Palaeogeography, Palaeoclimatology, Palaeoecology 449 (2016) 79–84

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Determinants of soil erosion during the last 1600 years in the forest–steppe ecotone in Northern China reconstructed from lacustrine sediments

Mingmin Feng [a], Qiuyi Wang [a], Qian Hao [a], Yi Yin [a], Zhaoliang Song [b], Hongya Wang [a], Hongyan Liu [a,]*

[a] MOE Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
[b] Institute of the Surface-Earth System Science Research, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 14 October 2015
Received in revised form 23 January 2016
Accepted 3 February 2016
Available online 8 February 2016

Keywords:
Aridity
Vegetation cover
Soil erosion
Grain size
Chemical element
Inner Mongolia (China)

ABSTRACT

Wind erosion of soil in northern China contributes to the environment of East Asia and even the Northern Hemisphere. It is commonly thought that human-induced grassland degradation determines soil erosion in the semi-arid steppe region. In this study, we revealed determinants of soil erosion during the last ~1600 years through analyzing lacustrine sediment from Huangqihai Lake in this region. Our results showed that soil erosion indicated by sediment particle size was enhanced during three periods: 1570–1330 cal. yr. BP with warm and dry climate, 1250–1000 cal. yr. BP with warm and wet climate, and 470–150 cal. yr. BP with cold and dry climate. The common feature of vegetation regimes for enhanced soil erosion was replacement of forest by steppe, suggesting that decline in vegetation cover from forest to steppe, which was attributed to climatic changes, might lead to enhancement in soil erosion. The trend of historical soil erosion did not match the steady increase in historical human population in China and the very short history of massive cultivation in southern Inner Mongolia. In summary, our results supported nature- rather than human-dominated soil erosion in the semi-arid steppe region in north China during the last 1600 years.

1. Introduction

Soil erosion in semi-arid regions could significantly contribute to the environment at regional and even continental scales (Creamean et al., 2014). Wind erosion of grassland soil has become serious during the last decade in the semi-arid region of China (Liu S et al., 2013), which is significant for the environment of East Asia and even the whole Northern Hemisphere (Millennium Assessment, 2005). Dust transported from this area increases aerosol concentrations, lowers temperatures in the downwind areas, alters nutrient cycles in the Pacific Ocean and harms human health in East Asia and even North America (Uno et al., 2001; Mori et al., 2003; Creamean et al., 2014).

The wind erosion of grassland soil depends on strong wind and low vegetation cover, both of which are related to climatic drying (Nandintsetseg and Shinoda, 2015). The current grassland cover decline along the precipitation gradient implies that grassland cover decline driven by climatic drying enhances the soil erosion (Liu et al., 2008). We therefore hypothesized that soil erosion is determined by low vegetation cover under a dry climate. However, we cannot exclude the role of human disturbance such as overgrazing and cultivation on soil erosion, as stressed by studies on contemporary soil erosion (e.g. Xu et al., 2007).

Environmental change during the past two millennia remains a hotspot of past global changes (PAGES) because of its close relationship with human activities (Newman et al., 2010). Paleoenvironmental reconstruction might help identify the roles of natural and anthropogenic factors in controlling environmental change. Previous studies suggested that low-frequency magnetic susceptibility of sediment well indicates soil erosion (Wang et al., 2012). In regions dominated by wind-erosion process, coarse magnetic grains were blown into lakes, leading to increase in both low-frequency magnetic susceptibility and mean soil grain size in sediment (Wang et al., 2010). In this study, we first reconstructed soil erosion, climatic aridity and vegetation cover with sediments collected from Huangqihai Lake in the semi-arid forest–steppe ecotone in Inner Mongolia, China. We further combined these reconstructions with reconstructed regional temperature and vegetation type from previous studies to reveal relationships between different environmental factors during the past 1600 years, which were rarely considered in previous studies in the semi-arid region of China (Zhao et al.,

* Corresponding author.
E-mail address: lhy@urban.pku.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.palaeo.2016.02.004
0031-0182/

2009). In particular, we tried to identify what determined soil erosion under the changing climate of the past 1600 years.

2. Study area and methods

2.1. Study area

The study area, Huangqihai watershed, is located at the southeastern edge of the Inner Mongolian Plateau (40°47′–40°54′N, 113°05′–113°23′ E) in the marginal belt of the Pacific monsoon influence (Fig. 1). Mean annual temperature is 4.5 °C and mean annual precipitation is 372.7 mm, with about two-thirds of annual rainfall occurring during June–August (Hao et al., 2014).

The Huangqihai Lake is mainly supplied by surface runoff. There are four main rivers flowing into the lake: Bawang, Quanyulin, Mopanshan and Longshengzhuang Rivers. The lake water area has shrunk in recent decades, leaving a current area of about 80 km^2 (Hao et al., 2014).

2.2. Methods

2.2.1. Sampling

A 70-cm section was dug in September 2012. The location of the section was selected to avoid direct inflow influences, to ensure continuous deposition of the lake sediments. The section was sampled at 1-cm intervals in the field. The samples were packed and transferred to the laboratory of Peking University, where they were dried.

2.2.2. Chronological model

Nine samples were selected from different depths, and dated by accelerated mass spectrum (AMS) ^{14}C in the AMS Laboratory of Peking University (Table 1). All dates were calibrated to years before present (cal. yr. BP) based on IntCal13 (Reimer et al., 2013) (Table 1). A possible reservoir effect of 1440 years – the sum of 1378 years and the difference between 2012 and 1950 (before which BP is defined) – was removed from the sediment surface as also performed for a 820-cm core at Huangqihai Lake (Hao et al., 2014). Because of its high temporal variability in old carbon effect and gradual accumulation of 'old carbon' in inland lakes, we assumed a gradually increasing old carbon effect from bottom to top of the section, as we did in previous work at this lake (Hao et al., 2014) and Hulun Nuur, a lake 200 km northeast of Huangqihai Lake (Yin et al., 2015).

Using the original ^{14}C measurements, the possible carbon reservoir effect and their associated uncertainty as prior information, we obtained a probable distribution of chronology using Bayesian age–depth analysis (Fig. 2). Two samples from respective depths of 34–35 and 44–45 cm were located far from the curve because of possible reversal of ^{14}C ages and, therefore, uncertainties of calibrated ages were larger in the middle than in the upper and lower sections.

Table 1
AMS radiocarbon dates and calibrated years of samples from the Huangqihai sediment core.

Code	Depth(cm)	Sediment type	^{14}C age	Cal. age (cal. yr. BP)
BA12653	3–4	Bulk sediment	1540 ± 25	1464–1511
BA13266	11–12	Bulk sediment	1525 ± 30	1346–1447
BA13263	18–19	Bulk sediment	2060 ± 25	1967–2073
BA13261	27–28	Bulk sediment	1640 ± 20	1512–1574
BA13264	34–35	Bulk sediment	3285 ± 25	3450–3569
BA13262	44–45	Bulk sediment	3230 ± 25	3380–3484
BA13265	58–59	Bulk sediment	2740 ± 25	2771–2879
BA13260	63–64	Bulk sediment	2585 ± 25	2710–2757
BA12655	67–68	Bulk sediment	2740 ± 50	2775–2874

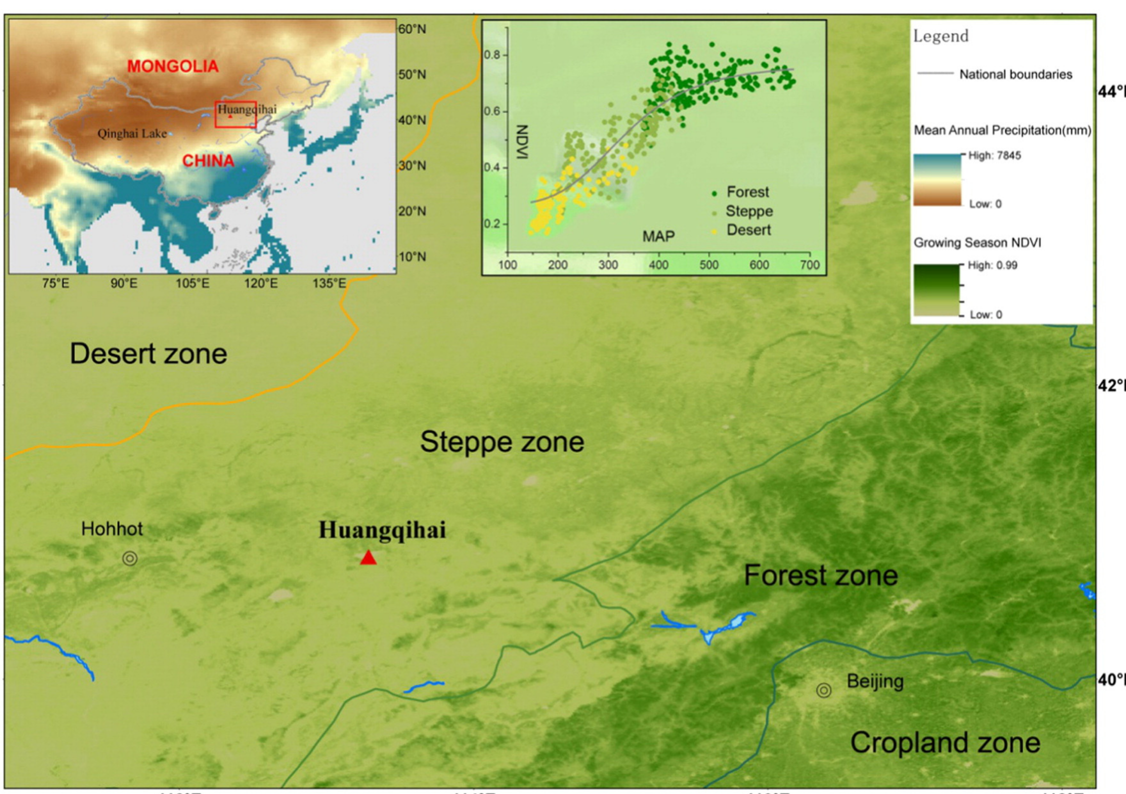

Fig. 1. Geographic features of the study area. (a) Location of Huangqihai Lake in China on the contour map of mean annual precipitation (MAP). (b) Change of vegetation cover as indicated by normalized difference vegetation index (NDVI) of forest, steppe and desert along the MAP gradient in northern China (Liu G et al., 2013). (c) Location of Huangqihai Lake in the vegetation map of the study region and surrounding region. The NDVI can roughly differentiate forest, steppe and desert as indicated in b. Dark green indicates approximate distribution of forest.

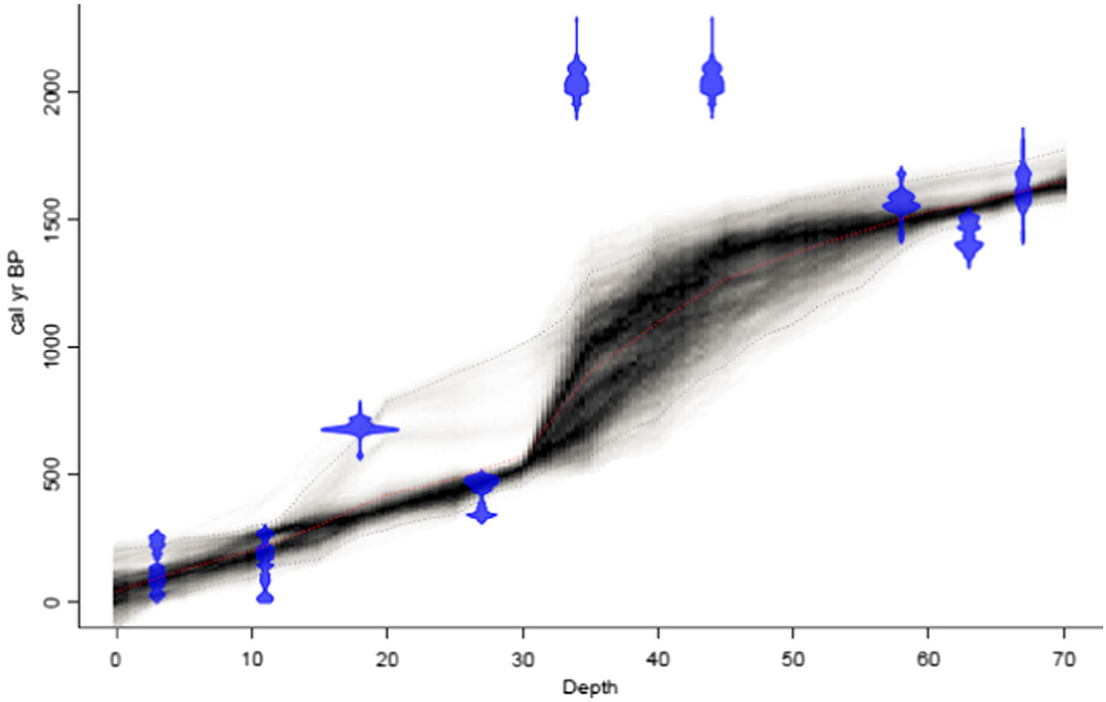

Fig. 2. Age–depth curve of Huangqihai Lake. Blue squares represent original calibrated ages of the AMS ^{14}C measurements at corresponding depths; blue stars represent age estimation using a Bayesian age–depth model that considers a possible 'old carbon' effect; the gray area indicates the likelihood of calibrated age distribution along the depth axis, the margins are for 90% probability intervals.

2.2.3. Chemical elements

Mass percentages of K_2O, Na_2O, CaO, MgO, Fe_2O_3 and MnO_2 of sediments were measured at the Geochemical Laboratory of Peking University. In northern China, K, Na, Ca and Mg are concentrated in soil and further transported to lake when the climate is dry, and sediments are rich in Fe and Mn when climate is wet (Guan, 1992). Therefore, their ratio can be used as a proxy for climatic wetness when the soils were eroded and transported into lakes (Liu et al., 2002). Thus we proposed a ratio of ($K_2O + Na_2O + CaO + MgO$) to ($Fe_2O_3 + MnO_2$) (abbreviated as 'ER' for 'element ratio') as a proxy of climatic aridity. When ER was high, the climate was more arid and when ER was low, it was more humid.

2.2.4. Grain size

Sediment grain size was measured for each sample by Malvern Mastersizer 2000 (Malvern Instruments Ltd., Worcestershire, United Kingdom). The detailed procedure was described in Hao et al. (2014). Grain size distribution was categorized into three groups: clay (<2 μm), silt (2–63 μm) and sand (>63 μm). Mean grain size was calculated for each sample.

We used mean grain size to indicate intensity of soil erosion. It is the quotient of dividing the sum of the diameters at the 16th, 50th and 84th percentiles by three (Peng et al., 2005). It has been demonstrated that coarse particles were mostly brought into the lake center by wind rather than water due to the small difference in elevation across the basin and the disk shape of the lake in this basaltic platform (Zhai et al., 2006; Yin et al., 2011; Hao et al., 2014). Also, the intense wind activity and the long frozen period in winter and spring helped wind move coarse particles into the center of the lake (Zhai et al., 2006; Yin et al., 2011). Therefore, mean grain size in sediment can indicate intensity of wind erosion.

2.2.5. Total organic carbon (TOC) and total nitrogen (TN)

Total carbon (TC) and TN were measured by an Elementar Vario EL (Elementar Analysensysteme GmbH, Hanau, Germany). Then TOC was calculated by subtracting total inorganic carbon, measured by weight change before and after adding enough HCl to the sample, from TC (Hao et al., 2014).

Higher cover of a definite terrestrial vegetation type normally represents higher productivity and higher soil organic carbon content (Waters et al., 2015). As there are great differences in soil organic carbon contents for different vegetation types (Meyer et al., 2006), we tried to interpret vegetation cover by considering vegetation type. We also used carbon to nitrogen ratio (C/N) to indicate the relative contribution from terrestrial vegetation to organic carbon in the sediment, because organic carbon in sediment comes from both aquatic organisms living in and terrestrial plants growing around lakes, while nitrogen is mainly from the former (e.g. Talbot and Livingstone, 1989; Beuning et al., 1997).

3. Results

3.1. Chemical and physical features of sediments

Both TOC and TN remained stable from 1600 to ~600 cal. yr. BP and then increased. Their ratio, C/N, showed a continuous decrease from 1580 to ~600 cal. yr. BP and remained relatively stable since ~600 cal. yr. BP (Fig. 3).

The indicators for wet climate, Fe_2O_3 and MnO_2, showed high values during the middle of this period (1300–200 cal. yr. BP) while K_2O, Na_2O, CaO and MgO showed inconsistent trends. The ER value showed a decreasing trend until ~230 cal. yr. BP, followed by a reversal (Fig. 3).

Clays were obviously high during 1000–280 cal. yr. BP. The highest proportion was silt, which showed great variations, while sand occupied an extremely low fraction. The mean grain size showed a slight decreasing trend until 480 cal. yr. BP, followed by a slight reversal (Fig. 3).

3.2. History of environmental change during the last 1600 years

Seven stages can be distinguished during the last 1600 years. Paleoenvironmental features of each stage are summarized below.

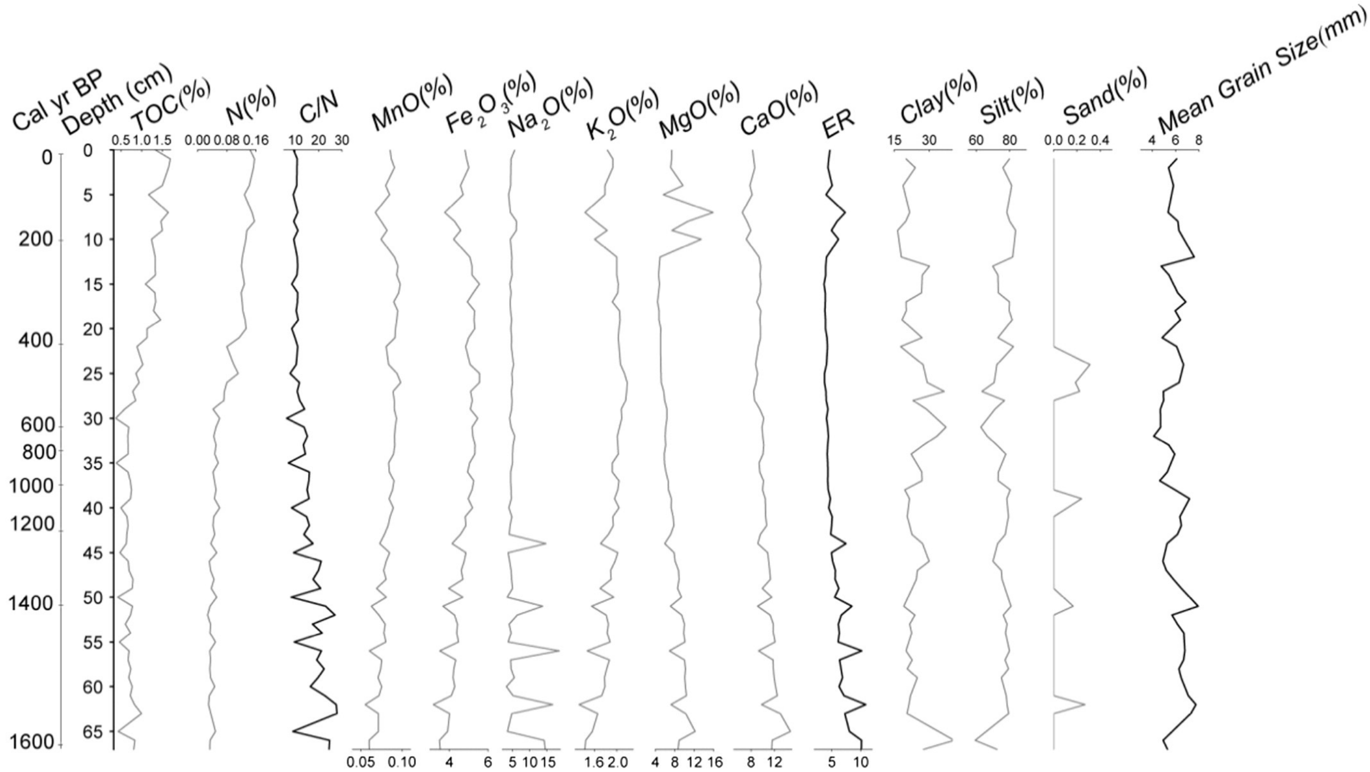

Fig. 3. Changes in total organic carbon (TOC), total nitrogen (TN), TOC/TN, chemical elements and grain size of the Huangqihai profile. ER means element ratio without units, and units of MnO, Fe_2O_3, Na_2O, K_2O, MgO and CaO are percentages (%).

Stage I (before 1570 cal. yr. BP): Temperature decreased while aridity as indicated by ER increased. Percentage of TOC decreased and mean grain size increased. Vegetation was dominated by coniferous forest.

Stage II (1570–1330 cal. yr. BP): Temperature rose and aridity decreased with great variations, characterized by three extreme drought events. The TOC value fluctuated at a low level. The mean grain size was high. Vegetation early was dominated by coniferous forest, followed by a marked replacement of forest by steppe.

Stage III (1330–1250 cal. yr. BP): This short period was cold and slightly wet. The TOC value was at a low level, while the mean grain size dropped to a medium level. The coniferous forest recovered.

Stage IV (1250–1000 cal. yr. BP): This period was the warmest during the past 1600 years. The aridity indicated by chemical elements decreased remarkably, implying a wet climate. The TOC value was at a low level. The grain size was at a high level and decreased at the end of this period. The fraction of steppe increased.

Stage V (1000–470 cal. yr. BP): The climate was cold and wet. The TOC value remained low. The other proxies showed no significant changes. The mean grain size slightly increased, followed by a marked decrease. Gradual replacement of forest by steppe continued.

Stage VI (470–150 cal. yr. BP): The temperature decreased with great variation. It was the coldest and wettest period during the first half of this stage, followed by amelioration in both temperature and aridity. The TOC value increased very significantly. The mean grain size increased remarkably with great variations. Parallel to the changes in mean grain size, the coniferous forest decreased remarkably while both broadleaf forest and steppe recovered.

Stage VII (150 cal. yr. BP–present): The temperature gradually increased but aridity decreased. The TOC value was the highest during the last 1600 years. The mean grain size was at a medium level. Vegetation was dominated by steppe and characterized by an expansion of steppe late in this stage.

There were three periods with enhanced soil erosion during the last 1600 years: Stages II, IV and VI (Fig. 4). There were different climate combinations for these three periods: cold and dry during Stage II, warm and wet during Stage IV, and cold and wet during Stage VI. Vegetation was either forest-dominated, for example, during Stages II and IV; or steppe-dominated, for example, during Stage VI (Fig. 4). For all three stages, there was a marked expansion of steppe and shrinkage of forest, implying that the low cover of steppe vegetation was weaker for soil conservation than high cover forest (Fig. 4).

4. Discussion

The reconstructed soil erosion indicated by sediment particle size was enhanced during three stages: Stage II (1570–1330 cal. yr. BP), Stage IV (1250–1000 cal. yr. BP), and Stage VI (470–150 cal. yr. BP), which match the low frequency magnetic susceptibility (χ_{lf}) curve of this lake very well, although the latter has a coarser resolution (Wang et al., unpublished data). As suggested by previous works, χ_{lf} indicates the concentration of ferrimagnetic minerals of different grain-sizes and types deposited in lakes at least partly derived by erosion (e.g. Dearing, 1999). Variations in the concentrations of χ_{lf} of lake-sediments can indicate changes in the relative intensity of the erosion process (Dearing, 1999; Wang et al., 2012). In southern Inner Mongolia Plateau, coarser magnetic grains were blown into lakes when erosion intensified during the late Holocene (Wang et al., 2010). Therefore, our reconstruction of soil erosion by grain size in sediment is acceptable.

The reconstructed soil erosion did not completely match the reconstructed aridity change as hypothesized, but it matched the rapid conversion from forest to steppe very well (Fig. 4). For example, during Stage II, strong soil erosion was suggested under a low temperature with three extreme drought events. This cold and dry climate might have forced the conversion from forest to steppe. During Stage IV, high temperature might have caused forest fires in the forest–steppe ecotone, and forests (particularly pine forest) retreated from the study region (Yin et al., 2015). The cold climate during Stage VI might have

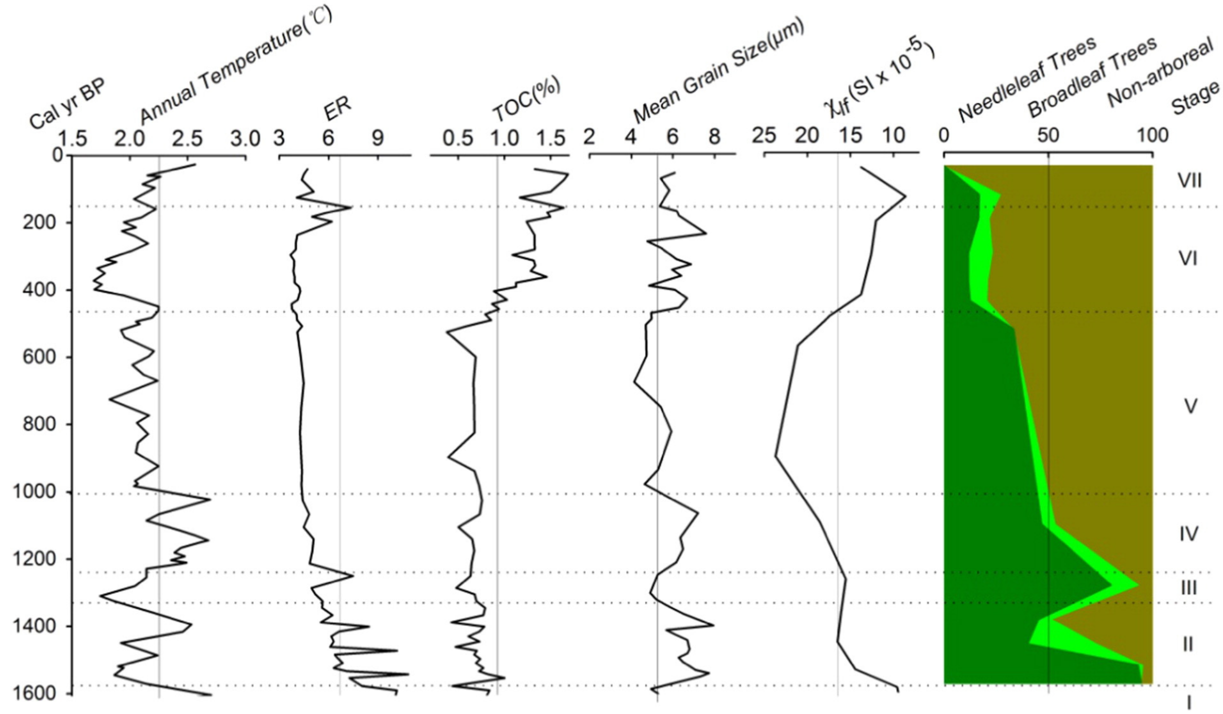

Fig. 4. Climate–soil–vegetation patterns of the Huangqihai section during the last 1600 years. Vertical solid line shows medium value of each proxy, while horizontal dashed line shows transition between stages. Curve of reconstructed annual temperature is cited from Liu et al. (2009) while reconstructed vegetation is from Hao et al. (2014). χ_{lf} is drawn from the unpublished data provided by Wang H et al.

led to the retreat of warmth-preferring pine forests from the study region. Our results imply that the forest to steppe or steppe to forest conversions did not keep pace with climate changes. Climatic changes such as drying, warming and cooling might determine these conversions (Liu et al., 2002).

Soil erosion in our study region showed no temporal trend during the last 1600 years, different from human population evolution. During the same period, the human population in China steadily increased from about 10–15 million during Stage I to over 100 million during Stage VI, although wars during dynastic transitions might have reduced the human population (Wang, 1988). There was an exponential increase in human population during Stage VII. Our study site was located in the semi-arid region, which has historically had a very low density of human population. Mass cultivation and overgrazing in the study region commenced about 100–150 years ago during Stage VII. Changes in soil erosion did not match the steady increase in human population in the whole country. No evidence of enhanced soil erosion during the last two centuries was found. Therefore, we suggest that human activities were not the main determinant of soil erosion in the study region during the last 1600 years.

Although we can conclude that nature rather than human factors determines soil erosion in our study region during the last 1600 years, there are still some uncertainties in our climate and vegetation reconstructions. Our reconstructed aridity changes showed inconsistent pattern with the temperature changes reconstructed in previous studies (Liu et al., 2009). During Stage IV, the climate was warm and wet, followed by a milder and wetter Stage V. During the coldest period of Stage VI, the climate became even wetter (Liu et al., 2009; Fig. 4). Our study site was located in the marginal zone of the Pacific monsoon influence, while the temperature change was calculated from tree-ring reconstruction at the northwest edge of the monsoon influence, about 1000 km from our study region (Liu et al., 2009). The temperature trend might have regional discrepancies, particularly in the marginal area of the monsoon influence. As there are few temperature series from the marginal area of the Pacific monsoon influence, we cited the abovementioned series in our study. The aridity trend generally reflected the monsoon influence. It became wetter in the monsoon-dominated region since 1700 cal. yr. BP (Dykoski et al., 2005), which is roughly consistent with our results.

The exact vegetation cover reconstruction for soil erosion, however, remains a challenge for future works. The TOC value indicated a high vegetation cover after 550 cal. yr. BP, although enhanced soil erosion was suggested during most of this period. As the greatest transition of TOC occurred in the period of forest to steppe transition at around 550 cal. yr. BP, we suggest that this high TOC was caused by a much higher soil organic carbon content in steppe than in coniferous forest (Meyer et al., 2006). A general decreasing trend of C/N indicated the gradual reduction in water depth and bloom of aquatic vegetation, as found in other studies in this region (Li et al., 2004; Liu et al., 2010; Wen et al., 2010). During the last 550 cal. yr. BP, high percentages of Poaceae and Cyperaceae pollen were observed, also indicating a steppe-dominated terrestrial vegetation and shallow water table in the lake (Hao et al., 2014).

5. Conclusions

In this study, lacustrine sediment of Huangqihai Lake located at the forest–steppe ecotone of the southern Inner Mongolian Plateau was analyzed for grain size, chemical elements, TOC and TN to indicate paleoenvironmental changes during the past 1600 years. Our results showed that there was a trend of humidification during 1600–230 cal. yr. BP, followed by a reversal, roughly matching the Pacific monsoon dynamics. The aridity change did not necessarily match the temperature dynamics as reconstructed by previous tree-ring studies in the marginal distribution of the Pacific monsoon influence. Soil erosion was determined by reduction in vegetation cover when the forest was converted to steppe. We found no evidence of human-determined soil erosion during the last 1600 years.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant numbers 41530747, 41325002, and 31321061), and special grant to Mingmin Feng by undergraduate student research training program of the Ministry of Education.

References

Beuning, K.R.M., Talbot, M.R., Kelts, K., 1997. A revised 30, 000-year palaeoclimatic and palaeohydrologic history of Lake Albert, East Africa. Palaeogeog. Palaeoclim. Palaeoecol. 136, 259–279.

Creamean, J.M., Spackman, J.R., Davis, S.M., White, A.B., 2014. Climatology of long-range transported Asian dust along the West Coast of the United States. J. Geophys. Res.-Atmos. 119 (21), 12171–12185.

Dearing, J.A., 1999. Holocene environmental change from magnetic proxies in lake sediments. In: Maher, B.A., Thompson, R. (Eds.), Quaternary Climates. Environments and Magnetism. Cambridge University Press, Cambridge, pp. 231–278.

Dykoski, C.A., Edwards, R.L., Cheng, H., Yuan, D., Cai, Y., Zhang, M., Lin, Y., Qing, J., An, Z., Revenaugh, J.R., 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. Earth Planet. Sci. Lett. 233 (1), 71–86.

Guan, Y., 1992. Chemical elements, clay mineral and depositional environment in Horshin sandy land. J. Desert Res. (China) 12, 9–15 [In Chinese with English abstract].

Hao, Q., Liu, H., Yin, Y., Wang, H., Feng, M., 2014. Varied responses of forest at its distribution margin to Holocene monsoon development in northern China. Palaeogeog., Palaeoclim. Palaeoecol. 409, 239–248.

Liu, H., Xu, L., Cui, H., 2002. Holocene history of desertification along the woodland-steppe border in northern China. Quat. Res. 57 (2), 259–270.

Liu, H., Yin, Y., Ren, J., Tian, Y., Wang, H., 2008. Climatic and anthropogenic controls of topsoil features in the semi-arid East Asian steppe. Geophys. Res. Lett. 35 (4), L04401. http://dx.doi.org/10.1029/2007GL032980.

Liu, H., Yin, Y., Zhu, J., Wang, H., 2010. How did the forest respond to Holocene climate drying at the forest–steppe ecotone in northern China? Quat. Int. 227 (1), 46–52.

Liu, G., Yin, Y., Liu, H., Hao, Q., 2013. Quantifying regional vegetation cover variability in North China during the Holocene: implications for climate feedback. PLoS One 8, e71681. http://dx.doi.org/10.1371/journal.pone.0071681.

Liu, S., Wang, T., Mouat, D., 2013. Temporal and spatial characteristics of dust storms in the Xilingol grassland, northern China, during 1954–2007. Reg. Environ. Chang. 13 (1), 43–52.

Liu, Y., An, Z., Linderholm, H.W., Chen, D., Song, H., Cai, Q., Sun, J., Tian, H., 2009. Annual temperatures during the last 2485 years in the mid-eastern Tibetan Plateau inferred from tree rings. Sci. China Ser. D Earth Sci. 52 (3), 348–359.

Li, X., Zhou, J., Shen, J., Wen, C., Zhao, H., Sun, Q., 2004. Vegetation history and climatic variations during the last 14 ka BP inferred from a pollen record at Daihai Lake, north-central China. Rev. Palaeobot. Palynol. 132 (3), 195–205.

Meyer, H., Kaiser, C., Biasi, C., Hämmerle, R., Rusalimova, O., Lashchinsky, N., Baranyi, C., Daims, H., Barsukov, P., Richter, A., 2006. Soil carbon and nitrogen dynamics along a latitudinal transect in western Siberia, Russia. Biogeochemistry 81 (2), 239–252.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Desertification Synthesis. World Resources Institute, Washington, DC.

Mori, I., Nishikawa, M., Tanimura, T., Quan, H., 2003. Change in size distribution and chemical composition of kosa (Asian dust) aerosol during long-range transport. Atmos. Environ. 37 (30), 4253–4263.

Nandintsetseg, M., Shinoda, B., 2015. Land surface memory effects on dust emission in a Mongolian temperate grassland. J. Geophys. Res. Biogeosci. 120 (3), 414–427.

Newman, L., Kiefer, T., Otto-Bliesner, B., Wanner, H., 2010. The science and strategy of the Past Global Changes (PAGES). Curr. Opin. Environ. Sustain. 2, 193–201.

Peng, Y., Xiao, J., Nakamura, T., Liu, B., Inouchi, Y., 2005. Holocene East Asian monsoonal precipitation pattern revealed by grain-size distribution of core sediments of Daihai Lake in Inner Mongolia of north-central China. Earth Planet. Sci. Lett. 233, 467–479.

Reimer, P.J., Bard, E., Bayliss, A., et al., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55 (4), 1869–1887.

Talbot, M.R., Livingstone, D.A., 1989. Hydrogen index and carbon isotopes of lacustrine organic matter as lake level indicators. Palaeogeog. Palaeoclim. Palaeoecol. 70, 121–137.

Uno, I., Amano, H., Emori, S., Matsui, I., Sugimoto, N., 2001. Trans-Pacific yellow sand transport observed in April 1998: a numerical simulation. J. Geophys. Res.-Atmos. 106 (D16), 18331–18344.

Wang, H., Liu, H., Zhu, J., Yin, Y., 2010. Holocene environmental changes as recorded by mineral magnetism of sediments from Anguli-nuur Lake, southeastern Inner Mongolia Plateau, China. Palaeogeog., Palaeoclim. Palaeoecol. 285, 30–49.

Wang, H., Liu, H., Zhao, F., Yin, Y., Zhu, J., Snowball, I., 2012. Early- and mid-Holocene palaeoenvironments as revealed by mineral magnetic, geochemical and palynological data of sediments from Bai Nuur and Ulan Nuur, southeastern inner Mongolia Plateau, China. Quat. Int. 250, 100–118.

Wang, Y.M., 1988. An Introduction to Historical Geography of China. People's Education Press, Beijing.

Waters, C.M., Melville, G.J., Orgill, S.E., Alemseged, Y., 2015. The relationship between soil organic carbon and soil surface characteristics in the semi-arid rangelands of southern Australia. Rangel. J. 37 (3), 297–307.

Wen, R., Xiao, J., Chang, Z., Zhai, D.Y., Xu, Q.H., Li, Y.C., Itoh, S., 2010. Holocene precipitation and temperature variations in the East Asian monsoonal margin from pollen data from Hulun Lake in northeastern Inner Mongolia, China. *Boreas* 39 (2), 262–272.

Xu, Z., Zhao, P., Wang, Y., Xu, Q., Min, Q., Li, W., 2007. Evaluation of the impacts of human disturbances on soil erosion in the typical grassland. Chin. J. Grassland 29 (2), 1–6 (in Chinese with English Abstract).

Yin, Y., Liu, H., He, S., Zhao, F., Zhu, J., Wang, H., Liu, G., Wu, X., 2011. Patterns of local and regional grain size distribution and their application to Holocene climate reconstruction in semi-arid Inner Mongolia, China. Palaeogeog., Palaeoclim. Palaeoecol. 307, 168–176.

Yin, Y., Liu, H., Hao, Q., 2015. The role of fire in the late Holocene forest decline in semi-arid North China. The Holocene http://dx.doi.org/10.1177/0959683615596820.

Zhai, Q., Guo, Z., Li, Y., Li, R., 2006. Annually laminated lake sediments and environmental changes in Bashang Plateau, North China. Palaeogeog., Palaeoclim. Palaeoecol. 241, 95–102.

Zhao, Y., Yu, Z., Chen, F., Zhang, J., Yang, B., 2009. Vegetation response to Holocene climate change in monsoon-influenced region of China. Earth Sci. Rev. 97, 242–256.