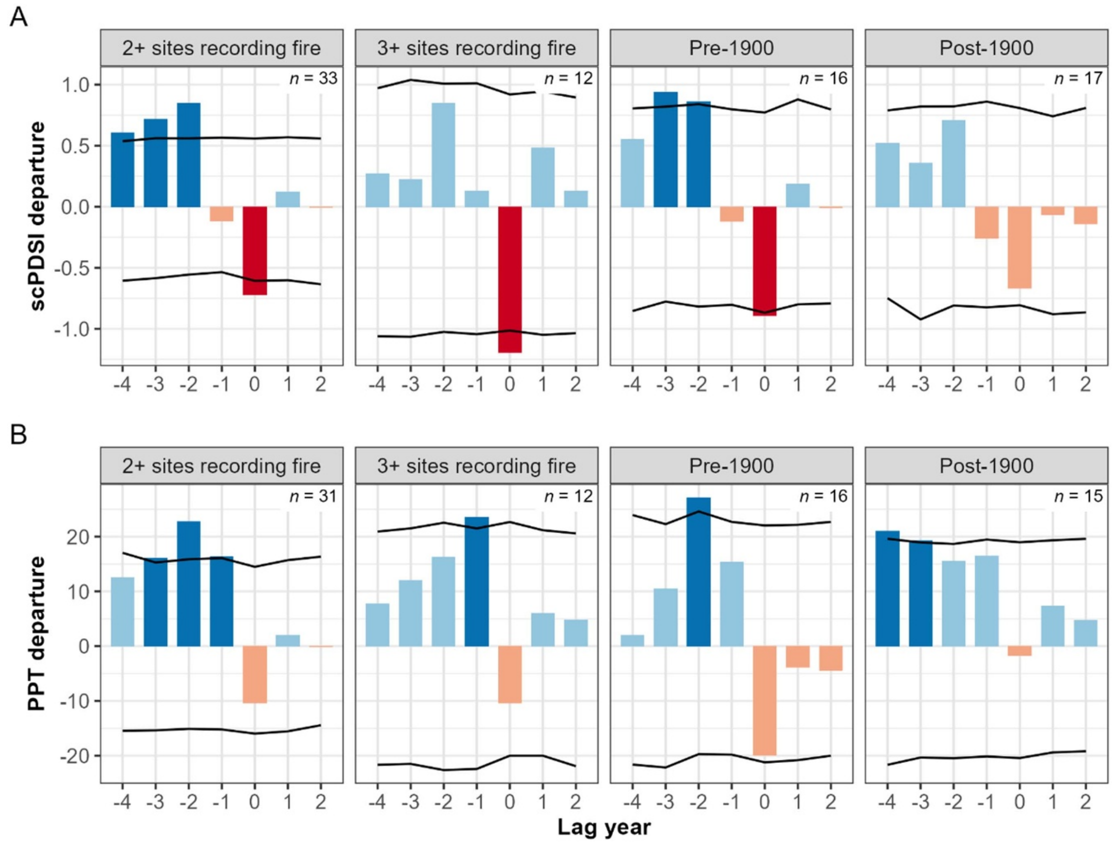

Figure 5. SEA results for synchronous fires (25% scarred, min two scarred) using both climate reconstructions (scPDSI and water-year precipitation). Fire years (lag year zero) were grouped by for the whole record by the degree of synchrony (min two or min three sites) and early and late time periods (min two sites only). Black lines represent 95% Confidence Intervals based on bootstrap resampling of the climate time series. Significant departures ($p < 0.05$) of each climate series are indicated by darker blue (positive values) and dark red colors (negative values).

influence of human activities. Here, we discuss the spatial and temporal influences on the Buryatia fire history record and compare with other studies in southern Siberia and northern Mongolia.

4.1. Spatial patterns and influences on fire return interval

There was moderate variation in MFI among sites, as shown by a range of 8–35 years for widespread fires (table 2). Fire return intervals were consistent with other fire histories from the forest-steppe ecotone (Ivanova *et al* 2010, Hessl *et al* 2016, Wang *et al* 2021). In the Tuva region to the west, 25 fires were documented from 1760 to 1999 for an MFI of 10 years. Over a similar time period, MFI values from sites in northern Mongolia ranged from 10 to 25 years for widespread fires (Hessl *et al* 2016). These MFI values are shorter than values reported for the northern Boreal forest (Kharuk *et al* 2011, 2016), owing to higher levels of fine (grass) fuels, dryer climate and a longer growing season in southern Siberia that support more frequent fire.

Traditional livelihoods of agriculture and nomadic pastoralism in Buryatia likely influenced the differences in MFI at individual sites. Throughout the 18th and 19th centuries, Russian peasant farmers settled along the forest-steppe ecotone of Siberia, where they practiced agriculture in open grasslands (Moon 1997). Intentional burning was a key practice in traditional agriculture, used to break up soils, remove plant residues and prepare the fields for ploughing. These practices persisted through the 20th century until official prohibitions were implemented in 1972 (Pyne 1996). Russian settlers cut timber extensively as they migrated through Siberia (Pyne 1996, Moon 1997), which helps explain the younger forests and a lack of remnant material in the western sites (SI figure 1).

The sites with the lowest MFI values (TUG, UBI, SUB) are located less than 1 km from agricultural fields, leading to shorter fire return intervals in the western region. These results lend support for an association between agricultural burning and elevated fire frequency in the nearby forests (SI table 1). This is consistent with satellite-based studies that documented the apparent spread of fires from agricultural areas into other land cover types (Kovacs *et al* 2004). For example, in central Siberia, thermal anomalies representing burned forest were strongly correlated with burned agricultural areas (Kovacs *et al* 2004). In the steppe grasslands of Kazakhstan, fire activity on ungrazed grasslands and abandoned croplands was associated with spreading fires from nearby cultivated croplands (Dara *et al* 2019).

The second major land-use activity in Buryatia is nomadic pastoralism, practiced by the indigenous Buryat people (Forsyth 1992, Moon 1997). For centuries, pastoral nomads moved seasonally with small herds of livestock and did not own land or settle in one location (Forsyth 1992). Intentional use of fire by pastoral nomads has not been documented, though it is possible that fire was used to improve grazing conditions, clear areas for hunting or promote growth of edible plants (Pyne 1996, Moon 1997). Given the frequent movements, it is likely that these practices did not lead to increased fire activity (Hessl *et al* 2012, Saladyga *et al* 2013).

We suggest that pastoralist land-use activities contributed to longer fire return intervals at certain sites. When pastoralist groups repeatedly visit one location, their livestock consume fine fuels and people often use woody debris for heating and cooking, thus disrupting fuel abundance and continuity. This limits fire spread and lengthens fire return intervals (Saladyga *et al* 2013, Guiterman *et al* 2019). The two sites (OKI, TAL) with relatively long MFI values (33 and 35 years) had culturally modified trees and other signs of past settlement. Some Buryat clan leaders acquired large herds during the 18th century, thus supporting the idea that pastoralist activities modified fuels and lengthened fire return intervals in certain locations (Forsyth 1992).

These interpretations are consistent with sites in northern Mongolia, where the dominant traditional livelihood for centuries has been semi-nomadic pastoralism. In a watershed near Ulaanbaatar, Mongolia, pastoral nomads moved seasonally with small herds until 1920. Prior to this, fires were spatially random, moderately frequent (5–20 year MFI) and synchronous among multiple sites (Saladyga *et al* 2013). As pastoralist movements became more restricted and herd size increased during the 20th century, this led to more intense grazing and fuel wood gathering surrounding permanent settlements. Fire declined dramatically at certain fire history sites in response to the reduction of available fuels (Hessl *et al* 2012, Saladyga *et al* 2013).

The western sites had shorter fire return intervals for the whole record, yet prior to 1900, there was no statistical difference between the regions (SI figures 3(A) and (B)). One uncertainty of comparing the regions is the low sample depth in the western site prior to 1900. By 1815, there were only three sites recording fire in the western sites, whereas five sites in the eastern region had been recording since the 1700s (table 1). Younger forests in the western sites may relate to cutting of forests along the Selenga River Valley to support development and population growth during the 19th century (Forsyth 1992, Pyne 1996, Moon 1997). After 1900, fire return intervals became significantly shorter in the western region compared to the eastern sites (SI figure 3(C)). Agricultural shifts and more extensive grasslands in the western region helps explain the shorter fire return intervals in the western sites during the 20th century. This is discussed further in the next section.

4.2. Temporal variations in fire frequency

Our study revealed multi-decadal variations in fire frequency with significantly more frequent fire occurring circa 1790, 1865–1880, 1948–1955 and 1995–2005 (figure 3(C)). These periods generally corresponded with migration waves and socio-economic changes in Buryatia. To expand the Russian empire, settlers from western Russia established forts and military presence in Buryatia starting in the mid-17th century (Forsyth 1992). Migration and settlement continued with the establishment of the Great Land Route (*Trakt*) in the late 18th century that connected western Russia to the trade city of Kyakhta on the Mongolian border (figure 1). Using this route, significant migration occurred from 1860 to 1890, when more than 1 million settlers crossed into Siberia, partly influenced by the end of serfdom in western Russia, when many freed peasants migrated to the eastern Frontier (Forsyth 1992, Moon 1997). As settlement increased, fire regimes were possibly affected by increased agricultural burning as settlers practiced farming in the adjacent valleys of many sites.

The completion of the Trans-Siberian Railway brought an influx of more than 4 million settlers to Siberia between 1906 and 1914, thus tripling the population of Buryatia to 800 000 inhabitants (Forsyth 1992). The rise in fire frequency and synchrony in the early-mid 20th century (figures 3(C) and (D)) suggests that population growth was associated with increased human-caused ignitions, socio-economic change and civil unrest following the establishment of the Soviet Union. Following the increased migration, new land allocations led to increased agricultural production and a decline in traditional pastoralist activities (Forsyth 1992). More importantly, during the collectivization period starting around 1930, food production was transferred to large state-controlled farms in the western region (Forsyth 1992). These agricultural shifts possibly contributed to increased fire frequency at individual sites in the western region (TUG, UBI), and to significantly high fire frequency from 1948 to 1955 (figures 3(A) and (C)). In contrast, completion of the railway may be responsible for declining fire frequency (longer fire return intervals) in the eastern sites after 1900 (figure 3(B), SI figure 3(D)). The railway bypassed the Uda Valley, possibly leading to relocation of people and resources away from the eastern region (figure 1).

Across the study area, fire activity moderately declined from late 1950s until 1979 (figure 3(C) and (D)), possibly in response to more effective fire prohibitions and active fire suppression during the Soviet Era. Starting in the 1960s, the Soviet Union developed a centralized fire management and research program, effectively suppressing up to 70% of fire activity surrounding settlements (Pyne 1996, Goldammer *et al* 2013). With the exception of widespread fires in 1969 and 1978, there were very few fires in Buryatia during this period, despite a period (1978–1982) of extreme drought (Andreev *et al* 1999). The decline in fire frequency in Buryatia is consistent with the Tuva region, where fire declined following an extensive fire in 1943, attributed to centralized fire-fighting efforts (Ivanova *et al* 2010).

A period of significantly high fire frequency, including many synchronous fire years, occurred from 1995 to 2005 (figures 3(C) and (D)). This episode followed the breakdown of the Soviet Union, when fire-fighting capacity was drastically reduced, thus limiting enforcement and suppression of fires related to arson, illegal logging, and agriculture. For example, abandoned slash piles may ignite and burn into forested areas, and arson is used to justify subsequent logging of fire-killed trees (Goldammer and Furyaev 1996, Ivanova *et al* 2010, Kukavskaya *et al* 2013a).

We found correspondence in the temporal patterns of fire occurrence with a study in the Transbaikal region near Romanovka approximately 400 km to the east (Wang *et al* 2021). Wang *et al* (2021) documented an increasing trend in fire occurrence (# fires/decade) from 1720 to 1920, when fire frequency peaked before a steady decline until 2010. We observed more temporal variations within the 20th century and a slightly later peak in fire frequency, but the relatively high fire occurrence around 1920 is consistent with our study. This suggests a common influence of rising populations in the Transbaikal region in the early 20th century. However, our record contrasts the Romanovka record in recent decades, when fire frequency and synchrony increased in our study area. This may relate to our sites being adjacent to broad grasslands with settlements and agricultural areas. In contrast, the Romanovka sites were located in larch-dominated forests with limited grasslands nearby. Our study is consistent with increasing trend in fire number since 1990 observed in regional-scale satellite and documentary records from southern Siberia (Ivanova *et al* 2010, Kukavskaya *et al* 2016, Kim *et al* 2020).

One of the most interesting trends of southern Siberia and northern Mongolia is that continuous fire activity occurred over the 400 year record, and that fire activity does not decline during 20th century. This contrasts other regions with extensive pine-dominated forests (e.g. northern Europe and much of western US), where fire frequency declined prior to the 20th century in response to land-use changes, effective fire suppression efforts and declining fuel availability (Swetnam and Baisan 1996, Wallenius 2011, Guiterman *et al* 2019, Kitenberga *et al* 2019). Fire history in central Siberia provides an exceptional opportunity to compare dendrochronology-based records with satellite and documentary records.

4.3. Fire–climate relationships

Synchronous fire years showed a significant association ($p < 0.05$) with regional drought, and this relationship was stronger when three or more sites burned in an event year (figure 5(A)). The relationship between water-year precipitation also showed negative departures in the event year, though the association was not significant. The significant associations with drought are consistent with northern Mongolia and further east in the Transbaikal region, where more extreme drought conditions influenced more extensive fires within each region (Hessl *et al* 2016, Wang *et al* 2021).

For 2 and 3 years prior to the event year, fires were significantly associated with increased moisture, indicated by the significant positive association of scPDSI and precipitation for 1–3 years prior to the event (figure 5). Such inter-annual wet/dry associations with synchronous fire years have been documented in temperate pine forests with grass understories, including pine-dominated stands in northern Mongolia (Swetnam and Baisan 1996, Hessl *et al* 2016, Guiterman *et al* 2019). These associations are generally ascribed to increased moisture promoting fine fuel (e.g. grasses and pine needle) production followed by widespread burning during dry years. When prior years are not significantly wet, as with the smaller subset of more synchronous fires (figure 5), it suggests that fuel availability was already sufficient for fire spread during the event year. This is consistent with the Wang *et al* (2021) study further east in the Transbaikal region, where larch-dominated sites have sufficient fuels.

Fire–climate relationships weakened after 1900, suggesting that human activities led to fire events that were out-of-sync with regional climate during the 20th century. This is consistent with the Krasnoyarsk region of Siberia, where fire activity did not correspond with climate after 1900, also attributed to the completion of the Trans-Siberian railroad and increased human-caused ignitions (Swetnam 1996). With additional human-caused ignitions, small fires consume fuels surrounding roads and infrastructure, leading to more discontinuous fuels on the landscape. Therefore, fires spread is less extensive, even when sufficient ignitions and extreme climate conditions coincide. In northern Mongolia, fire–climate relationships were non-existent at sub-regional scales related to intense grazing and limited fuels since 1920 (Saladyga *et al* 2013). Our results contrast the strong and significant relationship between fire and drought in the Romanovka study area to the east (Wang *et al* 2021). With limited grasslands surrounding larch-dominated sites, the strong fire–climate relationships persisted after 1900, suggesting that human influences on fire regimes can be variable within regions.

We also suggest that weaker fire-drought relationships after 1900 may result from a disconnect between additional seasonal climatic influences on fire activity and the summer PDSI metric we used for the SEA. Recent analysis for southeast Siberia showed that higher area burned was associated with warmer late-winter (February/March) temperatures, windy conditions and earlier snowmelt prior to the April–May fire season (Kukavskaya *et al* 2016, Kim *et al* 2020), which may not influence the summer PDSI values. Furthermore, especially in grass-dominated sites as ours, fires can occur following short, intense drought conditions in April and May, that would not have influenced summer PDSI values (Farukh *et al* 2009, Ivanova *et al* 2010). As winter and spring temperatures become warmer throughout the region (Demina *et al* 2022), climate conditions that promote extensive fire spread may occur more often during spring season.

5. Conclusions

Our study expands fire history knowledge for the forest-steppe ecotone of the southern-central Siberia (Ivanova *et al* 2010, Saladyga *et al* 2013, Hessl *et al* 2016) and provides an important long-term context for trends observed in shorter satellite-based records (Farukh *et al* 2009, Kukavskaya *et al* 2016). There is vast potential for more fire-scar collections in the pine-dominated forests of the southern Boreal forests. If additional networks can be developed, there is immense opportunity for evaluating human, fire and climate interactions at regional scales, especially with more detailed information on land-use history and human activities. Furthermore, multiple regions can be combined to address questions about fire–climate relationships and potential carbon emissions at subcontinental scales. Finally, Siberia is possibly the only region in the world, where overlap among fire-scar and satellite records allows for a detailed comparison of area burned and fire frequency estimates between the two methods.

Given the close associations between human activities and fire that we describe, we suggest that fire regimes are possibly more tied to changes in human-caused ignitions than climate during the 20th century, despite years of extreme drought and warming temperatures in recent decades (Kukavskaya *et al* 2016, Kim *et al* 2020, Demina *et al* 2022). The close association with human activities suggests that effective conservation planning and fire management strategies can be achieved. Further work to disentangle these two factors is warranted and necessary to support appropriate conservation plans and fire management along the forest-steppe ecotone.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.ncei.noaa.gov/products/paleoclimatology/fire-history. Data will be available from 01 April 2022.

Acknowledgments

We thank Josh Farella, Sergey Zhila and Eleonora Maady for field assistance. The Baikal Institute of Nature Management SB RAS provided generous logistical support, including vehicles, equipment and connections with local foresters. Anna Penaloza prepared and crossdated samples at the Laboratory of Tree-Ring Research. Materials are archived at the LTRR. We thank Erin Hanan for helpful comments on a preliminary draft of the manuscript. We thank two anonymous reviewers for thorough and helpful comments on the submitted manuscript. This work was supported by NASA Terrestrial Ecosystems Program Grant # 08-TE08-0029.

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