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What drives the recent intensified vegetation degradation in Mongolia – Climate change or human activity?

Fang Tian,[1,2] Ulrike Herzschuh,[1,2] Steffen Mischke[2,3] and Frank Schlütz[4]

Abstract

This study examines the course and driving forces of recent vegetation change in the Mongolian steppe. A sediment core covering the last 55 years from a small closed-basin lake in central Mongolia was analyzed for its multi-proxy record at annual resolution. Pollen analysis shows that highest abundances of planted Poaceae and highest vegetation diversity occurred during 1977–1992, reflecting agricultural development in the lake area. A decrease in diversity and an increase in *Artemisia* abundance after 1992 indicate enhanced vegetation degradation in recent times, most probably because of overgrazing and farmland abandonment. Human impact is the main factor for the vegetation degradation within the past decades as revealed by a series of redundancy analyses, while climate change and soil erosion play subordinate roles. High *Pediastrum* (a green algae) influx, high atomic total organic carbon/total nitrogen (TOC/TN) ratios, abundant coarse detrital grains, and the decrease of $\delta^{13}C_{org}$ and $\delta^{15}N$ since about 1977 but particularly after 1992 indicate that abundant terrestrial organic matter and nutrients were transported into the lake and caused lake eutrophication, presumably because of intensified land use. Thus, we infer that the transition to a market economy in Mongolia since the early 1990s not only caused dramatic vegetation degradation but also affected the lake ecosystem through anthropogenic changes in the catchment area.

Keywords

central Mongolia, grain size, human impact, lake eutrophication, pollen, vegetation degradation

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Introduction

Mongolia's seemingly endless green steppes are presumed to represent a cultural landscape formed by nomadic herders thousands of years ago (Lehmkuhl et al., 2011; Miehe et al., 2007; Rösch et al., 2005) with very few exceptions (Schlütz et al., 2008). However, the type and intensity of land use changed strongly in the course of the 20th century, particularly when Mongolia was transforming from a centrally planned to market economy in the early 1990s. On one hand, livestock privatization and market factors have given herders a strong incentive to keep more livestock and therefore stimulated the growth of livestock populations, and on the other hand, large amounts of cropland have been abandoned from cultivation (Wang et al., 2013). Previous investigations have shown that about 70–80% of Mongolian pastures suffered from degradation of varying intensity (Batkhishig, 2011; Buren, 2011), as a result not only from overgrazing but also from the establishment and subsequent abandonment of cropland (Hirano and Batbileg, 2013; Wang et al., 2013). However, other studies suggest that large-scale desertification is caused mainly by recent climate change (Batjargal, 1997; Hoshino et al., 2009; Liu et al., 2013). Indeed, because of its intermediate location, Mongolia can be expected to be highly vulnerable to climate change (Gomboluudev and Natsagdorj, 2004) as it is placed in the transition zone between the Siberian taiga and the central Asian deserts and between the monsoon-dominated southeastern Asia and the westerly dominated Siberia. Hence, there remain open questions as to what extent the vegetation cover has changed in recent decades and what is the main driving force.

Long-term monitoring studies that reflect the environmental change in the course of the 20th century in Mongolia are lacking. Lake records may therefore represent the most suitable archive for investigating past environmental conditions, and they have been successfully used for similar studies in Mongolia but focusing on changes at millennial (Felauer et al., 2012; Wang et al., 2009) and centennial time-scales (Tian et al., 2013). Studies from Central Asia demonstrate that pollen analyses of sediment cores from small and shallow dryland lakes are suitable for tracking short-term vegetation changes (Herzschuh et al., 2006; Zhao et al., 2008). Furthermore, modern pollen assemblages from Mongolia are found to be indicative of grassland systems that

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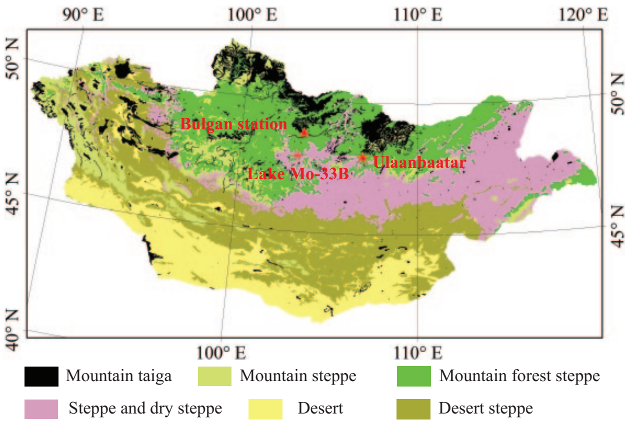

Figure 1. Vegetation zones in Mongolia and location of Lake Mo-33B.

result from varying types and intensity of human impact (Ma et al., 2008). Hence, it should be possible to investigate the temporal evolution of grassland degradation by high-resolution pollen analysis of lake sediments which may additionally contain proxies for simultaneously occurring limnological changes.

In this study, we investigate the pollen assemblage, non-pollen palynomorphs (NPPs), grain size, carbon and nitrogen element concentrations, and stable isotope record for a short sediment core from a small lake (Lake Mo-33B, working name) in central Mongolia. Our objectives are (1) to infer vegetation change since the mid-20th century; (2) to quantify the main drivers of vegetation variability: that is, human impact, climate, soil erosion; and (3) to detect the relationship between vegetation and lake-ecosystem change.

Study area

Lake Mo-33B (47.9°N, 103.2°E, 1173 m a.s.l.) is located in the southern part of Bulgan Province in central Mongolia, in an area of subdued relief. The present-day climate in the lake region is a typical temperate continental climate, with cold, dry winters dominated by the Siberian/Mongolian high pressure system, and warm, wet summers influenced by the Asian low pressure system (Wang et al., 2009). The Atlantic air masses carried by the westerlies are the dominant moisture source for this area (Alpat'ev et al., 1976), and the region receives most of its precipitation during summer (Angerer et al., 2008), with mean annual precipitation (P_{ann}) of about 286 mm, mean annual temperature (T_{ann}) of −0.3°C, and mean temperature of −19.3°C for the coldest month and 16.7°C for the warmest month (Bulgan meteorological station, about 100 km north of the lake; http://www.ncdc.noaa.gov). The lake is surrounded by dry steppe vegetation on typical dark chestnut soil dominated by herbaceous taxa (such as Poaceae and *Artemisia*) and small-shrub taxa (such as *Caragana* and *Armeniaca sibirica*). Today, the lake catchment is an important herding district, predominantly for goats and sheep (Saandar and Sugita, 2004). Lake Mo-33B is a small (open water area: *c.* 100 m^2) and shallow (maximum water depth: 4.1 m) closed-basin lake with a pH of 8.5 and a salinity of 0.2 g/L (own measurements in July 2005).

Materials and methods

Coring and dating methods

A 21.4-cm-long sediment core was collected in 2005 from the center of Lake Mo-33B at a water depth of 4.1 m (Figure 1). The core was sub-sampled in the field at 0.4 cm intervals, resulting in 53 samples for laboratory analysis. In order to achieve a reliable chronology, we used $^{210}Pb/^{137}Cs$ dating techniques for the whole core, which was performed at the Liverpool University Environmental Radioactivity Laboratory (UK).

Pollen and NPP analyses

Sub-samples of 0.5 mL of original sediment were processed for pollen analysis. Pollen preparation followed the standard protocol (Faegri and Iversen, 1989), including HCl, KOH, HF, and acetolysis treatment, and sieving to remove fine particles, which has been demonstrated to be acceptable also for the preparation of NPPs (Clarke, 1994). Two tablets of *Lycopodium* spores were initially added to each sample for calculation of pollen and NPP concentrations (Maher, 1981).

Pollen grains and NPPs were counted using a Zeiss optical microscope at 400× magnification; pollen grain identification followed the relevant literature (Beug, 2004; Moore et al., 1991; Wang et al., 1997). More than 500 terrestrial pollen grains were counted for each sample. Pollen percentages were calculated based on the total number of pollen grains from terrestrial pollen taxa. They were used for the construction of the pollen diagram as well as for numerical analysis. The identification of pollen zone boundaries was based on the results of a Constrained Incremental Sum of Squares cluster analysis (CONISS) performed with Tilia software (Grimm, 1987, 1991).

Pediastrum boryanum var. *boryanum, Pediastrum boryanum* var. *cornutum, Glomus*-type, *Sporormiella* type, and *Sordaria* type were identified according to Jankovská and Komárek (2000), Komárek and Jankovská (2001), Van Geel et al. (1989, 2003, 2007), Aptroot and Van Geel (2006), and Punt et al. (2007), respectively. At least 50 NPPs were recorded for most levels, with most samples being well in excess of this minimum. The NPP influx was inferred from the relationship between their concentration and sedimentation rate.

Grain-size analysis and end-member modeling

Grain-size analysis of the bulk sediment was carried out for all 53 samples. A Laser Coulter LS200 particle size analyzer was used at the AWI in Potsdam, resulting in 92 size classes from 0.375 to 1822 µm. We applied the End-Member Modeling Algorithm (EMMA) developed by Weltje (1997) to obtain robust end-members (EMs) from the total set of grain-size measurements, and to determine the proportional contributions of these EMs to all sediments in the lake on the basis of the measured grain-size distributions (Weltje and Prins, 2003, 2007). To avoid a fixed single outcome and to extract reliable and robust EMs, models were run considering different numbers of EMs (between the minimum and maximum numbers of potential EMs) and flexible weight transformations. The minimum number of potential EMs was determined by the cumulative explained variance of at least 95%; the maximum number of EMs was determined by the maximum value of the mean coefficient of determination. We tested the robustness of the EMs and then extracted the final robust EM(s) and residual member. All these computations were made using MATLAB software. A detailed description of the EMMA method applied can be found in Dietze et al. (2012).

Elemental and isotope analysis

Freeze-dried material from 53 samples was triturated for further elemental and isotope analysis. Sediment samples were treated using 10% HCl solution to remove carbonate for total organic carbon (TOC), total nitrogen (TN), nitrogen stable isotope ($\delta^{15}N$), and organic carbon stable isotope ($\delta^{13}C_{org}$) measurements. Total carbon (TC), TN, and TOC contents were measured with a vario MAX C analyzer at AWI Potsdam. The atomic TOC/TN ratio was calculated using the percentages of TOC, TN, and the molar masses of C and N (Meyers and Lallier-Vergès, 1999). $\delta^{15}N$ and

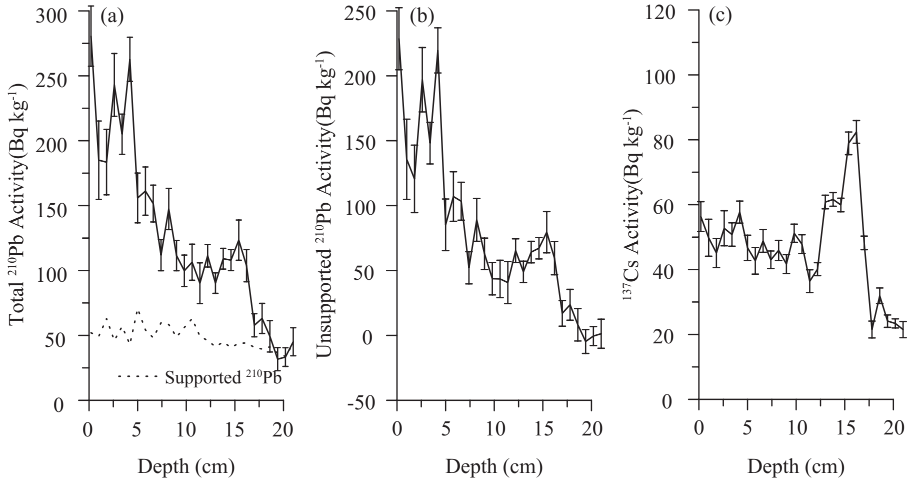

Figure 2. Fallout ^{210}Pb and ^{137}Cs records in core Mo-33B showing (a) total and supported ^{210}Pb (arising from decay of the natural ^{226}Ra in the sediments), (b) unsupported ^{210}Pb (resulting from atmospheric fallout), and (c) ^{137}Cs concentrations versus depth (modified from Peter Appleby's report on core Mo-33B).

$\delta^{13}C_{org}$ were analyzed at GFZ Potsdam using Finnigan DELTA-^{plus}XL mass spectrometer equipped with a Carlo Erba elemental analyzer and a ConFlowIII gas split system.

Numerical analyses

In order to detect the factors underlying the variations in the pollen percentages and to identify relationships between different taxa, Principal Component Analysis (PCA) was performed using Canoco version 4.5 (ter Braak and Šmilauer, 2002). Square-roots of 23 pollen taxa (those with percentages > 0.5% in at least three samples) were used in PCA (as correlation biplot with centering of species data); pre-1960 samples were included as supplementary data in the PCA. A second PCA (as correlation biplot with centering and scaling of species data) was performed for lake data (*Pediastrum boryanum* var. *boryanum, Pediastrum boryanum* var. *cornutum*, TOC, TN, atomic TOC/TN, $\delta^{15}N$, and $\delta^{13}C_{org}$). For both PCAs, P_{ann}, T_{ann}, EM1 scores, EM2 scores, total sown area, and livestock number were included as supplementary components. For the PCA of lake data, the axis-1 and axis-2 scores derived from the PCA of pollen data were included as supplementary data.

Redundancy analysis (RDA) was run for pollen data with each environmental variable separately to qualify the influence of that variable on the pollen assemblages, and with all (or groups of the) six variables together to discern how much variation in the pollen assemblage is explained by these variable groups individually and together. The six environmental variables were grouped as climate variables (P_{ann} and T_{ann}), soil-erosion variables (EM1 and EM2), and human-impact variables (livestock number and total sown area in Bulgan; NSO: http://www.nso.mn/v3/index2.php). For each environmental group, RDA was carried out with the other two groups as covariables, and for each of the two groups, RDA was run with the third subset as covariables. From the sum of eigenvalues in these 13 RDA runs, we calculated the proportions of variation in pollen data explained by two or three subsets together. A series of RDAs was performed for lake data similar to that of the pollen data but with two extra variables (PCA-1 and PCA-2 sample scores obtained from pollen data) that were taken as the fourth environmental group. As the climate and human-impact variables only have data for the post-1960 period, we used only the post-1960 samples for both RDAs. Statistical significance of all the RDA models was assessed by unrestricted Monte Carlo permutations (999). Computations were made using Canoco version 4.5 (ter Braak and Šmilauer, 2002).

Taxa richness was estimated using rarefaction analysis, a method to standardize and compare taxa richness from samples with different pollen count sums (Heck et al., 1975). The inverse Simpson index was calculated to best portray diversity changes in the vegetation. These two indexes were calculated using the *diversity* and *rarefy* functions, respectively, in the vegan package version 2.0-4 (Oksanen et al., 2012) for R 2.15.0 (R Core Team, 2012) based on the original pollen counting data.

Results

Dating

Relatively high total ^{210}Pb and unsupported ^{210}Pb concentrations between 13.6 and 16.4 cm suggest that sediments at these depths are no more than 45 years (about two ^{210}Pb half-lives) older than the collection year (2005) of the core (Figure 2a and b). The ^{137}Cs concentration has a relatively well-defined peak between 15.2 cm and 16.4 cm that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons (Figure 2c). All this indicates that the sediment above 16.4 cm is recent sediment accumulated after 1963. The core Mo-33B age model was established by interpolation between 0 and 16.4 cm and extrapolation below 16.4 cm based on the dates of 1963 at 15.8 cm and 2005 at 0 cm (Figure 3).

The steep decline in unsupported ^{210}Pb concentrations below 17 cm implies that there is a hiatus in the sediment record. The post-1963 ^{210}Pb record, which is unaffected by the hiatus, suggests a mean post-1963 sedimentation rate of 0.39 cm/yr, which is in good agreement with the values (0.38 cm/yr) determined from the ^{137}Cs record. The sedimentation rates are markedly lower in the 1960s and 1990s (~0.32 cm/yr) than during the late 1970s and early 1980s when peak rates reached more than 0.57 cm/yr (Figure 3). Dates of sediments pre-dating 1960 are very uncertain, although it does appear that the hiatus dates from the late 1950s as indicated by the unexpectedly low unsupported ^{210}Pb concentration.

Pollen data and results of multivariate analyses

A total of 57 pollen taxa were identified in the sediment core. *Artemisia* (range: 16–75%), Chenopodiaceae (range: 4–48%), Cyperaceae (range: 3–19%), and Poaceae (range: 4–17%) were the most common taxa throughout the core. The arboreal pollen content ranged between 2.5% and 10.3% of the total terrestrial pollen (median: 5.6%), mainly comprising *Betula, Larix, Pinus,* *Salix*, and *Ulmus*. The A/C ratios varied from 0.3 to 18.5 with the highest values between 1992 and 2005. The percentage diagram spanning the approximate period between AD 1950 and 2005 was divided into four major pollen zones by the cluster analysis CONISS (Figure 4). Rarefied taxa richness shows maximum values in zone 3 (1977–1992), while both the inverse Simpson and rarefied taxa richness decrease markedly after 1992.

The PCA of 23 terrestrial pollen taxa and 53 samples reflects the main features of the pollen diagram. The first component, capturing 50% of the pollen data variance (Figure 5a), divides the dataset into taxa indicating intensified vegetation degradation such as *Artemisia* and taxa indicating diverse meadows such as Poaceae, Brassicaceae, Fabaceae, and Chenopodiaceae. The second component accounts for only 12.5% of the total variance of species data and separates the variables into taxa preferring moist conditions such as Cyperaceae, Poaceae, and *Thalictrum* and drought-resistant taxa such as *Artemisia* and Chenopodiaceae (Figure 5a).

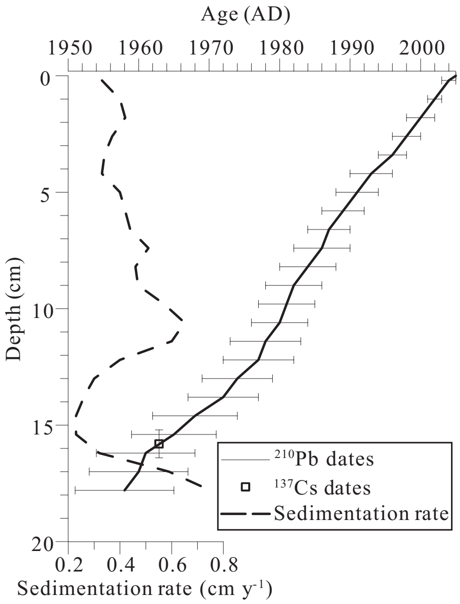

Figure 3. Radiometric chronology of core Mo-33B showing the 1963 depth recorded by the ^{137}Cs analysis, and the corrected CRS model ^{210}Pb dates and sedimentation rates calculated using the 1963 ^{137}Cs date as a reference point (modified from Peter Appleby's report on core Mo-33B).

NPP data and results of TOC, TN, atomic TOC/TN, $\delta^{15}N$, and $\delta^{13}C_{org}$ analyses

The NPPs (*Pediastrum boryanum* var. *boryanum, Pediastrum boryanum* var. *cornutum, Glomus*-type, *Sporormiella* type end-cell, *Sporormiella* type middle-cell, and *Sordaria* type) are shown in Figure 6 with the zone boundaries created for Figure 4 applied so that the description phases are common to both diagrams. The *Glomus*-type has the highest values before 1961, *Sporormiella* and *Sordaria* type become more abundant from around 1972, while both *Pediastrum boryanum* var. *boryanum* and var. *cornutum* show a strong increase after 1982 and strong reduction from the late 1990s.

TOC contents in the lower section of the core (pollen zone 1, 21.2–16.8 cm, *c*. 1950–1960) are lower (median: 3.4%) than in the middle (pollen zone 2, 16.8–12 cm, *c*. 1960–1977, median: 6.8%; pollen zone 3, 12–4.8 cm, *c*. 1977–1992, median: 8.9%) and upper section (pollen zone 4, 4.8–0 cm, 1992–2005, median: 10.6%, Figure 6). TN contents are low in pollen zone 1 (0.3–0.5%) and zone 2 (0.5–0.8%), then reach the highest values in zones 3 and 4 (0.8–1%). The atomic TOC/TN ratio varies between 11.3 and 16.8 (median: 13.1) with higher values (13.4–16.8, median: 14.8) since 1981 than in the period before 1981 (11.3–13.5, median: 12.0). $\delta^{15}N$ varies from 5.6‰ to 9.4‰ with relatively high values between 1981 and 1992. $\delta^{13}C_{org}$ varies between −30.7‰ and −24.7‰ with stable and high values before 1980 and decreasing and low values afterwards (Figure 6).

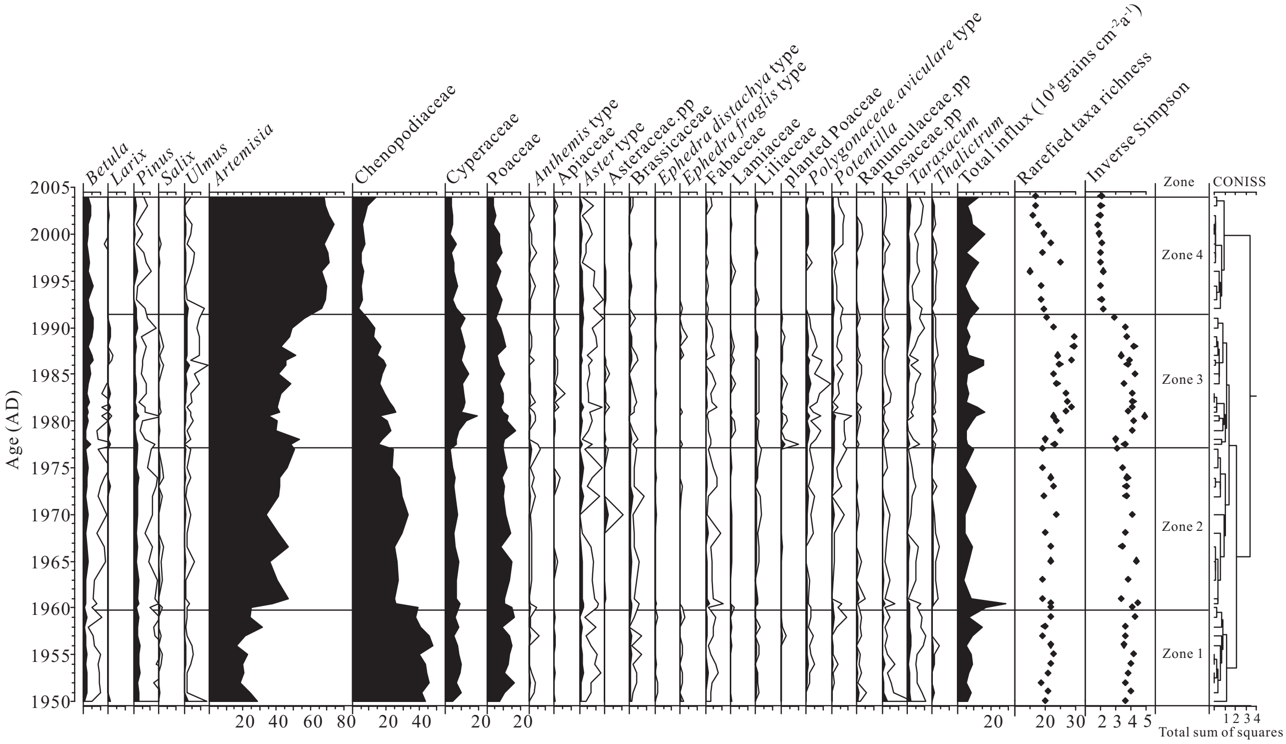

Figure 4. Pollen percentage data of common taxa, total pollen influx, rarefied taxa richness, and inverse Simpson index for the Mo-33B core. The original abundances of rare species are shown with a five-fold exaggeration (unfilled silhouettes).

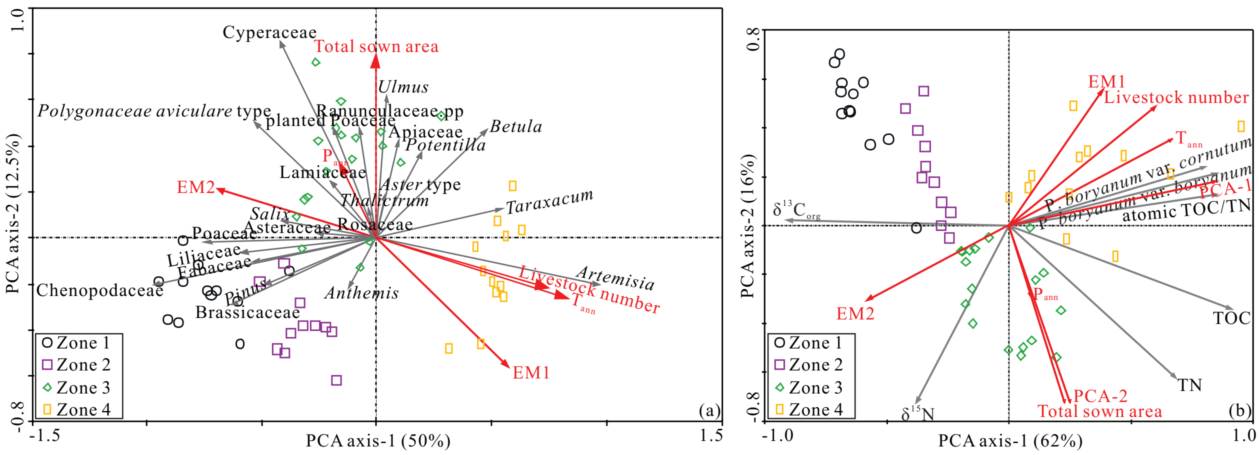

Figure 5. PCA ordination for (a) pollen data (23 taxa, >0.5% in at least three samples) together with the supplementary variables of EM1 and EM2 scores, P_{ann}, T_{ann}, total sown area, and livestock number in Bulgan Province; (b) lake aquatic ecosystem data together with the supplementary variables of P_{ann}, T_{ann}, total sown area and livestock number, EM1 and EM2 scores, and scores of the first two PCA axes for pollen data.

PCA: Principal Component Analysis; TOC: total organic carbon; TN: total nitrogen.

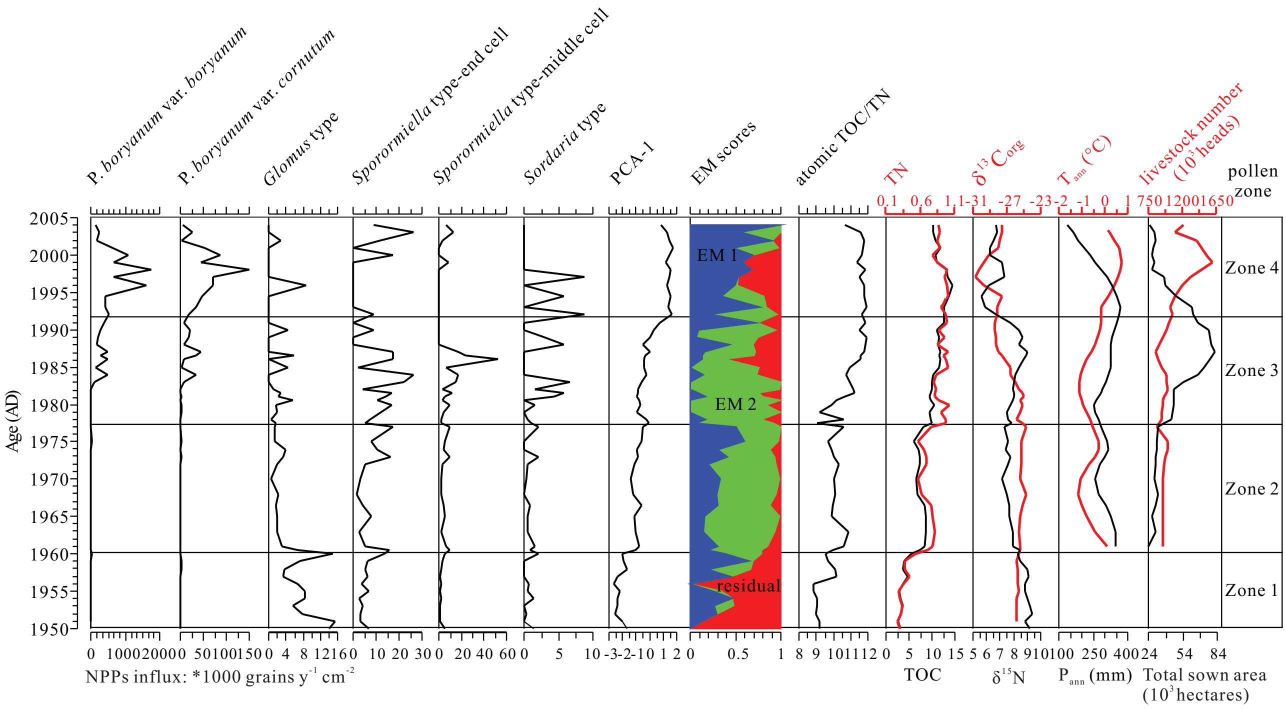

Figure 6. Non-pollen palynomorph influx; PCA-1 scores for pollen data; end-member scores from grain-size distributions; TOC, TN, atomic TOC/TN ratio, $\delta^{15}N$, and $\delta^{13}C_{org}$ variations of core Mo-33B as well as the observed data of climate and human-impact variables of Bulgan Province.

PCA: Principal Component Analysis; TOC: total organic carbon; TN: total nitrogen.

The first two PCA components capture 62% and 16% of the data variance (Figure 5b). The first axis is correlated with *Pediastrum* taxa, TOC, and $\delta^{13}C_{org}$, and the second axis with $\delta^{15}N$. The samples of the single zones form well-defined clouds in the sample plot and resemble the sample pattern of the pollen-based PCA.

Grain-size data and results from EM modeling

The grain-size spectra are dominated by silt fractions (22.5–84.5%, median: 62.7%), with the sand (1.2–75.6%, median: 22.9%) and clay (4.7–29.9%, median: 17.9) fractions accounting for a smaller part of the total. Two robust members and one residual member (describing the remaining noise) were identified and are presented in the loadings plot (Figure 7). The first robust member EM1 represents 22.8% of the total variance within the original data and corresponds to the coarse fraction (50–100 µm). The second robust member EM2 represents 52.9% and corresponds to the finer fraction (1–10 µm), while the residual member corresponds to a mixture of coarser fractions (around 40 µm, Figure 7).

Variance partitioning by RDA

RDA of the pollen data carried out with each environmental variable separately shows low and insignificant correlations with P_{ann}, while high and statistically significant correlations are identified with other variables (Supplementary Appendix S1, available online). RDA results also show that the human-impact subset has the strongest influence on pollen data variances. Relatively small portions of the variances can be explained by climate change and soil erosion (Figure 8a).

Results of RDA using each variable separately also highlight the low and insignificant correlations between lake-ecosystem data and P_{ann} (Supplementary Appendix S2, available online). RDA results show that the pollen-spectra variances (PCA-scores) subset has the strongest impact on lake-ecosystem changes, and that the human-impact subset has a relatively weak influence on the lake ecosystem (Figure 8b).

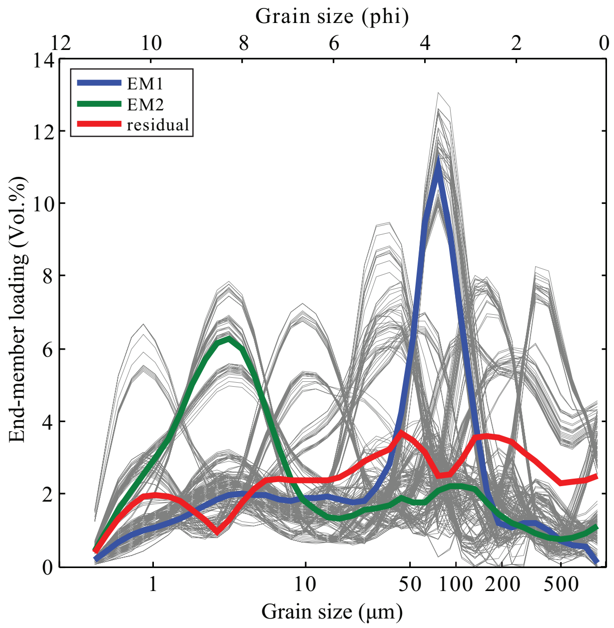

Figure 7. End-member loadings for the core Mo-33B indicating sedimentologically interpretable unmixed grain-size distributions (gray and black lines: all end-members from 55 EM model versions).

Discussion

The chronology and sedimentation rate

Previous studies in arid central Asia suggest that the sedimentation rates of lakes are commonly between 0.01 and 0.05 cm/yr, which is quite different from our study (~0.36 cm/yr), for example, Lake Ugii Nur (Wang et al., 2009), Lakes Saihanxili, and Bayan Nur in Hunshandake Sandy Land (Yang et al., 2013), Lakes Khubsugul, Gun Nur, Telmen, and Juyanze (An et al., 2008). The runoff has only a prominent influence on particle transportation over a very short distance after entering the lake (Yin et al., 2011). For large lakes with a long distance between the lake center and lake shore, little material from the surroundings are transported into the centers. In small lakes, material from the surroundings can be easily transported to the center by runoff or wave action because of the short distances between the lake center and the lake shore. Thus, small lakes have relatively high sedimentation rates (~0.45 cm/yr), for example, Lake Baoritalegai (Herzschuh et al., 2006) and Lake Gahai (Zhao et al., 2008) in northwest China. Lake Mo-33B has a surface area of only *c.* 100 m^2, and the lake surroundings have a low vegetation cover because of grazing. Sediment and organic matter are easily transported to the lake center by sheet floods and wind, causing the relatively high sedimentation rate (around 0.36 cm/yr).

Vegetation changes in the Mo-33B region during the last 55 years

Zone 1 (1950–1960) has the highest values of Chenopodiaceae percentages and the lowest values of *Artemisia*, TOC, TN, and atomic TOC/TN within the entire record and abrupt changes mark the transition to Zone 2, which may indicate the occurrence of a

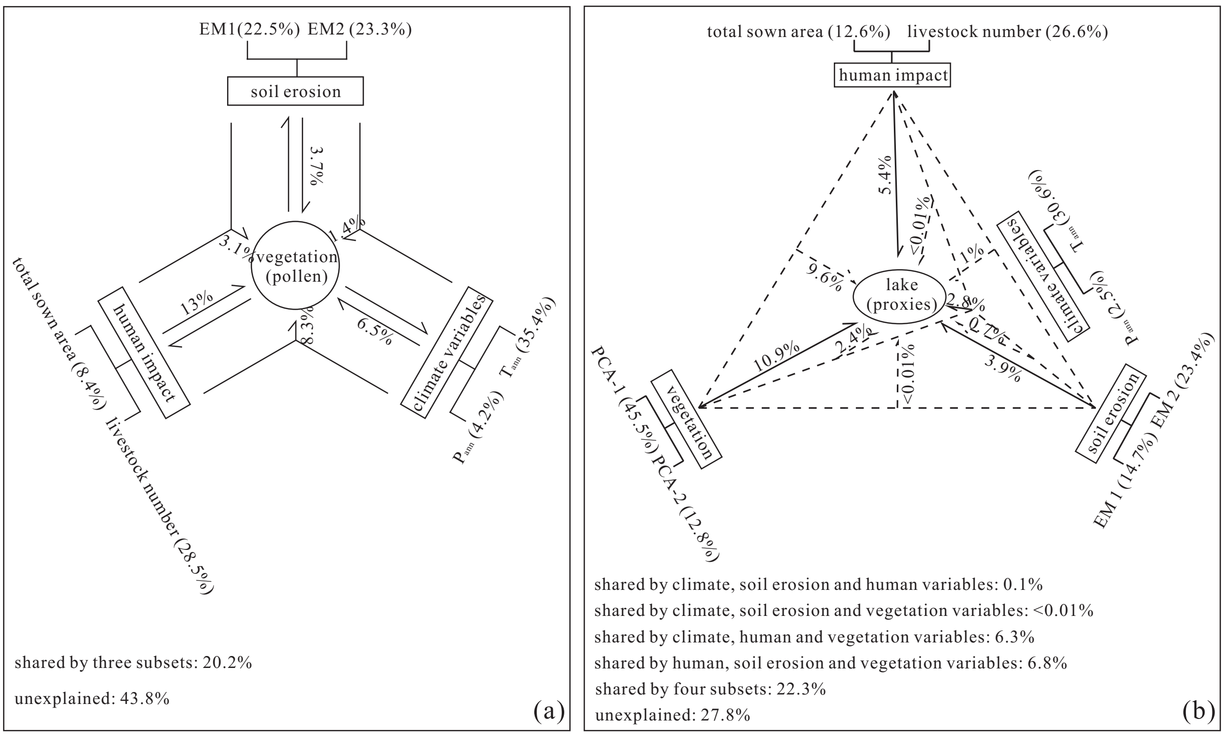

Figure 8. Partitioning of variation in (a) vegetation changes using three subsets of environmental data: climate factors (P_{ann} and T_{ann}), human-impact factors (livestock number and total sown area in Bulgan Province), and soil erosion (EM1 and EM2); and (b) lake aquatic ecosystem changes using four subsets including the three subsets for (a) and vegetation condition subset which was reflected by the scores of the first two PCA axes for pollen data.
PCA: Principal Component Analysis.

hiatus in the core around 1960 and thus increase the uncertainty in the dating of the pre-1960 sediments. Fungi producing *Glomus*-type spores live in symbiosis with roots of higher plants. The occurrence of spores of the *Glomus*-type therefore points to soil erosion in the catchment area of the lake (Miehe et al., 2009; Van Geel et al., 2003), possibly induced by human activity under dry conditions. The high *Glomus*-type influx and the input of mixtures of coarse fractions (highest residual scores in EM modeling of grain-size data) likely indicate strong soil erosion and possibly suggest that a sediment slump or even a lake-desiccation event occurred before 1960.

Zone 2 (1960–1977) has a reasonably stable pollen assemblage characterized by relatively high amounts of Poaceae, which probably indicates a wider distribution of relatively moist meadow steppe or even forest steppe communities (Hilbig, 1995). Such communities are particularly rich in Poaceae while *Artemisia* and Chenopodiaceae are the common taxa in dry steppe and desert communities. It may also reflect a relatively low livestock number (also indicated by the available statistical data from Bulgan) as Poaceae are preferentially grazed in comparison with Chenopodiaceae and *Artemisia* (Shimada et al., 2012).

Zone 3 (1977–1992) is characterized by relatively high Cyperaceae percentages and a taxa richness that probably reflects irrigation farming. However, the increase in taxa richness could also result from regionally wetter conditions.

The highest abundance of Cyperaceae pollen for the entire record is in zone 3 and may indicate the expansion of cold, wet tundra, forest steppe, or wetland (Gunin et al., 1999; Gunin and Vostokova, 1995; Hilbig, 1995) under the observed relatively wet and cold climate conditions. The highest planted Poaceae percentages likely reflect agricultural development during this period. Available survey information shows a corresponding maximum extent of total sown area in Bulgan Province. Based on surveying communities near and within cropland in north-central Mongolia, Hilbig (1995) found that areas where agriculture boomed have high weed species diversity, and that *Polygonum* and *Potentilla* plants are common components of the communities near irrigated croplands in northwest Mongolia because of moist soil conditions. Thus, the relatively high taxa richness as well as the high abundance of *Polygonum* and *Potentilla* pollen during the 1980s probably reflects the flourishing irrigation agriculture.

Ascospores of the coprophilous *Sordaria* type and *Sporormiella* type are thought to indicate herbivore dung (Davis, 1987; Davis et al., 1977; Davis and Turner, 1986; Lehmkuhl et al., 2011; Van Geel et al., 2007), and thus the former presence of livestock, which may have had a strong impact on the species composition of past vegetation (Zimov, 2005). They can be used as an indicator of the population densities of herbivores or, more likely for this zone, the fertilization of arable land.

The most obvious changes in the pollen assemblage of zone 4 (1992–2005) occurred around 1992 with abrupt decreases in Chenopodiaceae, Cyperaceae, taxa diversity and absence of planted Poaceae, and an abrupt increase in *Artemisia*. In addition, the contribution of medium-sized and coarse detrital sediments increased markedly. Previous studies in arid/semi-arid areas of China and Mongolia have shown that eolian input is likely to make up most of the sediment in lakes (Chen and Zhao, 2009; Felauer et al., 2012; Tian et al., 2013; Yin et al., 2011). We infer that EM1 (50–100 µm) is transported by wind to the lake from the nearby surroundings, with high influx at times of low vegetation density. This inference is supported by the PCA plot of the pollen data (Figure 5a) where EM1 is correlated with *Artemisia*. In contrast, EM2 (the fine-grained fraction) rather represents a background signal of sediments transported to the lake from far distances, which is relatively high when other sources supply less material. The residuals (mixtures of coarse fractions) are caused by erosion of the lake surroundings because of the intense grazing. Accordingly, the vegetation density decreased strongly during the last two decades around the lake. We assume that most of the residual fraction that contains unsorted material, but also particularly coarse-grained material, originates from within lake transportation processes and inwash after rain storms as well as from slump events that may occur as a result of the reduction in slope stability by large numbers of livestock in the lake shore area.

According to the regional climate information, the beginning of the 1990s was not characterized by a particularly extreme climate which could have caused the opening up of vegetation. Our detected signals rather indicate that the vegetation suffered from a stronger anthropo-zoogenic influence.

Driving forces of the vegetation change in central Mongolia

Climate variations, land-use changes, and soil erosion are considered to represent the major driving forces of changes in the composition and density of vegetation (Batkhishig, 2011; Buren, 2011; Dashbal, 2010; Liu et al., 2013). Our RDA results reveal that human impact (represented by livestock number and sown area) best explains pollen-inferred vegetation change (explained variance: 13%) among all three driving forces. For example, the reductions of Poaceae and Chenopodiaceae and the related relative increase of *Artemisia* inferred for the post-1960 and particularly for the post-1992 period, representing the major compositional changes in the entire record, can be explained by selective grazing (Shimada et al., 2012). However, not only composition abundance but also diversity became clearly affected by human impact. In our pollen record, the abundances of direct and indirect farmland indicators such as planted Poaceae, *Polygonum*, and *Potentilla*, and the diversity indexes of the pollen-spectra increase remarkably from about 1977, simultaneous with the increase in total sown area in Bulgan. In contrast, P_{ann} which is also thought to enhance diversity for annuals (Dan et al., 2013), remained relatively low until about 1990.

Thus, we suppose that the recorded marked vegetation changes are not a direct result of climate change but are caused directly by land-use changes such as intense grazing and the abandonment of large-scale state-operated farmland since privatization (Hirano and Batbileg, 2013; Wang et al., 2013). This is in agreement with the conclusion from an experimental study of Su et al. (2005) who observed that vegetation recovered after 5–10 years of grazing exclusion. However, it partly contradicts the numerical relationship observed between satellite-based vegetation density and driving forces by Liu et al. (2013) who found that precipitation and air-temperature variations best explain Mongolian steppe degradation while livestock increase is of subordinate importance.

Most probably, the observed vegetation degradation in Mongolia is a complex system of various interactions and feedbacks at various temporal scales. RDA results indicate that a large portion of the pollen-based vegetation changes are shared by the various combinations of driving variables or even remain unexplained. The drying climate, for example, but also overgrazing, farmland abandonment, and deforestation may reduce vegetation cover that enhances soil erosion which, in turn, irreversibly hinders the re-establishment of original vegetation (Batkhishig, 2011; Hilbig, 1995).

Reflection of vegetation and land-use change by lake ecosystems

Algae typically have atomic TOC/TN ratios lower than 10, while emergent and terrestrial plants have ratios above 20 (Meyers, 2003; Meyers and Teranes, 2002). As submerged plants (which have TOC/TN ratios in between) were lacking in the modern lake, we assume that our observed values between 10 and 20 are a rough measure for the ratio between allochthonous and autochthonous sources of organic matter. As atomic TOC/TN is negatively correlated with $\delta^{13}C_{org}$ in our record, we assume that it likewise represents a source signal, which agrees with the finding that terrestrial plants from northeast China commonly have more depleted $\delta^{13}C_{org}$ values (−28.5‰) than aquatic plants (average −24.9‰; Hong et al., 2001; Parplies et al., 2008). Carbon isotope discrimination related to algae productivity may be of minor importance as, in contrast to assumed higher $\delta^{13}C_{org}$ values during periods of high productivity, the $\delta^{13}C_{org}$ values are rather low at times of high *Pediastrum* abundance (Li et al., 2008). Accordingly, we infer a stepwise increase in terrestrial matter input, probably as a result of increased erosion from degraded vegetation in the lake catchment.

Various factors can affect $\delta^{15}N$ of lake sediments. It can be related to the different nitrogen sources as well with terrestrially derived organic matter having lower $\delta^{15}N$ values than organic matter of aquatic origin (Pang and Nriagu, 1977). However, the nitrogen isotope signal in our case is probably controlled by changes in the nitrogen source of algae that have high values when nitrogen originates from waste water and livestock (Heaton, 1986). We consider that the high $\delta^{15}N$ values during the 1980s originate from the fertilization of cropland as it corresponds temporally with the planted Poaceae curve and highest diversity in the pollen record and to the statistical information about sown area in Bulgan. Increased farm land use since about 1977 and herding since 1992 may also have driven the eutrophication of the lake as indicated by the *Pediastrum* data. *Pediastrum boryanum* var. *boryanum* and var. *cornutum* occur in a more or less wide range of eutrophic (but not very polluted) and usually slightly alkaline freshwaters as plankton and metaphyton of lakes, ponds, and swamps (Komárek and Jankovská, 2001). Mackay et al. (2013) ascribe the increase of *Pediastrum* spp. influx to nutrient enrichment in the Lake Baikal region because of increases in regional farming.

A strong relationship between land-use variables, vegetation transition, and change in the aquatic environment is also supported by the RDA results, indicating that human impact is the major driving force of the present-day aquatic ecosystem.

Implications for interpreting millennial-scale environmental change records

Comparisons with land-use data revealed that our pollen and non-pollen data are highly sensitive to environmental change. In contrast, pollen spectra from Lake Baikal (water area: 31,494 km^2; catchment area: 560,000 km^2 with 336 inflow rivers) failed to trace known agricultural activities and forest clearance in the lake surroundings during the last four centuries (Tarasov et al., 2007). Such differences in the sensitivity to land-use changes are probably related to the different extent of the pollen source areas of the two lakes (Jackson, 1990; Sugita, 1993). The sediments from Lake Mo-33B (water area: *c*. 100 m^2, without inflow river) should reflect the local to regional vegetation within a radius of a few kilometers while Lake Baikal has a sub-continental scale relevant pollen source area. If only our pollen record had been available, the supra-regional land-use activity would probably be over-estimated.

Although we infer that human impact is the major driver of the vegetation changes during the last 45 years, there is still an intrinsic link between human activity and climate conditions reflected by the high shared proportions explained. The comparison of pollen palynomorph and NPP data with climate, land-use, and erosion information indicates that environmental change was caused by an ensemble of various drivers that can barely be separated from each other when no land-use information is available. Accordingly, tracing pre-historical human impact in steppe areas of Asia might be challenging as it is concomitant with climate change and causes similar pollen signals.

Conclusion

The multi-proxy record (pollen, NPP, atomic TOC/TN, $\delta^{15}N$, $\delta^{13}C_{org}$, grain-size data) from a small lake in the steppe area of central Mongolia revealed that remarkable changes of both the vegetation and the lake ecosystem occurred during the last 55 years. The highest vegetation diversity, probably related to cropland establishment, occurred between 1977 and 1992, while thereafter the vegetation is characterized by low diversity and an increase of *Artemisia* probably as a result of increased grazing pressure. Accordingly, we assume that vegetation changes were mainly caused by human impact, including cropland cultivation and herding which explain *c*. 13% of total variance in the pollen spectra while climate variables and soil erosion explain only 6.5% and 3.7%, respectively. Furthermore, land use and human-induced vegetation degradation enhanced nutrient import to the lake that caused intensified lake eutrophication.

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