Regional fire history based on charcoal analysis of sediments from nine lakes in western Mongolia

Charles E. Umbanhowar, Jr,1* Avery L.C. Shinneman, 2 Gundsambuu Tserenkhand,3 Elizabeth R. Hammon,4 Pao Lor5 and Kelly Nail5

1Departments of Biology and Environmental Studies, Saint Olaf College, 1520 Saint Olaf Ave, Northfield MN 55057, USA; 2Limnological Research Center, University of Minnesota, Minneapolis MN 55455, USA; 3Institute of Botany, Mongolian Academy of Sciences, 210351, Ulanbaatar, Mongolia; 4Department of Earth Sciences, Dartmouth College, 6105 Fairchild Hall, Hanover NH 03755, USA; 5Department of Biology, Saint Olaf College, 1520 Saint Olaf Ave, Northfield MN 55057, USA

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Abstract: Fires are common in grassland regions of the world, and the frequency and severity of fire is linked to climate-driven changes in fuel loads. Western Mongolia is dominated by grasslands but the fire history of this region is largely unknown. We reconstructed modern fire (48 lakes) and historical fires (9 lakes) using sediment charcoal. Modern fuel loads were estimated using a combination of clipped plots, satellite-based estimates of annual aboveground net primary productivity (NPP) and NPP modeled from annual temperature and precipitation. Loss-on-ignition and environmental magnetics of lake sediments were analyzed as proxies for climate. We found little evidence for modern or historical fire in the landscape, as charcoal was absent from the surface sediments of 34 of 48 lakes. Charcoal influxes were uniformly low, averaging from 0.002 to 0.028 mm2/cm2 per yr, over the past 1200 years at nine lakes, and the past 6000–5000 years at two of the lakes with longer sediment records. In the modern landscape, livestock grazing has eliminated most of the fuels necessary to carry a fire, as measured fuel loads (27.3±4.9 g/m2) were only ~20% of aboveground annual NPP estimated using MODIS imagery or modeled from climate data. The historical absence of fire may indicate a longer history of intensive grazing than sometimes assumed, and cultural prohibitions against burning may also play a role. Regional summary indicated a >50% decrease in charcoal influxes since AD 1600 at most sites which may be related to lower temperatures or greater aridity during the ‘Little Ice Age’. Alternatively this decrease in charcoal influxes may reflect increases in livestock numbers or increased local concentrations because of restrictions on the movement of animals coincident with the establishment of Manchu rule in the late seventeenth century.

Key words: Mongolia, fire history, charcoal, climate, grazing, lakes.

Introduction

Grassland covers an estimated 52.5 × 106 ha worldwide, representing 40% of total terrestrial area excluding Greenland and Antarctica (Suttle et al., 2005). The majority of these grasslands were at one time fire maintained (Bond et al., 2005), with frequent fires often promoting the growth of grasses and inhibiting the establishment of woody plants (Whelan, 1995). Fire is still common in grasslands in many regions of the world, and estimates of burning during the twentieth century indicate that 80–90% of fires worldwide occurred in grassland and savanna areas (Mouillot and Field, 2005).

The intensity and frequency of fire in grasslands is often fuel-dependent (Wright and Bailey, 1980; Whelan, 1995), and fuel loads are tied to net primary productivity (NPP) which is both precipitation and temperature dependent (Sala et al., 1988; Briggs and Knapp, 1995; Mitchell and Csillag, 2001; Christensen et al.,...
Paleoecological studies in the central North American grasslands have suggested a positive correlation between fire and moisture over the past 10,000 years (Umbanhowar, Jr, 1996; Clark et al., 2002; Camill et al., 2003), and Keeley and Rundel (2005) concluded that the expansion of C4 grasses during the Miocene was due to increased burning associated with both greater growing season moisture and greater seasonality. In arid and semi-arid southwestern USA, fires were more common during dry years that followed fuel accumulation during prior wet years (Swetnam and Betancourt, 1990; Swetnam and Baisan, 1996), but intensive grazing in this region resulted in a reduction in fire frequency largely as a result of the consumption of fuels (Hobs, 1996; Swetnam and Baisan, 1996). Grazing-induced changes to fire regime are not unique to North America; for example Burney et al. (2003) suggested that increases in burning in Madagascar were due to the extirpation of large grazers.

The grasslands (steppe) of central Asia extend from southern Russia in the east to Mongolia and China in the west. These areas have been occupied by a variety of nomadic herding peoples for at least 4000 years, and these people depended on the grasslands for forage for their livestock (Bold, 2001). There is increasing concern about the sensitivity of these grasslands to both overgrazing and increased drought due to global climate warming (Xiao et al., 1990; Christensen et al., 2004; Batima, 2006). Moullot and Field (2005) described the central Asian grasslands as being very fire prone and estimated that area burned in this region increased from 3.79 to 15.5 million ha/yr during the late twentieth century as a result of increased investments in fire control. Paleoecological records of burning from this region are largely absent with the exception of the work of Huang et al. (2006) who found increased, but variable, charcoal deposition in loess-soil over the past 3100 years that they attributed to greater clearing of land for cereal cultivation.

In this study we undertake one of the first regional reconstructions of fire history based on charcoal in lake sediments in the steppe of northwestern Mongolia. We use sediment charcoal as a proxy for fire, and loss-on-ignition (LOI) and environmental magnetics as proxies for changes in the lake watershed. Our study is divided into three parts. First we describe modern fire regimes using charcoal extracted from surface sediments of 48 lakes and compare LOI and magnetics data with modeled annual precipitation and temperature (Climate Source, 2004) to look for correlations between lake sediment properties and modern climate. Second, we look for changes in burning and lake sediment properties over the past ~1200 years based on dated sediment cores from a set of nine lakes, paying particular attention to changes associated with the ‘Little Ice Age’ (~AD 1400–1850, LIA) and the preceding ‘Medieval Warm Period’ (~AD 900–1200, MWP). Yang et al. (2009) recently concluded that the LIA in central Asia was a cooler-moister period than the preceding MWP. Finally, for a subset of two lakes we use cores with slow sedimentation rates to look at changes in fire and climate over the past 6000 cal. yr BP.

Study region

Northwestern Mongolia (Figure 1; total study area ~510 000 km²) includes the Altai Mountains, Valley of the Great Lakes and Khangai Mountains, and elevation in this area ranges from ~750 to 2800 m a.s.l. The area displays a rich mix of desert-steppe, steppe, forest-steppe and taiga ecosystems and the majority of this region has been grass dominated over the past ~5000–7000 years (Tarasov et al., 1998, 2000; Guin et al., 1999; Grunert et al., 2000; Fowell et al., 2003). Common genera include C3 grasses (Stipa, Agropyron and Festuca), Carex, Allium, Ephedra and Caragena, as well as a range of herbaceous plants and shrubs in the genus Artemisia and Chenopodiaceae family (Anabasis, Kochia, Salsola). Larix sibirica occurs in scattered small stands at higher elevation. Hilbig (1995) provides a complete description of the flora of Mongolia, and see also Strauss and Schickhoff (2007) for a recent detailed description of vegetation in the Valley of the Great Lakes.

Average annual temperature in the region ranges from 10.4 to ~7.6°C, and annual precipitation (Figure 1D) ranges from <100 mm/yr to over 300 mm/yr with the majority of precipitation falling during the summer months (Mongolian Academy of Sciences, 1990; Climate Source, 2004). Climate is dominated by Westerlies and the Arctic High, and the East Asian and Indian monsoons have little influence in this region (An, 2000; Aizen et al., 2001; Huang et al., 2007). MODIS-based (Zhao et al., 2005) estimates of annual NPP for 2005 (for description of MOD 17 algorithm see Running et al., 2004) range from < 100 g/m² per yr to > 500 g/m² per yr (Figure 1C).

The five aimags or provinces (Bayan Olgii, Govi-Altai, Zavkhan,Uvs and Khovd) within this area supported a population of 6.84 million livestock (sheep, goats, cattle, camels, yak) and 418 000 people in 2002 (Soninkhishig Nergui, personal communication, 2005). In 2002, the number of livestock in these aimags was approximately 20–25% of the 23.9 million head recorded for the entire country. This compares with an estimated 12.7 million and 542 000 people for all of Mongolia in AD 1918 and 15 million and 695 000 respectively in AD 1220 (Bold, 1998).

Methods

Field work

A total of 48 lake sites were sampled during August of 2004 or 2005 (Figure 1A). Surface sediments (upper 2–5 cm) were collected from each of these lakes using a Wiegner gravity corer and transferred to airtight polycarbonate vials. Longer (~0.9–1.75 m) sediment cores were collected from nine lakes (Table 1, Figure 1A), working from a pair of inflatable kayaks arranged as a catamaran. Coring sites within lakes were selected with the aid of an acoustic hand-held depth meter and field-based observations of basin morphology to locate a deep, relatively flat portion of the basin assumed to be a zone of continuous deposition. Cores were taken with a ~7 cm diameter polycarbonate tube fitted with a piston and operated by rigid drive rods. Each core was extruded in the field at 1 cm intervals and stored in airtight polycarbonate vials for later analysis.

Plant cover and herbaceous fuel loads were sampled from 32 plots (Figure 1C). Plots were located a minimum of 100 m from the shore of adjacent lakes. Plots consisted of three parallel 20 m long transects oriented perpendicular to the shore and separated by 5 m. Five circular 0.25 m² quadrats were placed along each transect at a spacing of 5 m for a total of 20 quadrats per plot. Percent cover of live plants, litter, and bare soil were estimated visually using six cover classes (0, ~5, 5–25, 25–50, 50–75, 75–100%). Average plant height within each plot was measured using a ruler. For six quadrats in each plot plants were clipped to a height of ~0.5–1 cm, and clippings collected, dried and weighed for an estimate of biomass (g/m²). Quadrat data are averaged for each plot.

Sediment analysis

Age–depth models for the nine sediment cores were based on a combination of 210Pb-dating, and AMS-14C dating of charcoal (Dr Tom Brown, Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory, 2005). Lead-210 was measured via its granddaughter product, 210Po as quantified by alpha spectrometry methods (Appleby, 2001). Dates and sedimentation rates in eight of nine lakes were determined according to the
c.r.s. (constant rate of supply) model (Appleby, 2001; Appleby and Oldfield, 1978). The exception was Doroo where variable and high activity made the detection of unsupported $^{210}\text{Pb}$ ambiguous below the 4 cm depth. Using a constant initial concentration model (Robbins, 1978) on these uppermost four intervals allowed for the determination of approximate $^{210}\text{Pb}$ dates to 1930 (Figure 2). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford, 1990). A total of 17 AMS dates were obtained from charcoal fragments, the large error bars (see Table 4) being due to a paucity of charcoal in the sediments. Charcoal for dating was picked from the sediment and then treated with an acid-base-acid rinse (T.A. Brown, personal communication, 2005). $^{14}\text{C}$ dates were calibrated using CALIB 5.0 (Stuiver and Reimer, 1993; Stuiver et al., 1999). Age–depth models were constructed using linear interpolation or exponential models for the $^{210}\text{Pb}$ dates and the either linear interpolation or linear fits for the older portions of each core (Figure 3) based on number of dates and best fit to trend.

Charcoal analysis was based on 1 cm$^3$ subsamples taken from each 1 cm interval. Sediment was soaked in 10% KOH for 24–48 h and sieved gently with a 180 µm sieve (Whitlock and Millspaugh, 1996; Clark et al., 1998). Sieved material was spread over the bottom of a gridded petri plate and analyzed at 20× magnification using a dissecting microscope. Particle area (mm$^2$) and particle shape (length:width ratio) was recorded using a video camera mounted...
to the scope and ImageJ software. Charcoal concentrations are reported as the sum of area (mm²/cm³) and influx as mm²/cm² per yr based on the age-models constructed for each core.

Percent organic, residual and CaCO₃ fractions were characterized for all cores, following the loss-on-ignition procedure outlined by Dean (1974). As part of basic core description, we qualitatively described sediment color in the field, and in the lab analyzed grain size. Samples were prepared by heating ~2–3 g of sediment in 10% HCl for 15 min. Sediments were then digested in 30% H₂O₂ for 30 min (until reaction ceased), and 2 ml of 11-M HNO₃ were added for 10 min. The samples were rinsed into centrifuge tubes with deionized water and methanol, and centrifuged at 4500 rpm for 15 min. In order to minimize loss of sediment after rinsing, the supernatant was removed from the tubes using a siphon apparatus instead of being decanted (modified from Tripplett, 2002). Processed sediment was frozen until analysis, and grain size was measured using a Horiba LA-920 particle analyser.

Isothermal Remanent Magnetization (IRM) and Anhysteretic Remanent Magnetization (ARM) were measured at the Institute for Rock Magnetism at the University of Minnesota. IRM was acquired in a magnetic field of 1500 mT and reflects the concentration of ferrimagnetic magnetic minerals. ARM was acquired in a peak alternating field of 100 mT and a bias field of 50 µT. All remanence parameters were measured with a cryogenic magnetometer (2G-model 760-R). ARM is strongly influenced by the presence of small single-domain (SD) and small pseudo-single-domain (PSD) particles (Hunt et al., 1995). Changes in the ratio of ARM/IRM are used to characterize the relative importance of fine SD particles versus larger particles.

Regional fuel estimates and statistical analysis
To develop a wider regional perspective on fuel loads, the plot-based measurements were supplemented with 2005 MODIS-based estimates of NPP using the Mod17 algorithm (Zhao et al., 2005). MODIS was also modeled from 30-year averages (1960–1990) of temperature and moisture (Climate Source, 2004) using a model estimates of NPP using the MODIS satellite imagery (see text for further details of Zhao et al., 2005).

Changes in LOI or magnetics are commonly used as simple climate proxies, and so we correlated these proxies from the surface sediments with temperature and moisture. Temperature and precipitation were not strongly correlated with either the LOI or magnetics proxies (Figure 2). LOI-percent organic sediment (range 2.1–52.7%, mean = 21.6) was moderately positively correlated with annual precipitation but not significantly correlated with either temperature or precipitation. The

| Table 1 Summary information for nine lakes and sediment cores in western Mongolia |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|                  | Zagas            | Doroo            | Kholboo          | Airag            | Baga             | Bayan            | Tsagaan          | Takhilt          | Khundt           |
| Longitude (°E)   | 90.6099          | 90.6639          | 91.0914          | 93.3076          | 93.8493          | 95.1604          | 94.8670          | 96.8062          | 93.8493          |
| Surface Area (ha)| 2376             | 2394             | 2570             | 1030             | 981              | 1540             | 1382             | 1520             | 1933             |
| Water depth at core site (m) | 64                | 1445             | 10               | 18022            | 314              | 6401             | 1242             | 482              | 2678             |
| Length of core (m) | 1.55             | 1.16             | 0.91             | 1.19             | 1.56             | 1.70             | 1.75             | 1.52             | 1.72             |
| Max age (cal. BP)| 5791             | 6994             | 3120             | 1413             | 645              | 3092             | 2310             | 818              | 947              |
| Model-based NPP (g/m² per yr) | 109±1             | 110±2            | 148±4            | 45±8             | 163±2            | 121±9            | 150±3            | 192±3            | 198±3            |
| MODIS NPP (g/m² per yr) | 127±4             | 128±2            | 189±5            | 79±3             | 79±1             | 82±1             | 113±2            | 137±2            | 168±7            |
| Dry Biomass (g/m²) | 13.2              | 6.6              | 27.1             | 15.2             | 9.1              | Missing          | 35.8             | Missing          | 104.8            |
| Vegetation†      | Desert            | Desert            | Forest           | Desert           | Steppe           | Desert           | Desert           | Mountain         | Forest           |
|                 | steppe            | steppe            | steppe           | steppe           | (dunes)          | steppe           | steppe           | steppe           | steppe           |

* Average (+ 1 standard error of mean) annual terrestrial net primary productivity (NPP) within 4 km buffer around each lake is also given, based on modeling using annual average temperature and precipitation or based on the MODIS satellite imagery (see text for further details of Zhao et al., 2005).  
* Biomass is based on field measurement using clipping method, and vegetation classification is based on map from Hilbig (1995).  

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Results
Modern surface sediments
Most (34 of 48) samples of recent sediment contained no sieve (180 µm) charcoal (Figure 1B), and for the 16 samples that did contain charcoal, the average number of pieces (5.7±1.9) and sum area (0.465 ± 0.149 mm²/cm³) were quite low. Average area of individual pieces of charcoal in surface sediments was 0.06020.013 mm² and average L:w ratio was 3.49±0.48. Charcoal concentration was not significantly correlated with lake surface area (r = 0.197, z = -1.3769, p-value = 0.17). High-resolution elevation/topographic data were not available to calculate catchment areas, so the relationship between catchment area and charcoal influx could not be investigated.

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LOI-percent carbonates (range 4.8–68.9, mean = 26.1) was moderately positively correlated with temperature, despite considerable variation, and not significantly correlated with precipitation (Figure 2C.D). The residual LOI fraction of the sediment (range 11.6–93.1%, mean = 52.3; not shown in Figure 3) was not significantly correlated with either temperature or precipitation. The

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Figure 2  Correlation of annual precipitation (mm) and temperature (°C) with (A and B) percent organic matter (LOI), (C and D) percent carbonates, (E and F) IRM (Am²/kg), and (G and H) ARM/IRM. Correlations based on Spearman Rank method.
concentration of ferrimagnetic materials (IRM, range $8.2 \times 10^{-5} - 2.9 \times 10^{-2}$ Am$^2$/kg, mean = $2.5 \times 10^{-3}$ Am$^2$/kg) was significantly negatively correlated with precipitation but not correlated with temperature (Figure 2E,F). Size of magnetics particles (ARM/IRM, range 0.0047–0.13, mean = 0.037) was not significantly correlated with either temperature or moisture (Figure 2G,H). IRM was negatively correlated with percent organic LOI ($r = -0.54$, $z = -3.803$, $p = 0.0001$) and positively correlated with percent residual LOI ($r = 0.52$, $z = 3.646$, $p = 0.0003$).

**Fuel loads and terrestrial biomass**

Field measurements showed that fuels were virtually non-existent. Percent cover of live plants and litter averaged less than 30%, and 60% of area in plots was dominated by bare ground (Table 2). Clipped biomass averaged 27.3 g/m$^2$ and was on average 25% (range 4–118%) of MODIS-based estimates of NPP. NPP modeled from annual temperature and precipitation was only 11% greater than MODIS-based NPP and this difference was not statistically significant ($z = -1.0428$, $p = 0.297$; Table 2). Precipitation was the more important control on modeled NPP for 80% of the area, with temperature being more critical in the northeastern part of region including the locations of Khundt and Takhlit lakes (Figure 1A). MODIS estimates of terrestrial NPP in the 4 km buffer surrounding lakes averaged 112±5 g/m$^2$ per yr (Table 1), only slightly greater than what was estimated for the 32 individual vegetation sampling sites (Table 2). In part these estimates may have been higher because they included areas of Phragmites and other wetland communities on the edges of lakes. There was, however, no significant difference in the average MODIS NPP around lakes with and without charcoal (mean = 112 versus 111 g/m$^2$ per yr; Wilcoxon Rank Test, $z = -0.1066$, $p$-value = 0.915) to support this field-based observation.

**Sediment charcoal influx over past 1200 years**

Over the past 1200 years, charcoal influx to the sediment of all nine lakes was extremely low (Figure 4A, Table 3) ranging from an average of 0.002 mm$^2$/cm$^2$ per yr for Doroo and Tsagaan to a high of 0.028 mm$^2$/cm$^2$ per yr for Baga. Differences in average charcoal influxes among lakes were not significantly correlated with either elevation or longitude but were significantly positively correlated with latitude, more northern lakes having higher charcoal influxes ($r = 0.71$, $z = 1.973$, $p = 0.0485$). Based on the age–depth models we constructed, sedimentation rates were nearly twice as high for the more northern and eastern lakes than for the southern and western lakes (Figure 3, Table 1). Neither MODIS-based estimates of modern NPP or modeled modern NPP were significantly correlated ($P > 0.10$) with average charcoal influx for the lakes.

Regional summary of charcoal influxes (the charcoal series for each lake relativized to its maximum) indicates a drop of 50% or

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**Figure 3** Age–depth models for nine study lakes. Depth (cm) is depth from surface of sediment and age (cal. BP) as low-high range of calibrated ages encompassing 90% probability age range. Dates and calibrated ranges are provided in Table 4.
Figure 4  Summary diagrams for (A) charcoal influx (mm$^2$/cm$^2$ per yr), (B) loss-on-ignition, (C) IRM (Am$^2$/kg) and ARM/IRM for nine lakes in northwestern Mongolia and (D) qualitative sediment description (asterisks indicate depths for AMS dates, Table 4) and grain size. See Tables 1 and 3 and Figure 1 for lake location and basic core information. Solid line for charcoal series is based on mean smooth (250 years), and arrows indicate a significant ($p < 0.05$, bootstrapped 5000 times) local change point (closed arrow for increases, open arrow for decreases; see text for explanation). The mean for each series in individual panels (A–C) is given as a vertical line ±1 standard error of mean.
Table 2 Summary of herbaceous fuel characteristics (mean ± 1 standard error of mean) for 32 sites. See Figure 1B for approximate locations.

| Vegetation height (cm) | 11.9±3.5 |
| Live (% cover) | 27.2±4.2 |
| Litter (% cover) | 3.5±0.3 |
| Bare soil (% cover) | 62.0±3.1 |
| Dry biomass (g/m²) | 27.3±4.9 |
| MODIS Terra NPP estimate (g/m² per yr) | 100±8 |
| Modeled NPP estimate (g/m² per yr) | 111±8 |

more at ~ AD 1600, but there is considerable variability among sites for each period (Figure 5). Charcoal influx to five of nine (Bayan, Tsaagaan, Airag, Takhilt, Zagas) sites dropped almost to zero beginning as early as 1450 at Zagas and as late as ~ AD 1800 at Tsaagaan (Figure 4). Charcoal influxes did not show such a dramatic decline at Baga but did drop significantly by ~ 50% around AD 1400, while charcoal at both Kholboo and Khundt disappeared at ~ AD 1900. The record at Doroo is characterized by relatively little change with the notable exception of a relatively large influx of charcoal during the nineteenth century. There was similarly little change seen at Kholboo where most of samples (> 50%) lacked any charcoal. Khundt and Baga had charcoal in nearly every sample, notable exceptions being the period of AD 1937–1981 for Baga and AD 1200–1300 and AD 1500–1600 for Khundt where charcoal was largely absent.

Charcoal counts ranged from 0.26 pieces/cm³ at Takhilt to 2.08 pieces/cm³ at Baga (Table 3). Counts and sum area of charcoal were significantly positively correlated (r > 0.90, p < .001) for all nine cores indicating that changes in sum area of charcoal were not driven simply by the addition of a few larger pieces of charcoal. Charcoal particles were on average smallest in Tsaagaan (0.28 mm³) and largest at Takhilt (0.103 mm³). Length:width ratios varied from a low 2.62 (wood or herbaceous leaf charcoal) at Airag to a high of 5.39 (grass) at Khundt (Umbanhowar and McGrath, 1998).

LOI and magnetics over the past 1200 years

Sediments of the four western and southern-most lakes (Doroo, Kholboo, Zagas, Airag) were dominated by the residual LOI fraction (67–73%) while the eastern and more northern lakes, with the exception of Takhilt, were composed predominately of either carbonates (29.6–46.8%) or organic matter (20.9–54.5%) (Figure 4B). Sediments for all nine cores were generally massive in nature with only small changes in color or grain size (Figure 4D). Exceptions were Doroo and Airag, where segments of the core contained fine sands and the three easternmost lakes (Tsaagen, Takhilt and Khundt) where banding or laminations were evident in sections of the cores.

Sediments from Zagas, Airag, Doroo, Kholboo, Baga and Bayan all showed an increase in the residual LOI fraction that begins around AD 1400–1600, roughly coincident with the regional changes in charcoal influx. The increase in the residual fraction was a response to reduced organic matter (Baga, Kholboo, Doroo) and/or a drop in the carbonate-LOI fraction (Doroo, Zagas, Bayan) and carbonates decreased at Khundt but organic matter actually increased at ~ AD 1600.

IRM (concentration of magnetic particles) was 1–2 orders of magnitude greater in the western and southern lakes (1.2e⁻²–2.8e⁻³ Am²/kg) and dominated by the residual LOI fraction. In contrast, the eastern and northern lakes (1.0e⁻¹–6.0e⁻³ Am²/kg) lakes were dominated by either organic or carbonate fractions (Figure 4B,C). For seven of nine lakes (Kholboo and Zagas being the exceptions) IRM was significantly (p<0.01 for each lake) negatively correlated with increases in the carbonate-LOI fraction, and for five of nine sites there was a positive correlation between changes in the residual-LOI fraction and IRM (Figure 4C). Changes in the concentration of magnetic minerals were variously correlated with changes in the size of magnetic particles. At six of nine sites increases in the concentration of magnetic minerals (IRM) were accompanied by significant decreases in ARM/IRM (ie, larger ferromagnetic particles; Banerjee et al., 1981) while at Tsaagaan there was no significant correlation, and at Kholboo and Baga ARM/IRM there was a positive correlation (eg, smaller particles). Across the region, recent sediments were characterized by a doubling inIRM since AD 1900.

Charcoal over the past 6000 years

Sedimentation rates at Zagas and Doroo were among the lowest and so these records extended back to ~5500–6000 cal. yr BP (Figure 6). Longer term charcoal influxes to these lakes, indicate that charcoal influx rates over the past 6000 years were generally no higher than observed over the past 1200 years, averaging 0.0028 (±0.0004) at Zagas and 0.0026 (±0.0004) at Doroo. The records do differ in the timing of charcoal influxes. At Zagas, there

Table 3 Summary statistics (mean ± standard error of mean) for charcoal, LOI and environmental magnetics properties of sediments from nine lakes over past 12000 years.

<table>
<thead>
<tr>
<th>Location</th>
<th>Influx (mm²/cm² per yr)</th>
<th>Sum char (mm³)</th>
<th>Char pieces (#/cm³)</th>
<th>Length: width</th>
<th>Char size (mm³)</th>
<th>Organic matter (%)</th>
<th>Carbonates (%)</th>
<th>Residual (%)</th>
<th>IRM (Am²/kg)</th>
<th>ARM/IRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zagas</td>
<td>0.004±0.001</td>
<td>0.078±0.016</td>
<td>1.08±0.23</td>
<td>4.51±0.68</td>
<td>0.079±0.007</td>
<td>10.2±0.3</td>
<td>16.8±0.7</td>
<td>73.0±0.7</td>
<td>2.0e⁻²+5.2e⁻⁵</td>
<td>0.050±0.002</td>
</tr>
<tr>
<td>Doroo</td>
<td>0.002±0.001</td>
<td>0.137±0.057</td>
<td>1.86±0.70</td>
<td>3.42±0.56</td>
<td>0.086±0.01</td>
<td>6.6±0.2</td>
<td>26.1±1.0</td>
<td>67.3±1.0</td>
<td>2.8e⁻¹+1.5e⁻¹</td>
<td>0.028±0.004</td>
</tr>
<tr>
<td>Kholboo</td>
<td>0.005±0.005</td>
<td>0.035±0.015</td>
<td>0.39±0.11</td>
<td>3.72±0.68</td>
<td>0.101±0.05</td>
<td>17.7±0.4</td>
<td>5.2±0.1</td>
<td>67.3±1.0</td>
<td>2.0e⁻¹+1.1e⁻¹</td>
<td>0.073±0.004</td>
</tr>
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<td>Airag</td>
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<td>0.122±0.024</td>
<td>1.6±0.29</td>
<td>2.62±0.20</td>
<td>0.068±0.006</td>
<td>6.5±0.2</td>
<td>26.1±1.0</td>
<td>71.1±4.4</td>
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<td>0.029±0.004</td>
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<tr>
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<td>54.5±1.4</td>
<td>5.2±0.1</td>
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<td>6.0e⁻¹+2.9e⁻⁵</td>
<td>0.040±0.001</td>
</tr>
<tr>
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<td>0.023±0.006</td>
<td>0.53±0.13</td>
<td>3.94±0.60</td>
<td>0.119±0.009</td>
<td>38.5±2.0</td>
<td>42.6±1.7</td>
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<td>Tsaagaan</td>
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<td>5.37±0.61</td>
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<td>20.9±0.7</td>
<td>40.3±1.5</td>
<td>38.7±1.1</td>
<td>4.2e⁻¹+5.4e⁻⁵</td>
<td>0.103±0.009</td>
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<td>Takhilt</td>
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<td>5.25±1.06</td>
<td>0.109±0.015</td>
<td>16.5±0.2</td>
<td>23.5±0.5</td>
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<td>1.9e⁻¹+1.9e⁻⁵</td>
<td>0.032±0.001</td>
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<tr>
<td>Khundt</td>
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<td>2.57±0.29</td>
<td>5.39±0.33</td>
<td>0.3±0.011</td>
<td>36.7±0.4</td>
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<td>46.8±0.3</td>
<td>1.0e⁺⁵+5.7e⁻⁵</td>
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is an extended period of increased charcoal inputs from 2000 to 600 cal. yr BP, while at Doroo higher charcoal influxes were observed from 6000 to 4400 cal. yr BP. At both sites, L:W ratios increase at ~1200 cal. yr BP (AD 750). At Zagas, this increase is from 2.81 to 4.41 and at Doroo it is from 2.50 to 4.32 which suggests a shift toward increased relative abundance of grasses around both lakes independent of changes in the severity of fire.

Discussion

Our data suggest that wildfires are largely absent from the modern landscape in western Mongolia (Figure 1), have been uncommon and regionally variable over both the last 1200 and 6000 years (Figures 5, 6), and significantly decreased in many parts of the landscape ~AD 1600 (Figures 4, 5).

The absence of fire in the modern landscape is not a surprise given low measured aboveground biomass, plant cover and virtual absence of litter (Tables 1 and 3). The low biomass and cover, relative to estimated NPP (Figure 1, Table 3), that we observed are in large measure a result of livestock grazing, and do not appear to be unusual for western or central Mongolia (Fernandez-Gimenez and Allen-Diaz, 1999). Low biomass values have been reported for grasslands in neighboring Tuva (Hall et al., 1995) and Inner Mongolia (Ni, 2004). The minimal (GR1) fuel model for grasslands (Scott and Burgan, 2005) is the best approximation to our results, and it predicts low flame heights, slow rates of spread, and smaller fires. Knapp (1998) observed smaller fires in the western USA during drought years when fuels were low. Our results contrast with those of Mouillot and Field (2005) who describe a rise in burning for the Asian Steppe, suggesting either that their estimates are too high or more likely that increases in burning are not uniform across the region and perhaps limited to areas with greater fuels.

The low influx of charcoal over the past 1200 (Figure 5) and 6000 years (Figure 6) we observed (see also Beer et al., 2007 record from southern Kyrgyzstan) is in marked contrast to charcoal sediment records from arid and semi-arid regions in North America and elsewhere. Charcoal influx rates (and concentrations) for sediments in the northern Great Plains are ~10–100 times greater (Umbanhowar, Jr, 1996, 2004; Clark et al., 2002) than observed in western Mongolia even during the mid-Holocene arid period. Influx rates were similarly higher in southern California chaparral (Mensing et al., 1999), shrub-grasslands in the North American intermontane west (Mensing et al., 2006), grasslands in the desert southwest (Shafer, 1989; Davis and Shafer, 1992; Davis et al., 2002), and southern loess plateau (from soils) of China (Huang et al., 2006).

Low aboveground biomass and historically less frequent or less severe fires in western Mongolia may simply be a product of more arid conditions and consequent lower NPP. Annual precipitation in western Mongolia (Figure 1D; 97 to 245 mm 1961–1990) is much lower than the ~100 to 700 mm observed for North American grasslands (PRISM Group, Oregon State University, http://www.prismclimate.org, created 16 June 2006) over the same period. Reduced precipitation in western Mongolia reflects the strength and position of the prevailing westerlies as well as the dominance of the Siberian High (An, 2000; Huang et al., 2007; Chen et al., 2008), and conditions generally may have been cool and arid over the past 4000 years (Feng et al., 2006; Grunert et al., 2000). Orographic effects are also important owing to the presence of the Altai and Khangay Mountains which strip moisture from the prevailing winds.

In North American grasslands NPP is controlled primarily by precipitation (Sims and Singh, 1978b; Sala et al., 1988; Knapp and Smith, 2001), but in northwestern Mongolia, minimum temperatures may actually play a more important role in limiting NPP (Running et al., 2004).

Temperature was a component of the NPP model (Yao et al., 1999) we used (Figure 1B). Estimated NPP for areas near our sites ranged from 48 to 200 g/m² per yr which, at least at the upper part of the range, is comparable with the 100–400 g/m² per yr reported...
for the semi-arid to arid grasslands of the North American Great Plains and southwest (Sims and Singh, 1978a; Sala et al., 1988). Estimated NPP for western Mongolia is similar to other estimates for cold, temperate grasslands elsewhere in Asia (Scarlock et al., 2002) as well as the Festuca and Agropyron-Stipa grasslands of Canada (PytlEc and Romo, 2003). Annual productivity, and in particular accumulated litter over several years, should be more than sufficient to support fires so limitations to burning resulting from low NPP seem unlikely.

Overlaid on the low overall incidence of fire is what appears to be a slight regional increase in burning during the fourteenth to sixteenth centuries followed by the region-wide decrease that extends to the present (Figures 4,5). These changes are roughly coincident with the end of the MWP and onset of the LIA. If the ‘fuel limitation’ hypothesis (Umbanhowar, 1996; Clark et al., 2002) is correct, the regional rise and then fall in charcoal would suggest a brief period of greater precipitation and/or warmer temperatures in the fourteenth to sixteenth centuries followed by a period of decreasing precipitation and/or markedly cooler temperatures. But, the response of grasslands and grassland fires to the LIA is generally not well documented.

There is not unanimity about climate during the MWP and LIA in central Asia. Recently, Yang et al. (2009) described cooling and increased precipitation during the fourteenth through seventeenth centuries for central Asia followed by increasing temperatures and reduced precipitation up until the present. Conversely, the Sol Dav tree ring record (D’Arrigo et al., 2001) from western Mongolia suggests warmer temperatures from ~ AD 1400–1800 and then cooling, and Kalugin et al. (2005) indicate a relatively warm and humid period from 1210 to 1480 followed by cooling and several extended droughts (see also Solomina and Alverson, 2004; Panyushkina et al., 2005). Based on analysis of lake level and pollen data from Telmen Nuur (Figure 1), Fowell et al. (2003) concluded that while the LIA was a period of increasing moisture, the MWP included significant periods of increased moisture and that more generally, based on comparison with other climate records from Mongolia, temperature and moisture availability were not well correlated.

Cooler and wetter conditions beginning at ~AD 1400–1600 may explain the rise in the residual LOI fraction as well as the correlated increases in the concentration and size of magnetic particles observed at a majority of sites (Figure 4). Cooler conditions would result in lower in-lake productivity (because of lower water temperatures or shorter ice-free season) and less precipitation of carbonates, while increased precipitation would result in greater inputs of terrigenous material due to increased erosion from shorelines and the surrounding catchment. There are several reasons to be cautious about this interpretation of LOI and magnetic. First, in the modern sediments, neither of the two sets of proxies was unambiguously correlated with average annual temperature or precipitation (Figure 2). This may reflect the effects of local factors such as lake depth, catchment area, and the mineral composition of surrounding soils (carbonate content of soil samples collected at 14 sites in 2005 ranged from 1.4 to 36.1%; C.E. Umbanhowar, unpublished data, 2006), in addition to climate or land use. Second, within cores the two proxies varied considerably in terms of the direction and magnitude of change within and among lakes (Figure 4). This may be a product of local factors, but also highlights the influence of both authigenic and alloegenic processes on these proxies, which while relatively simple to measure, may be more difficult to interpret as a result (Shuman, 2003; Birks and Birks, 2006; Oldfield, 2007). Concentration (IRM) and size (ARM/IRM) of magnetic particles may increase as a result of increases in wind-borne dust or water-borne clastics owing to shifts in climate or changes in land use, increases in grazing for example; increasing organic matter associated with greater in-lake productivity may dilute the magnetic signal while at the same time result in greater anoxia causing increased dissolution of particles, especially small particles. Dissolution will resulting in a decrease in ARM/IRM while conversely conditions that favor magnetotactic bacteria will result in an increase in ARM/IRM as they produce smaller particles (Geiss et al., 2004).

Major differences exist in the timing of changes across sites (Figures 2, 5). This likely underscores the importance of local factors, but may in part be a product of errors in dating (Table 4), particularly our dependence on small charcoal samples for dates (Oswald et al., 2005). The differences, especially the ~2000 year difference in peak charcoal inputs observed for Zagas and Doroo (Figure 6), seem unlikely to be simply a product of errors in dating. Differences among sites may be a reflection of a regionally heterogeneous climate as underscored by Batima (2006) who reported a mix of both increases and decreases in precipitation to sites in northwestern Mongolia over the past 30 years. Dorofeyuk and Tarasov (1998) observed major N–S differences in the timing and direction of climate changes for lakes in north central Mongolia over the past 12 000 years, and Fowell et al. (2003) highlighted regional differences based on their work at Lake Telmen (Figure 1).

Ignored in the discussion above are the impacts that humans and human cultural practices may have on plant cover, fuels, and burning in western Mongolia. Climate is a major explanation for the semi-nomadic culture in Mongolia (Bold, 2001), and summer drought and harsh winters have both had major impacts on livestock and herders (Ewing, 1980; Fang and Liu, 1992; Zheng and Ni, 1999; Li et al., 2000; Begzsuren et al., 2004; Christensen et al., 2004; Zhang et al., 2005; Batima, 2006; Feng et al., 2006). Unlike the Americas, Australia, or Africa, in western Mongolia there is not a tradition of burning grasslands today, or in the past, and laws from thirteenth century prescribed severe penalties for causing wildfires (Germareda and Enechisch, 1999). While the reasons for differing attitudes may be simply historical, one reason that fire may not have been a common tool is that its use did not result in a regular increase in pasture productivity. A combination of more arid and/or cool conditions combined with the dominance of C3 grasses would result in limited increases or in fact decreases in productivity following a fire (Redmnan et al., 1993; Bennett et al., 2002; PytlEc and Romo, 2003), especially if precipitation was not available immediately following the fire event (Drewa and Havstad, 2001). In fact, burning might increase the risk of erosion with longer-term consequences for productivity during periods of drought (O’Dea and Guertin, 2003).

Grazing of domesticated animals today is a major explanation for why plot biomass and cover (Table 2) were lower than predicted based on modeling of satellite imagery or climate data (Figure 1, Table 2) or in comparison with other grassland regions. In the southwestern USA reductions in fire frequency are well understood as being the result of increased livestock grazing (Savage and Swetnam, 1990). Interpreted strictly as a response to grazing, increases in fire during the thirteenth and fourteenth centuries would indicate first fewer livestock and then increased live-stock densities in the seventeenth century relative to pasture productivity. Political upheaval associated with the fall of the Mongol empire and conflicts between western and eastern Mongolia until the final establishment of Manchu control in 1691 may have reduced herd size. Greater political stability, the rise of the Banner system (an administrative system that limited movement) and larger monastic herds combined with greater exports of livestock to either China or Russia (Moses and Halkovic, Jr, 1985; Bold, 2001) then may have increased herd size. Equally important may be changes in the rights to pasture and herder movements during the twentieth century associated with the beginning and end of the communist era (Bold, 2001; Sneath, 1998, 2001).
Unfortunately, as detailed by Bold (1998, 2001), we do not have good information on livestock numbers over this period of time. As a first order approximation, we can use Bold’s (1998) estimate of 15.2 million animals in Mongolia in 1220, assume that 25% of these animals were in the five western aimags that included our survey area to calculate 3.78 million animals. Then based on Yu et al. (2004) we can calculate a stocking density of 1168 kg/km² in AD 1220 versus 2115 kg/km² in 2002. Again based on Yu et al. (2004), these estimated densities are 2.6 and 4.7 times greater than a carrying capacity of 450 kg/km² calculated using an average annual NPP of 156 (Table 1). While these numbers should be used with caution, they do suggest that livestock historically could consume a large fraction of NPP and so significantly influence fuels and fire over the last 1200 years and perhaps further into the past (Figure 6).

Better understanding of the impacts of grazing on fire and vegetation will require broader interpretation of existing proxies (Craine and McLachlan, 2004) as well as the expanded use of newer proxies. Pollen data, for example, have been typically interpreted strictly in terms of climate, for example the aridity index (Artemisia + Chenopodium / Poaceae) used by Fowell et al. (2003). To the extent that grazing impacts grasses (biomass or simply flowering) more than forbs, then increased grazing will result in a rise in the aridity index absent any change in climate.

Conversely, increasing moisture that would favor grass productivity and reduce the aridity index would be masked by continued intensive grazing. Liu et al. (2006) have suggested that the Chenopodium/Artemisia ratio may also respond to both climate and human disturbance in the eastern steppe. A newer proxy for grazing density is Sporormiella fungal spores (Davis and Shafer, 2006) which can be counted on pollen slides and, recognizing that the density of grazers is clearly not independent of climate-driven changes in NPP, represent a different way of documenting grazing in the paleoecological record.

Conclusions

Our data suggest that fire has been virtually absent from the steppes of northwestern Mongolia over at least the last 1200 years if not longer, contrasting with common assumptions of the historic importance of fire in such grasslands, and highlighting the need for including paleoecological studies as part of modern conservation planning efforts (Willis and Birks, 2006). Planning efforts in Mongolia are focused on impacts of climate warming and an anticipated northward shift of desert and desert-steppe as well as a general decrease in NPP (Batima, 2006; Munkhtsetseg et al., 2007; Ojima and Chuluun, 2008) which our results suggest will even further reduce the risk of grassland fire unless increased climate variability – including severe winter weather (Begzsuren et al., 2004) – results in a large reduction in herd sizes permitting fuels to accumulate.

While climate clearly provides broad constraints on vegetation, our results suggest that cultural choices, such as the use of fire and grazing of livestock, may act to greatly modify the links between productivity and climate and fire. Where cultural impacts are large, real understanding will depend on combining historical, archeological and cultural scholarship in combination with the development of multiple proxies (Birks and Birks, 2006) that provide a better understanding of climate and that more directly address the importance of grazing (Davis and Shafer, 2006).

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