The Holocene 19,4 (2009) pp. 611–624

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 Lor[5] and Kelly Nail[5]

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

Received 23 April 2008; revised manuscript accepted 2 December 2009

A HOLOCENE RESEARCH PAPER

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 mm^2/cm^2 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/m^2) 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 × 10^6 ha worldwide, representing 40% of total terrestrial area excluding Greenland and Antarctica (Suttie *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*.,

*Author for correspondence (e-mail: ceumb@stolaf.edu)

10.1177/0959683609104039

2004). 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 (Hobbs, 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*., 1995; Christensen *et al*., 2004; Batima, 2006). Mouillot 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 decreased 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 steppes 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 km^2) 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; Gunin *et al*., 1999; Grunert *et al*., 2000; Fowell *et al*., 2003). Common genera include C3 grasses (*Stipa*, *Agropyron* and *Festuca*), *Carex*, *Allium*, *Ephedra* and *Caragana*, 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/m^2 per yr to > 500 g/m^2 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 polypropylene 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 polypropylene 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 m^2 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, 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/m^2). Quadrat data are averaged for each plot.

Sediment analysis

Age–depth models for the nine sediment cores were based on a combination of ^{210}Pb-dating, and AMS-^{14}C 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, ^{210}Po as quantified by alpha spectrometry methods (Appleby, 2001). Dates and sedimentation rates in eight of nine lakes were determined according to the

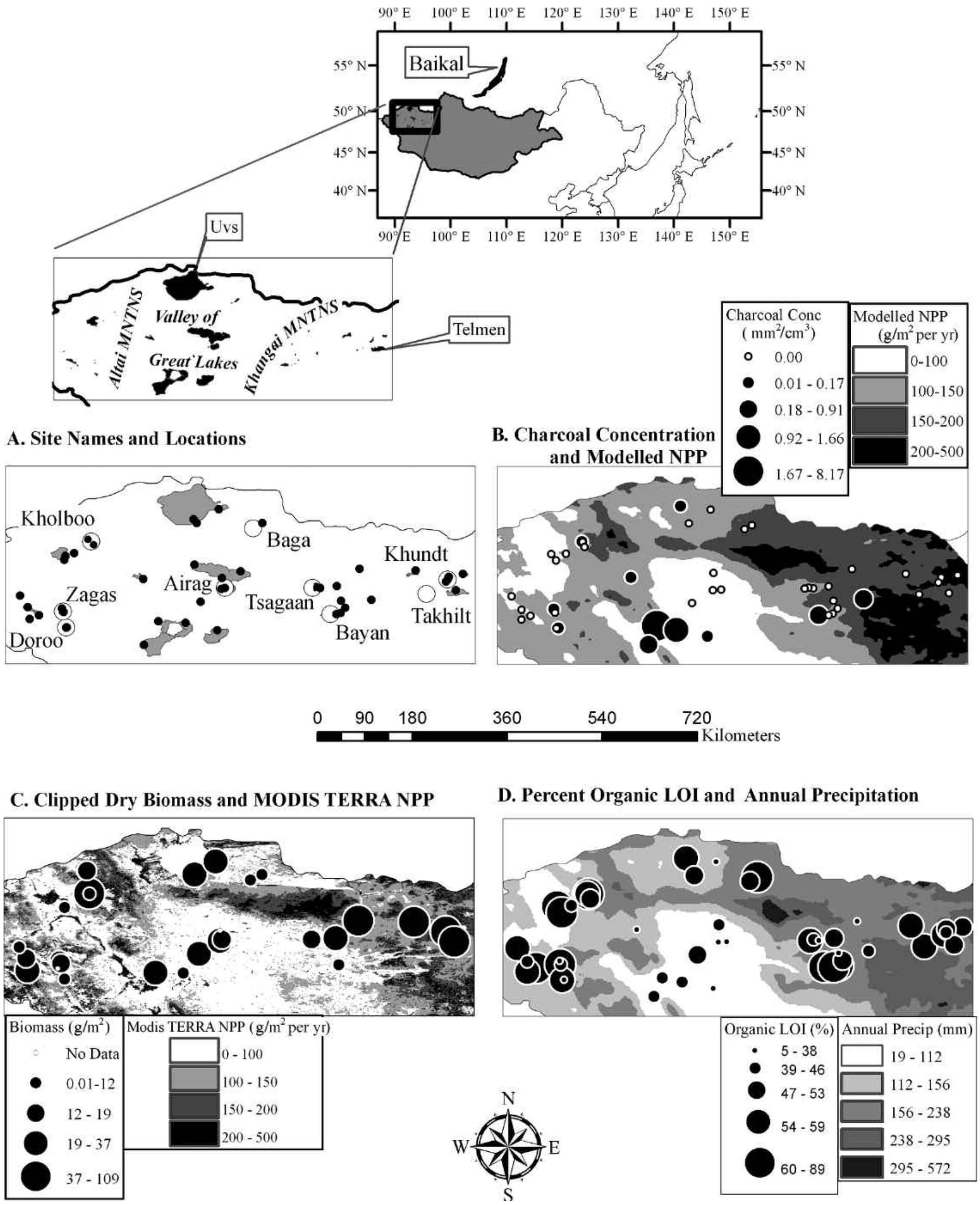

Figure 1 Location of study region in northwestern Mongolia. (A) Location of 48 study lakes for surface samples (small solid circles) and a subset of nine lakes for sediment cores (large open circles) described in this study; (B) charcoal concentrations (mm^2/cm^3) in surface sediments and Net Primary Productivity (g/m^2 per yr) modeled from annual temperature (°C) and precipitation (mm); (C) field-based terrestrial biomass (g/m^2) from 32 sites lake locations and MODIS-based NPP (g/m^2 per yr); and (D) percent organic matter (LOI) in surface sediments and annual precipitation. Precipitation and temperature data (1961–1990; Climate Source, 2004). See Table 1 for exact location and summary data for nine sediment cores

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}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}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}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}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 analysed at 20× magnification using a dissecting microscope. Particle area (mm^2) and particle shape (length:width ratio) was recorded using a video camera mounted

Table 1 Summary information for nine lakes and sediment cores in western Mongolia

	Zagas	Doroo	Kholboo	Airag	Baga	Bayan	Tsagaan	Takhilt	Khundt
Latitude (°N)	48.5061	48.2459	49.7014	48.9087	49.9208	48.4631	48.9118	48.8064	49.9208
Longitude (°E)	90.6099	90.6639	91.0914	93.3076	93.8493	95.1604	94.8670	96.8062	93.8493
Elevation (m)	2376	2394	2570	1030	981	1540	1382	1520	1933
Surface Area (ha)	64	1445	10	18022	314	6401	1242	482	2678
Water depth at core sitc (m)	8.7	9.1	2.9	9.1	7.1	14.0	6.6	5.4	6.8
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/m^2 per yr)[a]	109±1	110±2	148±4	45±8	163±2	121±9	150±3	192±3	198±3
MODIS NPP (g/m^2 per yr)[a]	127±4	128±2	189±5	79±3	79±1	82±1	113±2	137±2	168±7
Dry Biomass (g/m^2)[b]	13.2	6.6	27.1	15.2	9.1	Missing	35.8	Missing	104.8
Vegetation[c]	Desert steppe	Desert steppe	Forest steppe	Desert steppe	Steppe (dunes)	Desert steppe	Desert steppe	Mountain steppe	Forest steppe

[a] 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).
[b] Biomass is based on field measurement using clipping method, and vegetation classification is based on map from Hilbig (1995). Latitudes and longitudes based on WGS 84 datum and elevation is meters above average sea level.
[c] Vegetation classification based on Hibig (1995).

to the scope and ImageJ software. Charcoal concentrations are reported as the sum of area (mm^2/cm^3) and influx as mm^2/cm^2 per yr based on the age-models constructed for each core.

Percent organic, residual and $CaCO_3$ 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 analysed grain size. Samples were prepared by heating ~ 2–3 g of sediment in 10% HCl for 15 min. Sediments were then digested in 30% H_2O_2 for 30 min (or until reaction ceased), and 2 ml of 11-M HNO_3 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 sipper apparatus instead of being decanted (modified from Triplett, 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). NPP was also modeled from 30-year averages (1960–1990) of temperature and moisture (Climate Source, 2004) using a model described by Yang *et al*. (2002). A 4 km buffer was used around each lake site to calculate estimated average NPP based on both methods.

All statistical analyses were done using S-Plus software (Insightful Corporation, 2001). To better understand changes in our proxies in the nine short cores, we correlated LOI and magnetics data from the 48 surface samples both with each other and with the 30 year averages of temperature and precipitation. For the nine sediment cores, we summarized trends in the different proxies using a mean based 250-yr smoothing window that was centered on each sampled time point in a series.

Change-point analysis was used to identify locally abrupt changes in the charcoal series using a technique initially described by Webster (1973) and then by Legendre and Legendre (1998) that involved sliding a 250 yr wide window (divided into equal 125 yr halves) through each series from time point to time point. At each point the difference between the means of the two respective window halves was calculated and significance assessed based on 5000 bootstrapped (with replacement) replications of the series data to construct a 95% confidence interval. Means ± 1 standard error of the mean (SEM) are presented for each series for purposes of comparison (Figure 4).

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 mm^2/cm^3) were quite low. Average area of individual pieces of charcoal in surface sediments was 0.060±0.013 mm^2 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.

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 most of 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 temperature (Figure 2A,B).

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

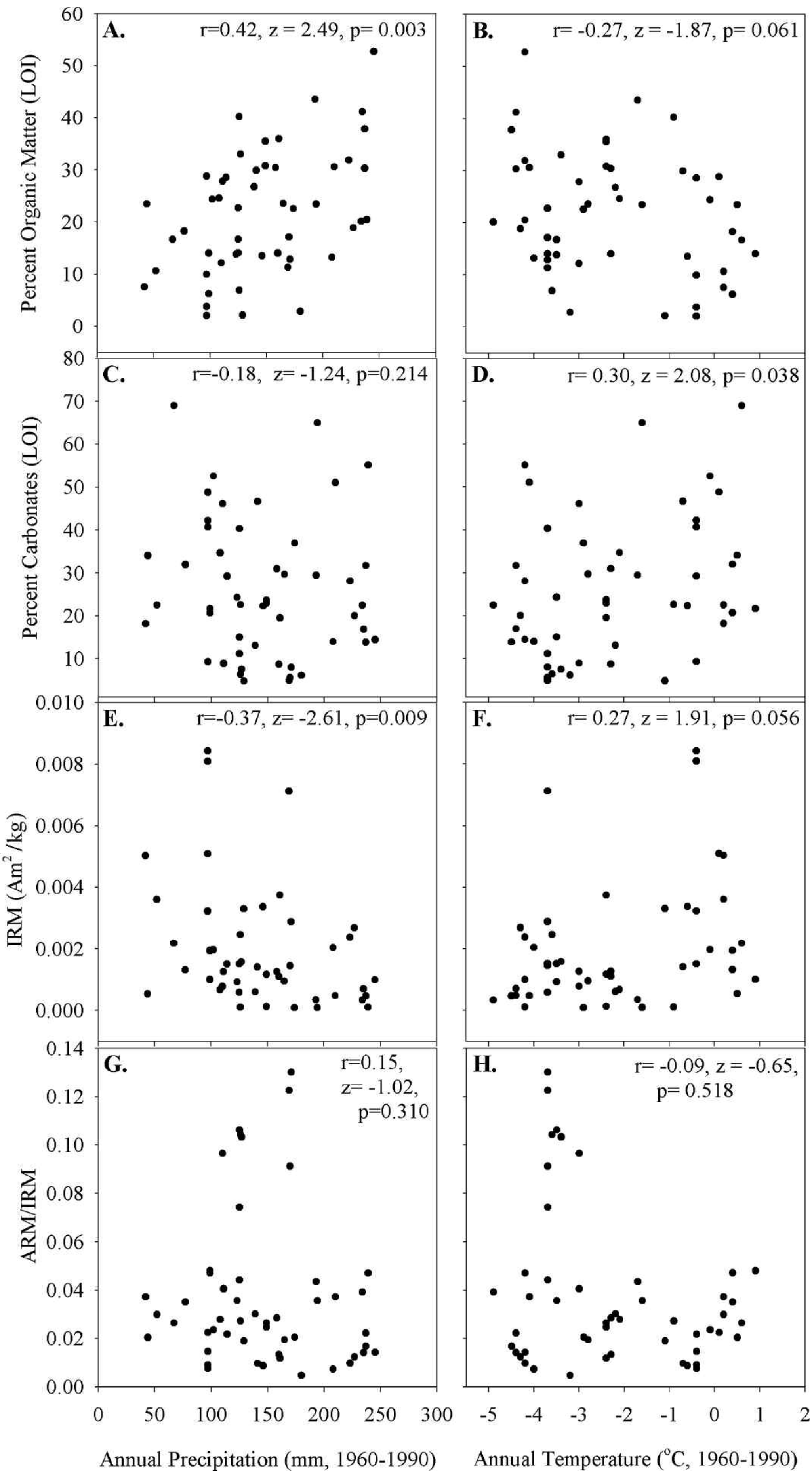

Figure 2 Correlation of annual precipitation (mm) and temperature (°C) with (A and B) percent organic matter (LOI), (C and D) percent carbonates, (E and F) IRM (Am^2/kg), and (G and H) ARM/IRM. Correlations based on Spearman Rank method

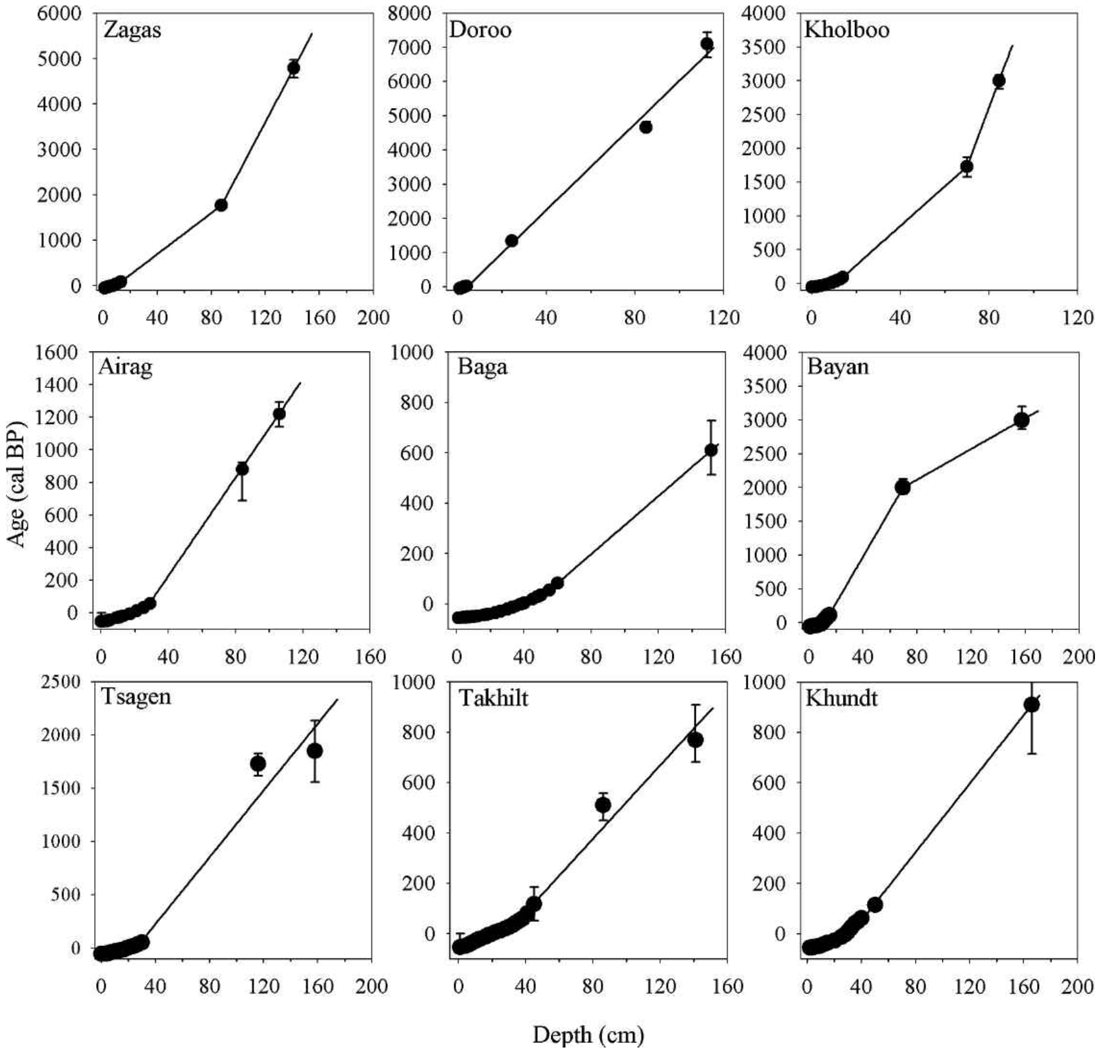

Figure 3 Age–depth models for nine study lakes. Depth (cm) is depth from surface of sediment and age (cal. BP) as low-high range of calibrated ages encompassing 90% probability age range. Dates and calibrated ranges are provided in Table 4

concentration of ferrimagnetic materials (IRM, range 8.2e-5–2.9e-2 Am^2/kg, mean = 2.5e-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 Takhilt 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

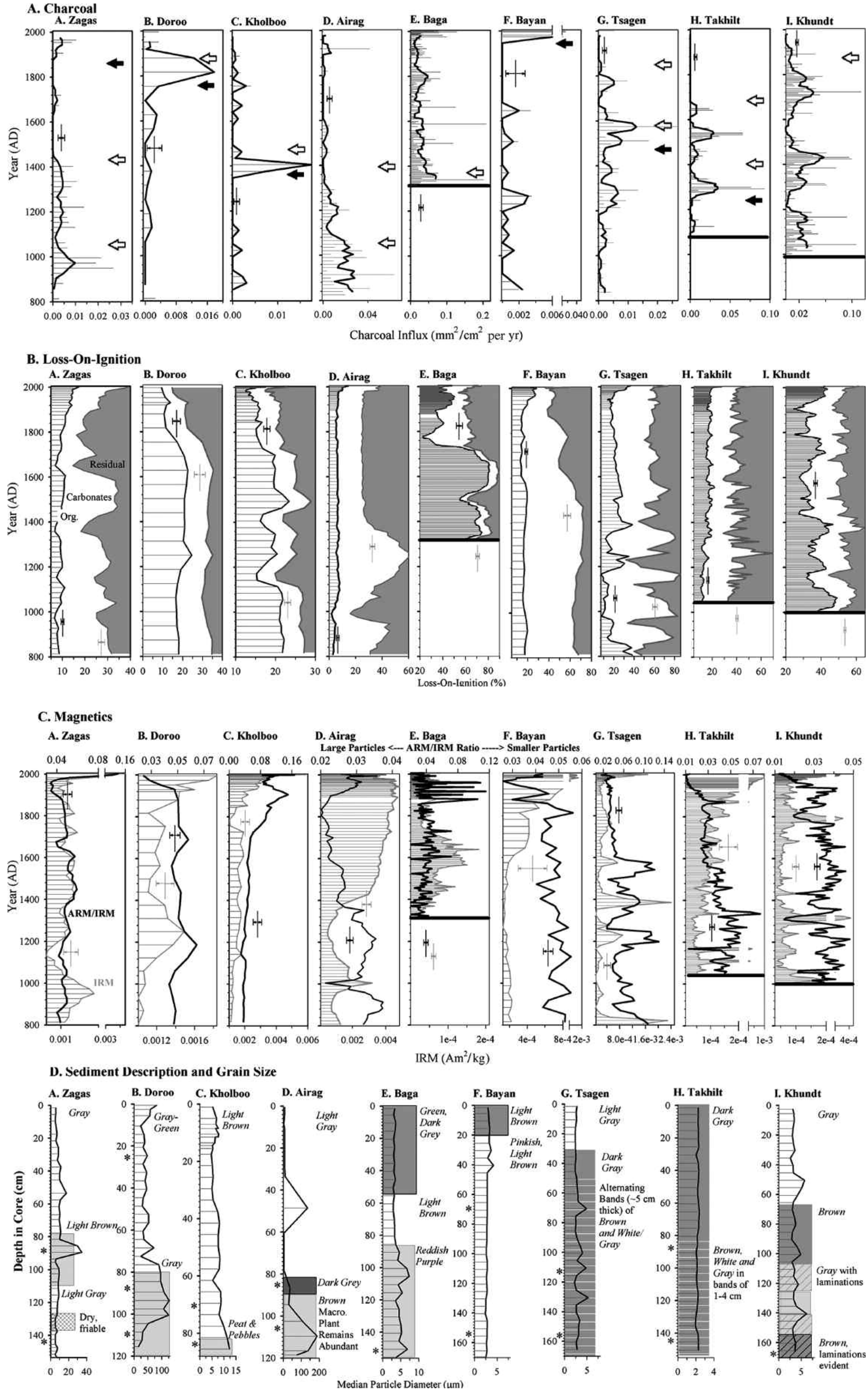

Figure 4 Summary diagrams for (A) charcoal influx (mm^2/cm^2 per yr), (B) loss-on-ignition, (C) IRM (Am^2/kg) and ARM/IRM for nine lakes in northwestern Mongolia and (D) qualitative sediment description (asterisks indicate depths for AMS dates, Table 4) and grain size. See Tables 1 and 3 and Figure 1 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±5.1
Dry biomass (g/m^2)	27.3±4.9
MODIS Terra NPP estimate (g/m^2 per yr)	100±8
Modeled NPP estimate (g/m^2 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, Tsagaan, Airag, Takhilt, Zagas) sites dropped almost to zero beginning as early as 1450 at Zagas and as late at ~ AD 1800 at Tsagaan (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/cm^3 at Takhilt to 2.08 pieces/cm^3 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 Tsagaan (0.28 mm^2) and largest at Takhilt (0.103 mm^2). 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 eastern-most lakes (Tsagen, 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} Am^2/kg) and dominated by the residual LOI fraction. In contrast, the eastern and northern lakes (1.0e^{-4}–6.0e^{-5} Am^2/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 ferrimagnetic particles; Banerjee *et al*., 1981) while at Tsagaan 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 in IRM 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 1200 years

	Zagas	Doroo	Kholboo	Airag	Baga	Bayan	Tsagaan	Takhilt	Khundt
Influx (mm^2/cm^2 per yr)	0.004±0.001	0.002±001	0.005±0.005	0.009±0.002	0.028±0.003	0.003±0.001	0.002±0.0003	0.006±0.002	0.016±0.002
Sum char (mm^2)	0.078±0.016	0.137±0.057	0.035±0.015	0.122±0.024	0.127±0.014	0.023±0.006	0.031±0.007	0.031±0.008	0.109±0.015
Char pieces (#/cm^3)	1.08±0.23	1.86±0.70	0.39±0.11	1.6±0.29	2.08±0.17	0.53±0.13	1.03±0.20	0.26±0.06	2.57±0.29
Length: width	4.51±0.68	3.42±0.56	3.72±0.68	2.62±0.20	4.25±0.25	3.94±0.60	5.37±0.61	5.25±1.06	5.39±0.33
Char size (mm^2)	0.079±0.007	0.086±0.01	0.101±0.051	0.068±0.006	0.059±0.006	0.119±0.009	0.028±0.003	0.103±0.009	0.050±0.011
Organic matter (%)	10.2+0.3	6.6+0.2	17.7+0.4	6.5+0.2	54.5+1.4	38.5+2.0	20.9+0.7	16.5+0.2	36.7+0.4
Carbonates (%)	16.8+0.7	26.1+1.0	5.2+0.1	26.1+1.0	15.9+0.8	42.6+1.7	40.3+1.5	23.5+0.5	16.5+0.3
Residual (%)	73.0+0.7	67.3+1.0	77.1+4	67.3+1.0	29.6+0.8	37.9+5.0	38.7+1.1	60.1+0.5	46.8+0.3
IRM (Am^2/kg)	1.2e^{-2}±5.2 e^{-5}	2.8e^{-3}±1.5 e^{-4}	2.0 e^{-3}±1.1e^{-4}	2.8e^{-3}+1.0e^{-4}	6.0e^{-5}+2.9e^{-6}	5.8e^{-4}+9.0e^{-5}	4.2e^{-4}+5.4e^{-5}	1.9e^{-4}+1.9e^{-5}	1.0e^{-4}+5.7e^{-6}
ARM/IRM	0.050±0.002	0.028±0.004	0.073±0.004	0.029+0.0004	0.040+0.001	0.046+0.001	0.050+0.003	0.032+0.001	0.032+0.0007

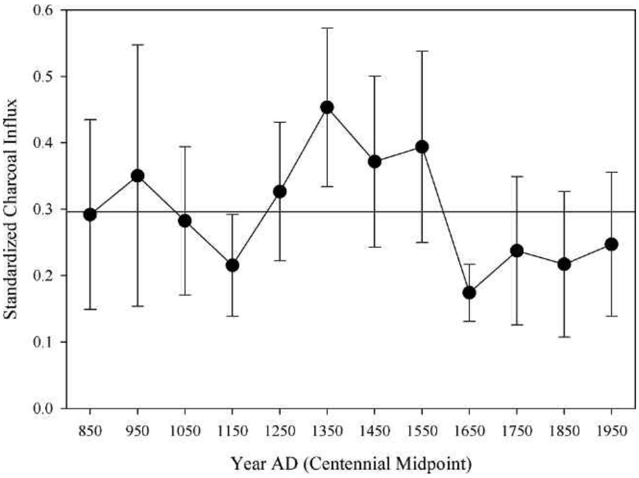

Figure 5 Regional summary of charcoal influx to lakes over the past 1200 years. Data for each series were standardized by dividing by the series maximum, and centennial means were summarized (mean ± 1 standard error of mean) across the nine lakes. The horizontal line represents the average standardized influx across the past 1200 years. See Figure 4 for individual summary diagrams

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

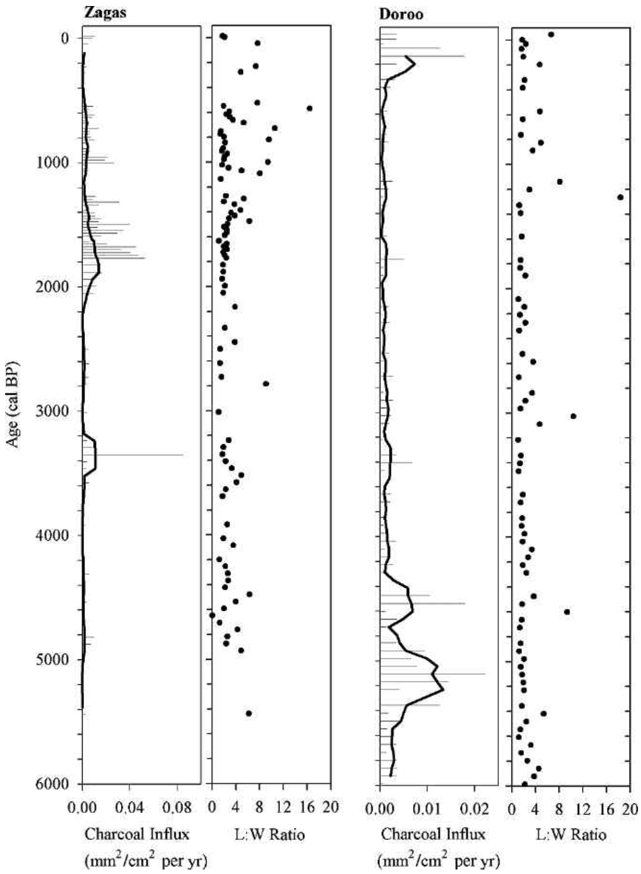

Figure 6 Summary diagram of charcoal influx (mm^2/cm^2 per yr; line is 400 year smooth average) and charcoal L:W ratios over the past ~5500 years for Zagas Nuur and Doroo Nuur. See Figure 1A for location of lakes

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/m^2 per yr which, at least at the upper part of the range, is comparable with the 100–400 g/m^2 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 (Scurlock *et al*., 2002) as well as the Festuca and Agropyron-Stipa grasslands of Canada (Pylpec 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 terriginous material due to increased erosion from shorelines and the surrounding catchment. There are several reasons to be cautious about this interpretation of LOI and magnetics. 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 allogenic 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 magnetotatic 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 (Germeraad and Enebisch, 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 (Redmann *et al*., 1993; Bennett *et al*., 2002; Pylpec 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 livestock 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 pasturage and herder movements during the twentieth century associated with the beginning and end of the communist era (Bold, 2001; Sneath, 1998, 2001).

Table 4 AMS ^{14}C dates (±1 SD) for nine sediment cores in northwestern Mongolia. Calibrated ^{14}C dates given as cal. BP, and calibration was done with CALIB 5.0. The median age (cal. yr BP rounded to nearest decade) was used for construction of time versus depth curves (Figure 3)

Lake	CAMS[a]	Depth (cm)	^{14}C dates	Error	Cal. age range[b]	Median age cal. BP[c]
Airag	113769	83–85	880	140	688–923	802
	112151	105–107	1285	70	1142–1293	1225
Kholboo	113768	68–72	1800	120	1576–1868	1727
	112152	84–85	2875	80	2877–3086	3002
Doroo	132980	22–27	1425	70	1273–1387	1329
	113011	84–87	4120	80	4530–4816	4658
	113010	112–113	6220	340	6712–7443	7443
Zagas	112153	87–88	1835	70	1700–1868	1770
	113770	139–143	4250	140	4568–4972	4795
Bega	126411	150–153	640	180	513–728	610
Tsagaan	132981	114–118	1800	35	1619–1824	1730
	129273	157–159	1910	120	1557–2135	1850
Bayan	132982	67–72	2050	45	1903–2128	2000
	129274	155–160	2875	50	2864–3198	3000
Khundt	124439	165–167	1000	100	715–1137	910
Takhilt	132983	84–88	475	35	450–558	510
	123410	139–143	850	120	681–909	770

[a] Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory.
[b] Calibrated age ranges include sum ages with a probability of >0.9.
[c] Median probability date as determined by CALIB 5.0.

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/km^2 in AD 1220 versus 2115 kg/km^2 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/km^2 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 permiting fuels to accumulate.

While climate clearly provides broad constraints on vegetation, our results suggests 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).

Acknowledgements

This material is based upon work supported by the National Science Foundation (NSF) under grants DEB-0316503 and DEB-0431529. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the NSF. The work was also supported by a grant to St Olaf College from the Howard Hughes Medical Institute and a St Olaf College Faculty Development Grant. Special thanks go to Bill Chang, Lkhagvasuren, Soninkhishig Nergui, Mark Edlund, Jim Almendinger, Tom Brown, B. Otgonbaatar and Phil Camill for their assistance. Thanks also to Zicheng Yu and two anonymous reviewers for their many helpful suggestions which greatly improved this paper.

References

Aizen, E.M., Aizen, V.B., Melack, J.M., Nakamura, T. and **Ohta, T.** 2001: Precipitation and atmospheric circulation patterns at mid-latitudes of Asia. *International Journal of Climatology* 21 535–56.

An, Z. 2000: The history and variability of the East Asian paleomonsoon climate. *Quaternary Science Reviews* 19, 171–87.

Appleby, P.G. 2001: Chronostratigraphic techniques in recent sediments. In Last, W.M. and Smol, J.P., editors, *Tracking environmental change using lake sediments volume 1: basin analysis, coring, and chronological techniques*. Kluwer Academic Publishers, 171–201.

Appleby, P.G. and **Oldfield, F.** 1978: The calculation of lead-210 dates assuming a constant rate of supply of unsupported 210Pb to the sediment. *Catena* 5, 1–8.

Banerjee, S.K., King, J. and **Marvin, J.** 1981: A rapid method for magnetic granulometry with applications to environmental studies. *Geophysical Research Letters* 8, 333–36.

Batima, P. 2006: Climate change vulnerability and adaptation in the livestock sector of Mongolia: a final report submitted to assessments of impacts and adaptations to climate change (AIACC), Project No. AS 06. The International START Secretariat.

Beer, R., Heiri, O. and **Tinner, W.** 2007: Vegetation history, fire history and lake development recorded for 6300 years by pollen, charcoal, loss on ignition and chironomids at a small lake in southern Kyrgyzstan (Alay Range, Central Asia). *The Holocene* 17, 977–85.

Begzsuren, S., Ellis, J.E., Ojima, D.S., Coughenour, M.B. and **Chuluun, T.** 2004: Livestock responses to droughts and severe winter weather in the Gobi Three Beauty National Park, Mongolia. *Journal of Arid Environments* 59, 785–96.

Bennett, L.T., Judd, T.S. and **Adams, M.A.** 2002: Growth and nutrient content of perennial grasslands following burning in semi-arid, sub-tropical Australia. *Plant Ecology* 164, 185–99.

Binford, M.W. 1990: Calculation and uncertainty analysis of 210Pb dates for PIRLA project cores. *Journal of Paleolimnology* 3, 253–67.

Birks, H.H. and **Birks, H.J.B.** 2006: Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany* 15, 235–51.

Bold, O.-B. 1998: The quantity of livestock owned by Mongols in the 13th century. *Journal of the Royal Asiatic Society* 8, 237–46.

—— 2001: *Mongolian nomadic society: a reconstruction of the 'Medieval' history of Mongolia*. St. Martin's Press.

Bond, W.J., Woodward, F.I. and **Midgley, G.F.** 2005. The global distribution of ecosystems in a world without fire. *New Phytologist* 165, 525–38.

Briggs, J.M. and **Knapp, A.K.** 1995: Interannual variability in primary productivity in tallgrass prairie: climate, soil moisture, topographic position, and fire as determinants of aboveground biomass. *American Journal of Botany* 82, 1024–30.

Burney, D.A., Robinson, G.S. and **Burney, L.P.** 2003: Sporormiella and the late Holocene extinctions in Madagascar. *Proceedings of the National Academy of Science* 100, 10 800–805.

Camill, P., Umbanhowar, C.E., Jr, Teed, R., Geiss, C.E., Aldinger, J., Dvorak, L., Kenning, J., Limmer, J. and **Walkup, K.** 2003: Lateglacial and Holocene climatic effects on fire and vegetation dynamics at the prairie-forest ecotone in south-central Minnesota. *Journal of Ecology* 91, 822–36.

Chen, F., Zicheng, Y., Yang, M., Ito, E., Wang, S., Madsen, D.B., Huang, X., Zhao, Y., Sato, T., Birks, J.B., Boomer, I., Chen, J., Chengbang, A. and **Wunnemann, B.** 2008: Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history. *Quaternary Science Reviews* 27, 351–64.

Christensen, L., Coughenour, M.B., Ellis, J.E. and **Chen, Z.Z.** 2004: Vulnerability of the Asian typical steppe to grazing and climate change. *Climatic Change* 63, 351–68.

Clark, J.S., Lynch, J., Stocks, B.J. and **Goldammer, J.G.** 1998: Relationships between charcoal particles in air and sediments in west-central Siberia. *The Holocene* 8, 19–29.

Clark, J.S., Grimm, E.C., Donovan, J.J., Fritz, S.C., Engstrom, D.R. and **Almendinger, J.E.** 2002: Drought cycles and landscape responses to past aridity on prairies of the Northern Great Plains, USA. *Ecology* 83, 595–601.

Climate Source 2004: Average annual precipitation and average mean temperature data for Mongolia (copyright 2000–2007).

Craine, J.M. and **McLachlan, K.K.** 2004: The influence of biotic drivers on North American palaeorecords: alternatives to climate. *The Holocene* 14, 787–91.

D'Arrigo, R., Jacoby, G., Frank, D., Pederson, N., Cook, E., Buckley, B., Nachin, B., Mijiddorj, R. and **Dugarjav, C.** 2001: 1738 years of Mongolian temperature variability inferred from a tree-ring width chronology of Siberian pine. *Geophysical Research Letters* 28, 543–46.

Davis, O.K. and **Shafer, D.S.** 1992: Holocene climatic record for the Sonoran Desert from pollen analysis of Montezuma Well, Arizona, USA. *Paleogeography, Paleoclimatology, Paleoecology* 92, 107–19.

—— 2006: *Sporormiella* fungal spores, a palynological means of detecting herbivore density. *Paleogeography, Paleoclimatology, Paleoecology* 237, 40–50.

Davis, O.K., Minckley, T., Moutoux, T., Jull, T. and **Kalin, B.** 2002: The transformation of Sonoran Desert wetlands following the historic decrease of burning. *Journal of Arid Environments* 50, 393–412.

Dean, W.E. 1974: Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology* 44, 242–48.

Dorofeyuk, N. and **Tarasov, P.** 1998: Vegetation and lake levels in northern Mongolia in the last 12 500 years as indicated by data of pollen and diatom analyses. *Stratigraphy and Geological Correlation* 6, 70–83.

Drewa, P.B. and **Havstad, K.M.** 2001: Effects of fire, grazing, and the presence of shrubs on Chihuahuan desert grasslands. *Journal of Arid Environments* 48, 429–43.

Ewing, T.E. 1980: Ch'ing policies in Outer Mongolia 1900–1911. *Modern Asian Studies* 14, 145–57.

Fang, J.-Q. and **Liu, G.** 1992: Relationship between climatic change and the nomadic southward migrations in eastern Asia during historical times. *Climatic Change* 22, 151–69.

Feng, Z.-D., An, C.B. and **Wang, H.B.** 2006: Holocene climatic and environmental changes in the arid and semi-arid areas of China: a review. *The Holocene* 16, 119–30.

Fernandez-Gimenez, M.E. and **Allen-Diaz, B.** 1999: Testing a non-equilibrium model of rangeland vegetation dynamics in Mongolia. *Journal of Applied Ecology* 36, 871–85.

Fowell, S.J., Hansen, B.C.S., Peck, J.A., Khosbayar, P. and **Ganbolde, E.** 2003: Mid to late Holocene climate evolution of the Lake Telmen Basin, North Central Mongolia, based on palynological data. *Quaternary Research* 59, 353–63.

Geiss, C.E., Banerjee, S.K., Camill, P. and **Umbanhowar, C.E., Jr** 2004: Sediment-magnetic signature of land-use and drought as recorded in lake sediment from south-central Minnesota, U.S.A. *Quaternary Research* 62, 117–25.

Germeraad, P.W. and **Enebisch, Z.** 1999: *The Mongolian landscape tradition: nomadic traditions and their contemporary role in landscape planning and management in Mongolia*. BGS.

Grunert, J., Lehmkuhl, F. and **Walther, M.** 2000: Paleoclimatic evolution of the Uvs Nuur basin and adjacent areas (Western Mongolia). *Quaternary International* 65/66, 171–92.

Gunin, P.D., Vostokova, E.A., Dorofeyuk, N.I., Tarasov, P.E. and **Black, C.C.** 1999: *Vegetation dynamics of Mongolia*. Kluwer Academic.

Hall, D.O., Ojima, D.S., Parton, W.J. and **Scurlock, J.M.O.** 1995: Response of temperate and tropical grasslands to CO_2 and climate change. *Journal of Biogeography* 22, 537–47.

Hilbig, W. 1995: *The vegetation of Mongolia*. SPB Academic Publishing.

Hobbs, N.T. 1996: Modifications of ecosystems by ungulates. *Journal of Wildlife Management* 60, 695–713.

Huang, C.C., Pang, J., Chen, S., Su, H., Han, J., Cao, Y., Zhao, W. and **Tan, Z.** 2006: Charcoal records of fire history in the Holocene loess-soil sequences over the southern Loess Plateau of China. *Palaeogeography Palaeoclimatology Palaeoecology* 239, 28–44.

Huang, X.Z., Chen, F.H., Fan, Y.X. and **Yang, M.L.** 2007: Dry late-glacial and early Holocene climate in arid central Asia indicated by lithological and palynological evidence from Bosten Lake, China. *Quaternary International* doi:10.1016/j.quaint.2007.10.002.

Hunt, C.P., Moskowitz, B.M. and **Banerjee, S.K.** 1995: Magnetic properties of rocks and minerals. In Ahrens, T.J., editor, *Rock physics and phase relations. A handbook of physical constants*. AGU Reference Shelf, 189–204.

Insightful Corporation 2001: *S-Plus 6 for Windows*.

Kalugin, I., Selegei, V., Goldberg, E. and **Seret, G.** 2005: Rhythmic fine-grained sediment deposition in Lake Teletskoye, Altai, Siberia, in

relation to regional climate change. *Quaternary International* 136, 5–13.
Keeley, J.E. and **Rundel, P.W.** 2005: Fire and the Miocene expansion of C4 grasslands. *Ecology Letters* 8, 683–90.
Knapp, A.K. and **Smith, M.D.** 2001: Variation among biomes in temporal dynamics of aboveground primary production. *Science* 291, 481–84.
Knapp, P.A. 1998: Spatio-temporal patterns of large grassland fires in the Intermountain West, U.S.A. *Global Ecology and Biogeography Letters* 7, 259–72.
Legendre, P. and **Legendre, L.** 1998: *Numerical ecology*. Elsevier Science.
Li, S.G., Harazono, Y., Oikawa, T., Zhao, H.L., He, Z.Y. and **Chang, X.L.** 2000: Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. *Agricultural and Forest Meteorology* 102, 125–37.
Liu, H., Wang, Y., Tian, Y., Zhu, J. and **Wang, H.** 2006: Climatic and anthropogenic control of surface pollen assemblages in East Asian steppes. *Review of Palaeobotany & Palynology* 138, 281–89.
Mensing, S.A., Michaelson, J. and **Byrne, R.** 1999: A 560-year record of Santa Ana fires reconstructed from charcoal deposited in the Santa Barbara Basin, California. *Quaternary Research* 51, 295–305.
Mensing, S.A., Livingstone, S. and **Barker, P.** 2006: Long term fire history in Great Basin sagebrush reconstructed from macroscopic charcoal in spring sediments, Newark Valley, Nevada. *Western North American Naturalist* 66, 64–77.
Mitchell, S.W. and **Csillag, F.** 2001: Assessing the stability and uncertainty of predicted vegetation growth under climatic variability: northern mixed grass prairie. *Ecological Modelling* 139, 101–21.
Mongolian Academy of Sciences 1990: *Information Mongolia: the comprehensive reference source of the People's Republic of Mongolia (MPR)*. Pergamon Press.
Moses, L. and **Halkovic, S.A., Jr** 1985: *Introduction to Mongolian history and culture*. Research Institute for Inner Asian Studies, Indiana University.
Mouillot, F. and **Field, C.B.** 2005: Fire history and the global carbon budget: a 1o x 1o fire history reconstruction for the 20th century. *Global Change Biology* 11, 398–420.
Munkhtsetseg, E., Kimura, R., Wang, J. and **Shimoda, M.** 2007: Pasture yield response to precipitation and high temperature in Mongolia. *Journal of Arid Environments* 70, 94–110.
Ni, J. 2004: Estimating net primary productivity of grasslands from field biomass measurements in temperate northern China. *Plant Ecology* 174, 217–34.
O'Dea, M.E. and **Guertin, D.P.** 2003: Prescribed fire effects on erosion parameters in a perennial grassland. *Journal of Range Management* 56, 27–32.
Ojima, D. and **Chuluun, T.** 2008: Policy changes in Mongolia: implications for land use and landscapes. In Galvin, K.A., Reid, R.S., Behnke, J.R.H. and Hobbs, N.T., editors, *Fragmentation in semi-arid and arid landscapes: consequences for human and natural systems*. Springer, 179–93.
Oldfield, F. 2007: Sources of fine-grained magnetic minerals in sediments: a problem revisited. *The Holocene* 17, 1265–71.
Oswald, W.W., Anderson, P.M., Brown, T.A., Brubaker, L.B., Hu, F.S., Lozhkin, A.V., Tinner, W. and **Kaltenrieder, P.** 2005: Effects of sample mass and macrofossil type on radiocarbon dating of arctic and boreal lake sediments. *The Holocene* 15, 758–67.
Panyushkina, I.P., Ovtchinnikov, D.V. and **Adamenko, M.F.** 2005: Mixed response of decadal variability in larch tree-ring chronologies from upper tree-lines of the Russian Altai. *Tree-Ring Research* 61, 33–42.
Pylpec, B. and **Romo, J.T.** 2003: Long-term effects of burning Festuca and Stipa-Agropyron grassland. *Journal of Range Management* 56, 640–45.
Redmann, R.E., Romo, J.T., Pylpec, B. and **Driver, E.A.** 1993: Impacts of burning on primary productivity of Festuca and Stipa-Agropyron grasslands in central Saskatchewan. *American Midland Naturalist* 130, 262–73.
Robbins, J.A. 1978: Geochemical and geophysical applications of radioactive lead isotopes. In Nriago, J.P., editor, *Biogeochemistry of lead in the environment*. Elsevier, 285–393.
Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M. and **Hashimoto, H.** 2004: A continuous satellite-derived measure of global terrestrial primary production. *Bioscience* 54, 547– 60.
Sala, O.E., Parton, W.J., Joyce, L.A. and **Lauenroth, W.K.** 1988: Primary production of the central grassland region of the United States. *Ecology* 69, 40–45.
Savage, M. and **Swetnam, T.W.** 1990. Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. *Ecology* 71, 2374–78.
Scott, J.H. and **Burgan, R.E.** 2005: *Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model*. Rocky Mountain Research Station, 72.
Scurlock, J.M.O., Johnson, K. and **Olson, R.J.** 2002: Estimating net primary productivity from grassland biomass dynamics measurements. *Global Change Biology* 8, 736–53.
Shafer, D.S. 1989: The timing of late Quaternary monsoon precipitation maxima in the southwest United States. PhD Thesis, University of Arizona.
Shuman, B. 2003: Controls on loss-on-ignition variation in cores from two shallow lakes in the northeastern United States. *Journal of Paleolimnology* 30, 371–85.
Sims, P.L. and **Singh, J.S.** 1978a: The structure and function of ten western North American grasslands II. Intra-seasonal dynamics in primary producer compartments. *Journal of Ecology* 66, 547–72.
—— 1978b: The structure and function of ten western North American grasslands: III. Net primary production, turnover and efficiencies of energy capture and water use. *Journal of Ecology* 66, 573–97.
Sneath, D. 1998: State policy and pasture degradation in Inner Asia. *Science* 281, 1147–48.
—— 2001: Notions of rights over land and the history of Mongolian pastoralism. *Inner Asia* 3, 41–59.
Solomina, O. and **Alverson, K.** 2004: High latitude Eurasian paleoenvironments: introduction and synthesis. *Paleogeography, Paleoclimatology, Paleoecology* 209, 1–18.
Strauss, A. and **Schickhoff, U.** 2007: Influence of soil-ecological conditions on the vegetation zonation in a western Mongolian lake shore-semi-desert ecotone. *Endkunde* 61, 72–92.
Stuiver, M. and **Reimer, P.J.** 1993: Extended 14C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35, 215–30.
Stuiver, M., Reimer, P.J. and **Reimer, R.** 1999: CALIB radiocarbon calibration (HTML Version 4.2).
Suttie, J.M., Reynolds, S.G. and **Batello, C.** 2005: *Grasslands of the world*. Food and Agriculture Organization of the United Nations.
Swetnam, T.W. and **Baisan, C.H.** 1996: Historical fire regime patterns in the Southwestern United States since AD 1700. In Allen, C.D., editor, *Proceedings of the second La Mesa fire symposium*. General Technical Report RM-GTR-286.: USDA Forest Service, 11–32.
Swetnam, T. and **Betancourt, J.** 1990: Fire-southern oscillation relations in the southwestern United States. *Science* 249, 1010–20.
Tarasov, P.E., Webb, T., III, Andreev, A.A., Afanas'eva, N.B., Berezina, N.A., Bezusko, L.G., Blyakharchuk, T.A., Bolikhovskaya, N.S., Cheddadi, R., Chernavskaya, M.M., Chernova, G.M., Dorofeyuk, N.I., Dirksen, V.G., Elina, G.A., Filimonova, L.V., Glebov, F.Z., Guiot, J., Gunova, V.S., Harrison, S.P., Jolly, D., Khomutova, V.I., Kvavadze, E.V., Osipova, I.M., Panova, N.K., Prentice, I.C., Saarse, L., Sevastyanov, D.V., Volkova, V.S. and **Zernitskaya, V.P.** 1998: Present day and mid-Holocene biomes reconstructed from pollen and plant macrofossil data from the former Soviet Union and Mongolia. *Journal of Biogeography* 25, 1029–53.
Tarasov, P.E., Volkova, V.S., Webb, T., Guiot, J., Andreev, A.A., Bezusko, L.G., Bezusko, T.V., Bykova, G.V., Dorofeyuk, N.I., Kvavadze, E.V., Osipova, I.M., Panova, N.K. and **Sevastyanov, D.V.** 2000: Last glacial maximum biomes reconstructed from pollen and plant macrofossil data from northern Eurasia. *Journal of Biogeography* 27, 609–20.
Triplett, L. 2002: *Standard operating procedures for grain size analysis sample preparation*. Limnological Research Centre.
Umbanhowar, C.E. 1996: Recent fire history of the northern Great Plains. *American Midland Naturalist* 135, 115–21.

Umbanhowar, C.E., Jr 2004: Interactions of climate and fire at two sites in the northern Great Plains, USA. *Palaeogeography Palaeoclimatology Palaeoecology* 208, 141–52.
Umbanhowar, C.E. and **McGrath, M.J.** 1998: Experimental production and analysis of microscopic charcoal from wood, leaves and grasses. *The Holocene* 8, 341–46.
Webster, R. 1973: Automatic soil-boundary location from transect data. *Mathematical Geology* 5, 27–37.
Whelan, R.J. 1995: *The ecology of fire*. Cambridge University Press.
Whitlock, C. and **Millspaugh, S.H.** 1996: Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6, 7–15.
Willis, K.J. and **Birks, H.J.B.** 2006: What is natural? The need for a long-term perspective in biodiversity conservation. *Science* 314, 1261–65.
Wright, H.A. and **Bailey, A.W.** 1980: *Fire ecology and prescribed burning in the Great Plains – a research review*. USFS, USDA.
Xiao, X., Ojima, D.S., Parton, W.J., Chen, Z. and **Chen, D.** 1995: Sensitivity of Inner Mongolia grasslands to climate change. *Journal of Biogeography* 22, 643–48.
Yang, B., Wang, J., Brauning, A., Dong, Z. and **Esper, J.** 2009: Late Holocene climatic and environmental changes in arid central Asia. *Quaternary International* 194, 68–78.
Yang, X., Wang, M., Huang, Y. and **Wang, Y.** 2002: A one-compartment model to study soil carbon decomposition rate at equilibrium situation. *Ecological Modelling* 151, 63–73.
Yao, J., Holt, R.D., Rich, P.M. and **Marshall, W.S.** 1999: Woody plant colonization in an experimentally fragmented landscape. *Ecography* 22, 715–28.
Yu, M., Ellis, J.E. and **Epstein, H.E.** 2004: Regional analysis of climate, primary production, and livestock density in inner Mongolia. *Journal of Environmental Quality* 33, 1675–81.
Zhang, J.Y., Dong, W.J. and **Fu, C.B.** 2005: Impact of land surface degradation in northern China and southern Mongolia on regional climate. *Chinese Science Bulletin* 50, 75–81.
Zhao, M., Heinsch, F.A., Nemani, R.R. and **Running, S.W.** 2005: Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sensing of Environment* 95, 164–76.
Zheng, W.Z. and **Ni, Y.Q.** 1999: A numerical experiment study for effects of the grassland desertification on summer drought in North China. *Advances in Atmospheric Sciences* 16, 251–62.