Reconstructing fire history in central Mongolia from tree-rings

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Abstract. Rising temperatures are expected to increase wildfire activity in many regions of the world. Over the last 60 years in Mongolia, mean annual temperatures have increased \(~2^{\circ}C\) and the recorded frequency and spatial extent of forest and steppe fires have increased. Few long records of fire history exist to place these recent changes in a historical perspective. The purpose of this paper is to report on fire history research from three sites in central Mongolia and to highlight the potential of this region as a test case for understanding the relationships between climate change, fire and land use. We collected partial cross-sections from fire-scarred trees and stumps at each site using a targeted sampling approach. All three sites had long histories of fire ranging from 280 to 450 years. Mean Weibull fire return intervals varied from 7 to 16 years. Fire scars at one protected-area site were nearly absent after 1760, likely owing to changes in land use. There is limited synchrony in fire occurrence across sites, suggesting that fire occurrence, at least at annual time scales, might be influenced by local processes (grazing, human ignitions, other land-use factors) as well as regional processes like climate. Additional data are being collected to further test hypotheses regarding climate change, land use and fire.

Additional keywords: climate change, forest-steppe, land use.

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Introduction

Rising temperatures are expected to increase wildfire activity in many regions of the world (IPCC 2007). In Mongolia, mean annual temperatures have increased \(~2^{\circ}C\) from 1940 to 2010 while spring precipitation has declined 17\% (Batima \textit{et al.} 2005). Most of the warming has occurred in winter, potentially leading to earlier snowmelt and a longer growing season (De Grandpré \textit{et al.} 2011). Mongolia has also experienced an increase in the frequency and intensity of droughts in the last three decades (Batima \textit{et al.} 2005). These changes in climate may be associated with increases in the frequency and areal extent of forest and steppe fires observed over the last \(~50\) years (Goldammer 2002). However, a longer-term record of fire history is necessary to put recent changes in the fire regime into historical perspective, particularly within the context of land-use change.
Although Mongolia has not had an effective fire suppression policy, it has undergone a series of important land-use changes alongside climate change in the last 100 years. Livestock production has been Mongolia’s dominant economic engine for millennia, but the intensity of pastoral land-use has varied over the last several centuries coincident with political and economic changes (Fernandez-Gimenez 2000). Mongolia’s human population is currently 2.5 million whereas the livestock (camels, cattle, horses, sheep and goats) population exceeds 40 million (FAO 2010). Approximately one-third of the people in Mongolia practice pastoralism, although approximately half of the nation’s population depends directly or indirectly on the pastoral economy for their livelihood (Fernandez-Gimenez 2000). As grazing intensity has varied over time, fine fuels undoubtedly varied as well, which might have affected the extent, timing and frequency of forest fires. Simultaneously, policies and regulations related to pastoralism and the use of non-timber forest products may have resulted in changes in fuels and human ignitions over time (Valendik et al. 1998; Wyss and Fimiarz 2006). These land-use changes have acted either independently or in concert with climate variability in affecting Mongolia’s fire regimes.

Records of long-term variability in fire regimes and their associated drivers (e.g. climate, land use) can help place current fire regimes into a historical perspective and disentangle the effects of land use and climate change on fire. A range of paleoclimatic information has been collected in Mongolia (Jacoby et al. 1996; D’Arrigo et al. 2000, 2001; Pederson et al. 2001; Fowell et al. 2003; Davi et al. 2006, 2009; Prokopenko et al. 2007; Schwanghart et al. 2009; De Grandpré et al. 2011); however, little long-term fire history information exists to evaluate whether recent fire activity is historically anomalous. The purpose of this paper is to report on preliminary fire history research from three sites in central Mongolia and to highlight the potential of this region as a test case for understanding the relationships between fire, climate change and land use. Our results cover three major forest types in Mongolia (forest-steppe, taiga and pine woodlands) and include forests with long histories of intensive human land use (Bogd Khan Mountain) as well as those with more limited

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**Fig. 1.** Vegetation land cover in Mongolia and general location of study sites (rectangle) near Ulaanbaatar (black star). Inset includes Ulaanbaatar (black star) and the three study sites (red triangles).
access (Forestry Research Center of the National University of Mongolia).

**Study area**

Mongolia is located in central Asia, bordered on the north by Russian Siberia and to the east and south by China (Fig. 1). Mongolia is characterised by an extremely continental climate. Mean monthly temperatures in central Mongolia range from approximately –18°C in winter to 16°C in summer, though winter temperatures have been rising since the 1940s (Davagdorj and Mijiddorj 1996; Jacoby et al. 1996; Valendik et al. 1998). Total annual precipitation in Mongolia is low (252 mm) and peaks in summer when ~72% of annual precipitation falls as rain (Davagdorj and Mijiddorj 1996). However, in the forested and mountainous areas of central and northern Mongolia, total annual precipitation is higher, ranging from 300 to 400 mm. The growing season extends from May to August. No single synoptic system strongly influences Mongolian climate except perhaps the winter Siberian High, which is centred over Mongolia from winter through late spring (Samel et al. 1999; D’Arrigo et al. 2005). Though decadal variability in drought exists (Pederson et al. 2001, Davi et al. 2006), it is of unknown cause.

Although most of Mongolia is either steppe or desert, approximately one-third of the country, mainly in the north, is forested. This ecoregion is dominated by *Larix sibirica* (Ledep.), *Pinus sibirica* (Du Tour), *P. sylvestris* (L.) and *Betula platyphylla* (Sukaczew). Other important tree species present in the region include *Populus tremula* (L.), *Picea obovata* (Ledebr.) and *Abies sibirica* (Ledebr.). As in other arid forests, fire regimes in central Mongolia are predominantly surface fires fuelled by fine grasses and woody fuels. Approximately 80% of fires occur in spring (Goldammer 2002) and ~90% of fires are ignited by people (Wyss and Fimiazi 2006).

We compared fire history derived from fire-scarred trees from three sites (Table 1: Fig. 1): Bogd Khan Mountain (Bogd), Forestry Research Center of the National University of Mongolia (Center) and Tujin Nars. The sites are located along a 300-km north–south transect that extends along the transition zone between forest-steppe in the south at Bogd and boreal forest regions in the north near Tujin Nars.

Bogd Khan Mountain, located 15 km south of Ulaanbaatar and originally protected by Chinggis Khan in the 12th century, is one of the world’s oldest officially protected areas (UNESCO World Heritage, see http://whc.unesco.org/en/tentativelists/936/, accessed 12 September 2011; De Grandpré et al. 2011). Though Bogd has been protected from logging for centuries, its proximity to the capital city indicates long-term intensive use for grazing and non-timber forest products. The Bogd site is dominated by *Pinus sylvestris* and *P. sibirica*, with occasional *Larix sibirica* and *Betula platyphylla* stands. The Center site, located ~40 km north of Ulaanbaatar, does not have a history of protection and is representative of typical pine–larch forests in central Mongolia with moderate land use. Finally, Tujin Nars (Mongolian for ‘always pine’) is a monospecific stand of *P. sylvestris* located just south of the Russian border and is characterised by recent fires and post-fire logging beginning in the 1990s. Historical land-use of Tujin Nars is not known, but it is within 10 km of a border town (Sukhbaatar). Although Center and Tujin Nars have evidence of recent stand-replacing fire, Bogd does not. At Bogd, fire-scarred collections were primarily obtained from *L. sibirica* stumps under a canopy of mature *P. sylvestris*, whereas fire scar samples were collected from *P. sylvestris* and *L. sibirica* trees, snags, logs and stumps at Center. At Tujin Nars, samples were collected entirely from *P. sylvestris* logs, stumps and live trees.

**Methods**

Sampling was conducted in June 2006 (as part of the International Dendroecological Field Week), June 2007 and July 2009. A targeted sampling approach was used in all three areas to find the longest and most complete record of fire for each site. In targeted sampling, trees are selected based on the numbers of fire scars visible in fire-created ‘catfaces’ (Fig. 2; insets). At Bogd and Center, sampling of fire-scarred trees and stumps was conducted on mid- to upper-elevation slopes between 1700 and 1800 m above sea level. Approximate search areas were ~60 ha at seven locations for Bogd and ~40 ha at two locations for Center. At Tujin Nars, sampling occurred on small swales and ridges at lower elevations (~760 m) within a total search area of ~60 ha at four locations. We searched each site for fire-scarred living trees, snags and stumps. Partial cross-sections of fire-scarred trees were collected with a chainsaw. Additional age structure and fire scar collections have been made in these and other stands throughout Mongolia to investigate fire severity; however, these data are not discussed here.

Samples were planed and sanded until individual cells were visible under magnification (600–1000-grit sandpaper). Fire scars were crossdated against both an existing master

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**Table 1. Description of the three study sites including latitude (Lat.), longitude (Lon.), elevation (Elev.), number of sample points, number of live trees, number of stumps or logs, total number of dated scars (#Scars), first ring and last ring for each fire history time series**

<table>
<thead>
<tr>
<th>Site</th>
<th>Lat.</th>
<th>Lon.</th>
<th>Dominant species</th>
<th>Area sampled (ha)</th>
<th>Elev. (m)</th>
<th>Points</th>
<th>Live trees</th>
<th>Stumps, logs</th>
<th>#Scars</th>
<th>First ring</th>
<th>Last ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogd</td>
<td>47°48'</td>
<td>106°57'</td>
<td><em>Larix sibirica</em></td>
<td>60</td>
<td>1750</td>
<td>7</td>
<td>0</td>
<td>17</td>
<td>56</td>
<td>1550</td>
<td>2005</td>
</tr>
<tr>
<td>Center</td>
<td>48°15'</td>
<td>106°53'</td>
<td><em>L. sibirica</em></td>
<td>40</td>
<td>1600</td>
<td>2</td>
<td>13</td>
<td>4</td>
<td>31</td>
<td>1660</td>
<td>2005</td>
</tr>
<tr>
<td>Tujin Nars</td>
<td>50°04'</td>
<td>106°22'</td>
<td><em>Pinus sylvestris</em></td>
<td>60</td>
<td>760</td>
<td>4</td>
<td>20</td>
<td>14</td>
<td>239</td>
<td>1704</td>
<td>2009</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>160</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>326</td>
<td>1550</td>
<td>2009</td>
</tr>
</tbody>
</table>
Fig. 2. Fire-scar chronologies from Tujin Nars, Center and Bogd. Horizontal lines mark time spans of individual fire-scarred trees. Inverted triangles indicate annually dated fire scars. Dashed lines represent periods between the inner ring date and the first fire scar. Pith and bark dates are indicated with a vertical tick. Slanted lines represent inner (\( / \)) and outer (\( \backslash \)) ring dates. Filtered fire scar events (\( \geq 10\% \) scarred and at least two trees) are noted with black vertical lines. Filtered fire events that are synchronous across sites (two or more) are noted with red vertical lines. Inset photos: a Scots pine (\( \text{Pinus sylvestris} \)) ‘cat face’ formed from repeated fire scars (black vertical ridges) and a partial cross-section from a \( \text{P. sylvestris} \) with multiple fire scars.
chronology derived from trees for the region (G. Jacoby, R. D. D’Arrigo and N. Pederson, 2009, International Tree Ring Data Bank, http://www.ncdc.noaa.gov/paleo/treering.html, accessed 12 September 2011) and locally developed skeleton-plot chronologies. The year and season of fire (if distinguishable) were recorded in FHDX2 for each fire scar observed in cross-section (Grissino-Mayer et al. 1995). Dormant-season fires were assigned to the spring of the following year because ~80% of forest fires in Mongolia occur from March to June (Goldammer 2002). Fire regime characteristics (number of scars, sample depth, percentage scarred over time) were summarised for the entire period of record at each site and fire charts were created in FHDX2 (Grissino-Mayer 2001). Fire-interval statistics for each site were calculated using a filter of ≥10% scarred and at least two trees. No clear changes in fire regimes were observed (e.g. no effect of fire suppression), so the entire period of record for each site was included in fire return interval statistics. Synchrony, the tendency for distant sites to record fires in the same year, was compared across sites and over time.

Results

All three sites had long histories of fire (450 years at Bogd, 350 years at Center and 280 years at Tujin Nars), though fire regimes at each site were distinct (Table 1; Fig. 2). At Bogd, fires were frequent before ~1766, with a Weibull median fire interval (WMFI) of 16 years (filtered data) (Table 2). After 1766, fire scars were nearly absent, even though a sample depth of >10 trees was maintained until 1900 (Fig. 2). At Center, fires occurred with similar frequency (filtered WMFI = 17 years), but continued into the 20th century, with the most recent fire recorded by two or more trees occurring in 1969 (Fig. 2). Tujin Nars recorded the highest frequency of fires (filtered WMFI = 7 years), and fire occurrences continued to the present, with the most recent fire recorded in 2002. At Bogd and Center, most fires occurred during the dormant or early growing season (90 and 95%). The remaining fires occurred throughout the growing season. At Tujin Nars, 13% of fires occurred in the dormant season, 67% in the early growing season and 16% occurred during the late growing season. There was limited synchrony at annual scales in fire occurrence across sites. Owing to the fire history at Bogd and the lack of temporal depth at the other two sites, Bogd has no synchronous fire years with Center or Tujin Nars. Center and Tujin Nars have only 3 fire years in common: 1901, 1944 and 1969.

Discussion and conclusions

The record of fire history here highlights its historical role in Mongolia and indicates variation with latitude, elevation and forest type. Preliminary results indicated that ample fire history data exist in Mongolia through living fire-scarred trees, stumps and other material (Fig. 2, inset). Although Bogd experienced nearly complete fire cessation since the 1760s, the other sites continued to experience fires to the present. Preliminary superposed epoch analysis (SEA; results not shown) comparing the filtered fire event dates identified here with independent reconstructions of climate from tree rings indicated that only fires at Tujin Nars occurred during drought years (n = 24, P < 0.05). At both Bogd and Center, results from SEA suggest that fire years were not significantly drier during the fire year (P > 0.05), though the number of events was small (n = 9 and n = 14 respectively). Among the synchronous fire years, 1944 was a moderate drought year (growing season Palmer Drought Severity Index, PDSI = −1.89) and 1969 was wet (growing season PDSI = 2.59) (Dai et al. 2004). No reliable instrumental data exist for 1901 in Mongolia; however, central Asia experienced near-normal conditions during the 1901 growing season (Dai et al. 2004), though other studies in southern Siberia report a major fire year (Valendik et al. 1992).

The limited fire synchrony between all three sites and the inconsistent results of the SEA across sites suggest that human drivers of fire might have been important in Mongolian forests alongside climate. Land-use change, either via changes in grazing intensity (fuels) or via changes in human ignitions, might have resulted in the pattern of fire cessation we observed at Bogd and the limited synchrony we observed across sites. The presence of grazing altered or eliminated surface fire regimes in other arid forests (Weaver 1959; Savage and Swetnam 1990; Grissino-Mayer et al. 1995; Hobbs 1996; Mast et al. 1998) and this may have been the case at Bogd. The city of Ulaanbaatar was initially founded in 1639 and became the capital of Mongolia in 1778. Both developments must have been associated with increased human and livestock populations. Fuel wood gathering can reduce available fuels for fires and may have been an important influence on fires in the past. Because grazing by ungulates reduces the biomass of plants available for burning, ungulates can reduce the frequency, aerial extent and intensity of fires, particularly in systems fuelled by mid-storey grass (Hobbs 1996). Additional fire history sites at the forest-steppe ecotone with different human histories and livestock densities are required to fully evaluate this hypothesis. Historical management of Bogd may have also included laws prohibiting ignitions. Although Mongolians do not have a tradition of intentional burning, unintentional ignitions (originating from cooking or camping fires for example) in combination with dry spring conditions are thought to have caused recent peaks in fire activity (Nyamjav et al. 2007).

Fire frequencies for larch- and pine-dominated stands reported here are consistent with previous studies in southern Siberian forests (Valendik et al. 1992) but much shorter than those reported farther north (Arbatskaya and Vaganov 1997). The short fire return intervals at Tujin Nars are similar to those observed in other Pinus sylvestris stands on sandy soils (Vaganov et al. 1996; Ivanova et al. 2010). A sudden increase
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in area burned across Mongolia has been documented by fire atlas data (Goldammer 2002; Nyamjav et al. 2007) and is expected based on recent increases in temperature and decreases in moisture (Batima et al. 2005). However, with data from these three sites alone, there is not a visible, distinct increase in fire frequency in recent decades. This is consistent with results from the nearby Tuva region of Russia, where fire intervals have not changed for at least 300 years, though fire severity may be increasing (Ivanova et al. 2010). It may be that the number of sites reported here is too small to observe an increase in frequency or that drying conditions have actually reduced fuel continuity and fire occurrence (Hessl 2011; Krawchuk and Moritz 2011). Alternatively, fire frequency may have remained stable while fire severity (not measured here) has changed. Additional data and statistical tests will be required to determine whether recent fires are within the range of historical variability.

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