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Key Points:
- Elevated temperatures have not increased fire activity relative to the past 500 years
- Historically, current year and antecedent drought were important drivers of fire activity
- Intensive grazing and drought since the 1990s synergized to reduce fuels and fire activity

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

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Fire and climate in Mongolia (1532–2010 Common Era)

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Abstract Recent increases in wildland fire, warming temperatures, and land use change have coincided in many forested regions, making it difficult to parse causes of elevated fire activity. Here we use 20 multicentury fire scar chronologies (464 fire scar samples) from Mongolia to evaluate the role of climate forcing of fire in the context of livestock grazing and minimal fire suppression. We observe no change in fire return intervals post-1900; however, since the 1500s, periods of drought are coincident with more fire and shorter fire return intervals. We observe same year and some antecedent year effects of drought on fire, a pattern typical of semiarid forests elsewhere. During the instrumental period, drought remains an important driver of fire; however, limited fire activity in recent decades may be due to the coincidence of drought and intensive grazing that have synergized to reduce fuel continuity and fire spread.

1. Introduction

Recent increases in wildland fire in semiarid regions have brought attention to the potentially severe atmospheric, ecological, and economic effects of changing climate and longer fire seasons [*Amiro et al.*, 2001; *van der Werf et al.*, 2006; *Attiwill and Binkley*, 2013]. In the western United States, warming temperatures, a longer snow-free season, fire suppression, and the spread of invasive fire-prone grasses have all coincided with increases in large forest fires [*Swetnam and Betancourt*, 1998; *Westerling et al.*, 2006; *Balch et al.*, 2013; *van Mantgem et al.*, 2013]. The coincidence of these processes in time and space makes drivers of change difficult to parse. While increases in temperature are nearly ubiquitous [*Intergovernmental Panel on Climate Change*, 2013], land use changes, including active fire suppression and grazing, have a more place and time-specific history. For example, in many semiarid regions worldwide, domesticated animals have grazed for millennia [*Di Cosmo*, 2002; *Hanotte et al.*, 2002; *Cribb*, 2004] and may have disrupted fuel continuity and fire spread [*Swetnam and Betancourt*, 1998]. Further, in developing countries, active fire suppression was often more limited and less effective than in the western United States and other developed regions [*Pyne*, 1996]. Differing land use histories in the presence of warming and drying climates can serve as a point of comparison between areas across the globe, potentially isolating important drivers of wildland fire that will continue to affect semiarid ecosystems in coming decades. Disentangling these interacting drivers requires large and long networks of fire activity spanning major changes in both climate and land use, ideally from multiple locations worldwide [*Hessl*, 2011].

Networks of fire scar and tree recruitment chronologies document long-term and broad-scale responses of fire regimes and forest demography to climate variations and land use change across North and South America [*Swetnam and Betancourt*, 1998; *Kitzberger et al.*, 2001; *Hessl et al.*, 2004; *Brown and Wu*, 2005; *Falk et al.*, 2011; *Iniguez et al.*, 2015]. These studies have found that drought during the year of fire is a widespread driver of past synchronous fire activity across regions [*Hessl et al.*, 2011; *DeRose and Long*, 2012; *Mundo et al.*, 2013], a result consistent with modern studies of fire and drought [*Littell et al.*, 2009; *Dennison et al.*, 2014]. Furthermore, where grassy fuels are abundant, elevated moisture in the few years preceding a fire may induce widespread events through the accumulation of fine fuels [*Swetnam and Betancourt*, 1990; *Veblen*, 2000; *Brown and Wu*, 2005; *Iniguez et al.*, 2015]. Temperature may modulate fire activity both during the summer season when it affects fire weather conditions [*Trouet et al.*, 2009] and in the spring and fall when high temperatures lengthen the fire season, allowing for greater fire spread [*Westerling et al.*, 2006]. However, not all fuel types may respond to warming with increased fire activity, particularly where human modifications of the landscape dominate [*Hessl*, 2011; *Bradstock et al.*, 2014].

Tree ring-based fire histories from western North America are limited in their assessment of fire regime responses to recent climate changes because of fire cessation that began in most forests in the late nineteenth century. Presettlement fires burned mainly through grass and herbaceous fuels, and widespread and intensive livestock grazing that accompanied settlement had a threshold impact on fuel continuity and biomass [*Savage and Swetnam*, 1990; *Swetnam and Betancourt*, 1998; *Mundo et al*., 2013]. Later in the twentieth century, active fire suppression had additional effects on many fire regimes [*Fulé et al*., 1997; *Collins and Stephens*, 2007], though others were apparently less affected [*Schoennagel et al*., 2004]. These land use changes altered fire regimes in concert with climate change during the twentieth century, making it difficult to separate climate from land use effects in recent decades.

Though much is known about wildfire and climate in western North America, less is known about fire in semiarid forests globally. Semiarid forests cover ~17% of the Earth's land surface and play a critical role in carbon regulation [*Lal*, 2003; *Rotenberg and Yakir*, 2010; *Poulter et al*., 2013]. In addition, semiarid forests are capable of rapid state changes from forest to grassland that can result in large impacts on local and global climate via changes in albedo [*Rotenberg and Yakir*, 2010]. Semiarid forests of Asia constitute the largest region of semiarid forest in the world, but little is known about wildland fire there [*Hessl et al*., 2011]. Relative to western North America, these forests have a profoundly different and much longer land use history, with potential to modify interactions between fire and climate.

Mongolia contains large areas of semiarid forest with grass understory, similar to the semiarid forests of the Intermountain West. Mongolian forests are located at midlatitude to high latitudes, are dominated by a few conifer species (several of which readily record fire scars), and experience a range of fire behaviors under highly variable moisture regimes. However, at least two key differences between the regions exist. First, Mongolia has a long tradition of nomadic pastoralism, practiced for more than 4000 years, though grazing intensity has varied spatially and temporally as a result of differing political, social, and economic forces [*Fernandez-Gimenez*, 2000; *Endicott*, 2012]. Second, due to limited funds, Mongolia's forests experienced only limited fire suppression for a few decades in the twentieth century (1969–1992), though Russian fire fighting may have reduced fire activity near the border since the 1950s (Col. Gongor Chuluun, Chief Aerial Fire Fighting Department, Mongolia, retired, personal communication, 2016).

Mongolia experienced a 1.4°C increase in mean temperatures from 1940 to 2001 [*Batima et al*., 2005] with stronger warming occurring since 2001 [*Cook et al*., 2013; *Pederson et al*., 2014; *Davi et al*., 2015]. Mongolian tree ring records indicate that the twentieth century was one of the warmest centuries of the last 1200 years [*D'Arrigo et al*., 2000, 2001; *Davi et al*., 2015]. Further, Mongolia experienced a severe drought in 1996–2011, characterized by elevated temperatures and reduced precipitation relative to the last 400–900 years [*Davi et al*., 2013; *Pederson et al*., 2014]. Observational records of the frequency and aerial extent of the forest and steppe fires in Mongolia indicate an increase in fire activity over the last ~50 years [*Goldammer*, 2002, 2004, 2007] coincident with warming temperatures. However, little is known about the long-term variability in fire activity making it difficult to attribute the effects of recent climate change on the observed increase in fire activity.

In this study, we develop a regionally extensive network of multicentury fire scar chronologies across northern Mongolia to evaluate the long-term role of climate forcing of fire in the context of intensive livestock grazing. We evaluate whether recent warming has caused unprecedented changes in fire regimes in the context of the past five centuries.

2. Materials and Methods

Located in Inner Asia, Mongolia is characterized by an extremely continental climate. Temperatures range from approximately −18°C in winter to approximately 16°C in summer. Total annual precipitation is low (252 mm) and peaks in summer when approximately 72% of precipitation occurs [*Davagdorj and Mijiddorj*, 1996]. In the forested and mountainous areas of central and northern Mongolia, total annual precipitation is higher, ranging from 300 to 400 mm [*Batima et al*., 2005]. No single synoptic system strongly influences the Mongolian climate except the Siberian High, centered over Mongolia from winter to late spring [*Samel et al*., 1999; *D'Arrigo et al*., 2005]. The westerlies currently dominate warm-season moisture transport [*Bohner*, 2006], though the East Asian Monsoon and El Niño–Southern Oscillation might have stronger influence on eastern Mongolia [*Yatagai and Yasunari*, 1995; *Grove*, 1998; *Samel et al*., 1999; *Endo et al*., 2006]. There is some

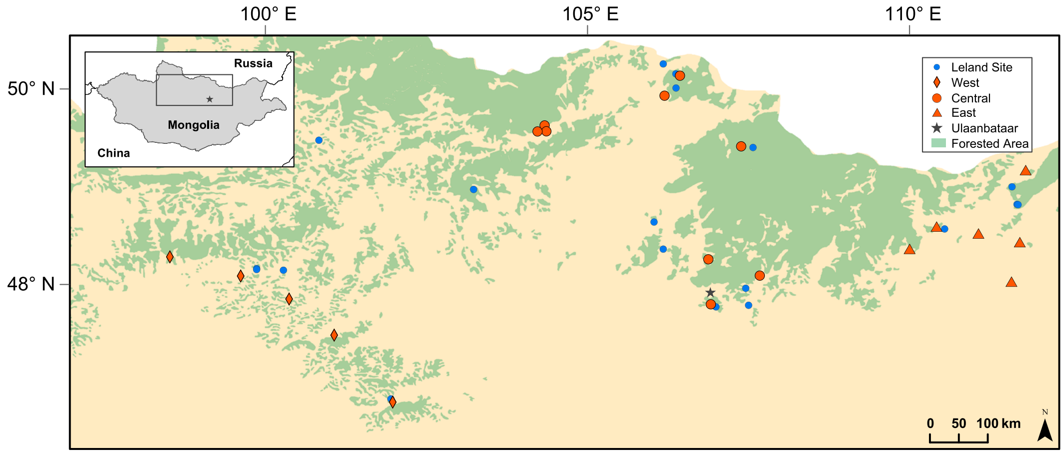

Figure 1. Fire chronologies and drought sites. Location of 20 fire sites in the western (diamonds), central (large circles), and eastern regions (triangles) and tree ring drought sites used in *Leland et al.* [2013] to generate the regional tree ring chronologies (small circles).

evidence that summer North Atlantic Oscillation affects climate in East Asia, although effects are yet to be confirmed [*Linderholm et al.*, 2013].

About one third of Mongolia, mainly in the Khangai and Khentii Mountains, is forested. Mongolian forests are situated at the interface between the western Siberian dark taiga dominated by *Pinus sylvestris* (L.), the eastern Siberian light taiga, dominated by *Larix sibirica* (Ledep.) and the Mongolian forest steppe zone [*Ermakov et al.*, 2002]. As in other arid forests, fire regimes in the forest steppe ecotone are characterized by surface fires fueled by fine grasses and woody fuels. The fire season in Mongolia has two peaks with 80% of fires occurring between March and mid-June and 5–8% occurring during a short period in September and October [*Valendik et al.*, 1998]. Fires are rare during the summer months when precipitation is greatest. Annually, 50–60 forest fires occur in Mongolia, of which 80–95% are thought to be human caused [*Goldammer*, 2004; *Wyss and Fimiarz*, 2006]. Unlike other pastoralists, Mongolian herders are not known to deliberately use fire to clear land or encourage grassland productivity, suggesting that the majority of human ignitions are unintentional.

We selected study sites in the forest steppe ecotone from three prior investigations (Figure 1), each with specific sampling designs [*Hessl et al.*, 2011; *Saladyga et al.*, 2013; B. Suran, unpublished data, 2016]. At all study sites, we collected 6–140 (median = 13) partial cross sections from fire-scarred trees, snags, logs, and stumps (Table S1 in the supporting information). Each site included 1–19 (mode = 1) target areas, each of which covered ~5 ha in size. In each target area, we searched for fire-scarred trees, stumps, and logs. Trees and stumps with multiple visible scars were prioritized for sampling to build the longest chronology possible for each site. At the northern and eastern sites (Table S1), fire-scarred samples were mostly obtained from *Pinus sylvestris*. The western sites contained fewer *P. sylvestris*, and samples were obtained primarily from dominant *Larix sibirica*.

Samples were sanded until individual cells were visible under magnification (600–1000 grit sandpaper). Fire scars were crossdated against existing master chronologies from the region [*Leland et al.*, 2013; *Pederson et al.*, 2013]. The year and season of fire (if distinguishable) were recorded in FHX2 format for each fire scar observed in cross section [*Grissino-Mayer*, 2001]. Since *Larix* species tend to produce “scarlets” (nonfire-related cambial lesions of an unknown source, Figure S1) once a tree has been scarred, only the most obvious fire scars were recorded. Scarlets were recorded as injuries that were later converted to fire scars if they occurred in >1 tree at a site during the same year. Since 80% of all fires in the modern record occur from March to mid-June, we assigned fire scars that fell within the dormant season to the subsequent year (i.e., spring fires that occurred before growth began for that year).

To identify synchronous fire events across Mongolia and to develop long records of fire capable of recording change over time, we developed time series of all fire events that scarred $\geq$2 trees and $\geq$10% of the recorder trees (those trees that were alive during that event year) at each site using FHAES software (https://www.frames.gov/partner-sites/fhaes/fhaes-home/). These methods have been used extensively to filter fire scar records, particularly where uneven sample size and sample area could affect results [*Falk et al.*, 2011].

From these site series, we compiled three regional fire history chronologies (west, central, and east) of number of sites burned (Figure 1 and Table S1). Regions were identified based on differences in hydroclimatology observed in drought-sensitive tree ring records over the last 400 years [*Leland et al.*, 2013]. We also developed a study area wide north central Mongolia (NCM) fire history including only those fire years when ≥10 samples recorded fire in at least three separate sites. We compared our NCM record to a national observational record of area burned (1981–2010) [*Goldammer*, 2002, 2004, 2007]. To evaluate the synchrony of fires burning at multiple sites in the same year, we calculated the joint probability of each combination of sites burning in each year relative to random timing among sites with the same fire return intervals.

We calculated site, regional, and NCM fire return intervals. Fire return intervals at individual locations are subject to the number of samples collected and the area sampled [*Van Horne and Fulé*, 2006; *Farris et al.*, 2013]. Here we calculated mean point fire return intervals (PFRIs) at individual sites and a filtered record of fire events (≥2 samples scarred and ≥10% scarred) for regions (west, central, and east) and all sites (NCM) to limit this effect. We evaluated change in fire frequency in the NCM record over the last two centuries by comparing the distribution of fire return intervals in the nineteenth century to that of the twentieth to 21st century using the Kolmogorov-Smirnov test.

We also compared regional fire history records (west, central, and east) to previously published regionalized tree ring indices of growing season drought derived from the same regions [*Leland et al.*, 2013]. We compared NCM fire history with a new version of the Monsoon Area Drought Atlas (MADA v2) [*Cook et al.*, 2010] and the Asia 2k June–August temperature reconstruction for Asia [*PAGES 2k Consortium*, 2013], each derived from hundreds of tree ring sites across Asia. MADA v2 is a gridded (0.5° grid) reconstruction of June–August scPDSI (self-calibrating Palmer Drought Severity Index) from which we subset the Mongolian region (39.25–54.75°N, 80.25–124.75°E).

We used superposed epoch analysis (SEA) to investigate the current year and lagged relationships between fire and nonfire years and tree ring-derived drought and temperature reconstructions. SEA identifies statistical, nonlinear relationships between climate variables and fire years. Mean values of drought were calculated for 7 year windows centered on fire and nonfire years identified by the fire event chronologies (regional and NCM). For the regional fire event series, we used the regionalized tree ring-inferred drought indices [*Leland et al.*, 2013]. For the NCM fire event series, we used reconstructed scPDSI from MADA v2 [*Cook et al.*, 2010] and reconstructed summer temperature from Asia 2k [*Cook et al.*, 2013]. We chose 7 year windows to evaluate conditions preceding the fire that may be linked to fuel buildup. These fire and nonfire drought values were compared with the tree ring drought indices over the entire period of study (1790–1994 for the regional indices and 1500–2010 for MADA v2) and tested for significance using Monte Carlo simulations that randomly pick years, identify 7 year windows, calculate expected means, and provide 95% bootstrap confidence intervals.

To explore the spatial pattern of climate drivers on fire activity, we compared our NCM record of fire and nonfire years during the period of instrumental record (1940–2010) with gridded composites of May–August scPDSI [*van der Schrier et al.*, 2013] and temperature (CRU TS3.23). We also compiled composites of reconstructed June–August scPDSI and temperature during fire and nonfire years using Asia2k and MADA v2, respectively.

3. Results

We reconstructed fire activity from 20 sites and 464 fire-scarred samples collected across the forest steppe region of north central Mongolia (Table S1). Fire scars occurred predominantly between rings (30%) or in the earlywood (50%), consistent with the modern record fire season (Table S2). Recorded fires begin in 1532 Common Era (C.E.) and extend to 2009 C.E., with the last samples collected in 2010 C.E. Fire activity was not constant over this time period. Fire was elevated during the late nineteenth century in the west and central regions and higher in the east between ~1750 and 1825 C.E. (Figure S2). In all three regions, but especially in the east, fire activity waned during the midtwentieth century, resuming in the late twentieth and early 21st century. Results of joint probability analysis indicate that fires are unlikely to occur across any three sites in the same year, with probabilities <0.008. Periods of high fire synchrony, when these probabilities are exceptionally low given fire return intervals at each site, are concentrated in the late 1800s, early 1900s, and the most recent 1996 and 1997 fire years (Figure S2).

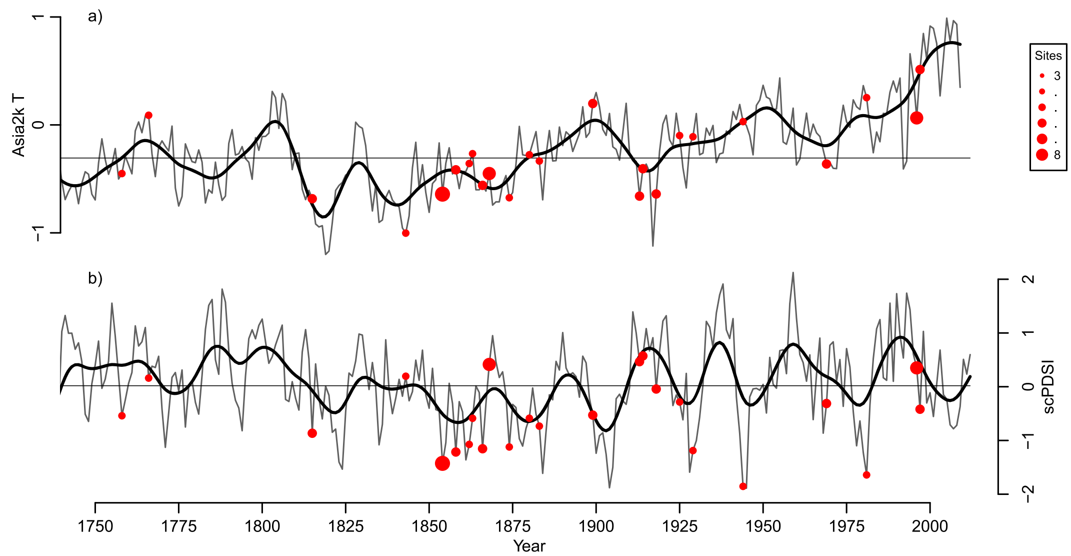

Figure 2. Comparison between reconstructed temperature, soil moisture, and fire activity. Asia 2k June–August (a) temperature reconstruction over Mongolia [*Cook et al.*, 2013] and (b) reconstructed June–August scPDSI (MADA v2 [*Cook et al.*, 2010]) over Mongolia. Thick black lines are smoothed series using a 20 year spline, and black lines are the mean for each series. The 48 fire events affecting ≥3 sites in the NCM chronology are plotted over each series (circles are scaled to the number of sites burning).

The largest fire years in the observational record (1982 to present) are 1996 and 1997, but these rank as third and twelfth (respectively) in our fire history record (Table S2). With the exception of 1913, 1914, 1918, and 1996, the top 10 years with the most fire activity in our NCM reconstruction occurred during the dry 1800s, suggesting that NCM has experienced large fire events in the last 500 years on par with or exceeding those observed in the late twentieth century.

PFRIs on individual samples range from 8 to 26 years with a mean of 18 years (Table S1). Intervals are slightly shorter in the west and longer in the east, which reflect differences in forest and fuel type. Western sites dominated by *L. sibirica* have more coarse fuel, and eastern forests dominated by *P. sylvestris* have more grassy fuel. Over the entire study area, a Kolmogorov-Smirnov test suggests that the distribution of filtered fire return intervals in the nineteenth versus the twentieth to 21st centuries are not significantly different ($D = 0.339$, $p = 0.19$) (Figure S3).

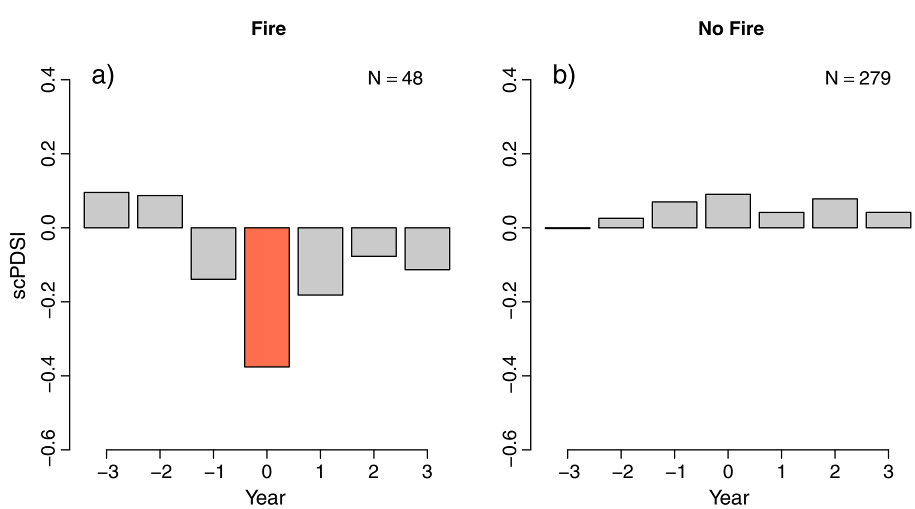

Figure 3. Soil moisture during fire and nonfire years. Superposed epoch analysis (SEA) of scPDSI during fire ($N = 48$) and no fire ($N = 279$) events synchronously affecting ≥3 sites in the NCM chronology. Significant ($p < 0.01$) lags in red are derived from 1000 Monte Carlo draws of reconstructed scPDSI (1500–2010) [*Cook et al.*, 2010], where values >0 indicate wet conditions and values <0 indicate dry conditions.

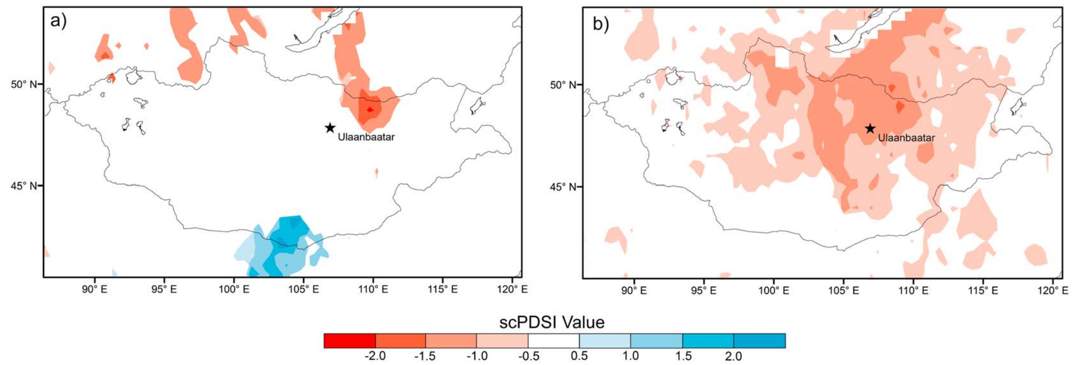

Figure 4. Composites of instrumental and reconstructed soil moisture during fire years. Mean of (a) May–August scPDSI [*van der Schrier et al.*, 2013] during fire years from the NCM chronology ($n = 8$) and (b) reconstructed June–August scPDSI from MADA v2 [*Cook et al.*, 2010] during fire years ($n = 48$) from the NCM chronology. Colored portions of the map indicate significant ($p < 0.05$) differences (negative departures) relative to the long-term means of instrumental (1940–2010) and reconstructed (1500–2010) scPDSI.

Rather than observing more fire activity in recent decades associated with recent warming, we instead observe an association between interannual to decadal-scale drought and fire activity that continued since the 1500s (Figure 2). Periods of drought, (i.e., 1850–1900) are coincident with greater fire activity, while periods of moisture, (i.e., 1775–1825) are coincident with the absence of fire. SEA results indicate strong same year and in some cases antecedent year effects of drought on fire and its absence (Figures 3 and S4). For the central and eastern regions, tree ring indices of moisture were elevated in $T-1$ to $T-3$ years and were significantly reduced during year T (Figure S4). Moisture indices during nonfire years showed an inverse pattern, with year T moisture significantly elevated (Figure S4). These patterns were not significant in the west where sites are larch dominated and fuels are coarser. At the scale of NCM, the pattern of moisture is similar, with reconstructed scPDSI from MADA v2 during the year of the fires (T) being significantly drier (Figure 3a). Nonfire years show no significant excursions in moisture (Figure 3b). We observed no significant departures in reconstructed temperature (Asia 2k) during fire and nonfire years (Figure S5).

During the instrumental period, the NCM fire chronology recorded eight fires that affected ≥3 sites and ≥10% trees at these sites (1944, 1969, 1978, 1981, 1994, 1996, 1997, and 2007). During this same period, 26 years had no fires recorded at any site. Seasonal composites indicate that growing season (May–August) scPDSI particularly in north central Mongolia was significantly drier during fire years (Figure 4). The spatial patterns of drought observed during the modern period were similar to composites using the reconstructed June–August scPDSI (Figure 4), even though fires were mostly recorded in the dormant and earlywood (Table S2). This could be due to (1) memory in the calculation of scPDSI such that dry spring scPDSI affects calculations of June–August or (2) persistently dry conditions during fire years that continue from spring through summer. We observed no significant departure from mean reconstructed or instrumental scPDSI during nonfire years nor any significant departures in reconstructed temperature during fire and nonfire years (results not shown).

4. Discussion

Increased fire activity driven by rising temperatures could have serious effects not only on Mongolia's forests and ecosystems but also at larger scales on the location of the southern extent of the boreal forest and global carbon dynamics. Despite elevated temperatures since 1940, we did not observe changes in fire frequency between the nineteenth and twentieth centuries. Mongolian and Soviet fire suppression may have reduced fire activity near the border with Russia between 1969 and 1992, but active fire suppression was greatly reduced thereafter and fire activity has not increased since. Extensive, synchronous fires in 1996 and 1997 occurred at the beginning of a severe drought that followed four decades of elevated moisture in Mongolia [*Davi et al.*, 2013; *Pederson et al.*, 2013, 2014], but these fires were not unprecedented in extent or synchrony relative to fires in the nineteenth century. Further, we observed no significant relationship between interannual variations in temperature and fire activity, a result that differs from previous studies in central Siberian larch forests where temperature may have a more direct effect on fuel condition in permafrost [*Kharuk et al.*, 2008, 2013]. In summary, our data do not support the hypothesis that elevated temperatures have increased fire activity in Mongolia.

We did, however, observe consistent spatial and temporal patterns of drought during fire years, both during the instrumental period and over the last 500 years, indicating that drought has been associated with fire despite a long history of changing land use and changing temperature. During the year of high fire activity, conditions were dry, especially in northern Mongolia over the Khentii Mountains. SEA results for the central and eastern regions also document elevated moisture conditions in the 1–3 years preceding fire years, a pattern observed in other semiarid forests where grassy fuels support fire spread [*Swetnam and Betancourt*, 1990; *Swetnam*, 1996; *Veblen*, 2000; *Heyerdahl et al*., 2002].

Ongoing and severe drought conditions in Mongolia since 1996 [*Davi et al*., 2013; *Pederson et al*., 2014] would then suggest continued elevated fire activity, but instead, we observe high fire activity only in 1996 and 1997 with near-average conditions since. We speculate that limited grassland productivity due to drought in combination with elevated livestock grazing reduced fuel connectivity thereby preventing the spread of large wildfires. This explanation is supported by more intensive work on one site included here (TUL) [*Saladyga et al*., 2013] where heavy use by people and their domesticated grazing animals following the fall of communism in the 1990s reduced, and in some cases eliminated, fire from individual sites. Where both fire and grazers are common, they may "compete" as consumers of grassy fuels [*Bond and Keeley*, 2005], a pattern that may explain the rise in fire activity observed in Australia and North America following megaherbivore extinctions [*Gill et al*., 2009; *Rule et al*., 2012]. In savanna and woodlands in Africa, the more recent introduction of domesticated grazers has also reduced connectivity and fire spread [*Archibald et al*., 2012]. Droughts reduce the availability of fine fuels for consumers, potentially synergizing with grazers to promote fire exclusion. Mongolia has hosted increasingly large numbers of domestic grazers in recent decades [*Saizen et al*., 2010; *Liu et al*., 2013] coincident with widespread drought, a pattern we observe across all aimags (provinces) studied here (Figure S6). This combination of forces may have been sufficient to reduce the effects of elevated temperature and recent drought on fire activity. In other regions where grassy fuels limit fire spread and where domesticated (or wild) ungulates occur in high densities, elevated temperatures and droughts may not result in sustained wildfire activity.

5. Conclusion

Fire scar records from 20 sites and 464 trees across NCM document no clear increase in widespread fire activity during the twentieth and 21st centuries. Rather, fires were associated with interannual variability in moisture conditions. Though persistent drought affected Mongolia for more than a decade in the early 2000s, fire activity did not continue to escalate but instead returned to near-mean conditions. We speculate that intensive grazing reduced grassland fuels and limited widespread fire. These results have major implications for heavily grazed semiarid forests, woodlands, and savannas as well as locations where grazing animals have been limited or removed from the landscape coincident with increased fire activity. In semiarid regions, carefully managed grazing may outcompete fire for fuel, thereby mitigating wildfire activity under a changing climate.

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