Lake Sediment Records on Climate Change and Human Activities in the Xingyun Lake Catchment, SW China

Wenxiang Zhang¹, Qingzhong Ming¹, Zhengtao Shi¹, Guangjie Chen¹, Jie Niu¹, Guoliang Lei², Fengqin Chang¹, Hucai Zhang¹*

¹ Key Laboratory of the Plateau Surface Process and Environment Changes of Yunnan Province, Key Laboratory of Plateau Lake Ecology and Global Change, Yunnan Normal University, Kunming, China, ² Key Laboratory of Humid Subtropical Eco-geographical Process, Ministry of education, Fuzhou, China

Abstract

Sediments from Xinyun Lake in central Yunnan, southwest China, provide a record of environmental history since the Holocene. With the application of multi-proxy indicators (total organic carbon (TOC), total nitrogen (TN), δ13C and δ15N isotopes, C/N ratio, grain size, magnetic susceptibility (MS) and CaCO3 content), as well as accelerator mass spectrometry (AMS) 14C datings, four major climatic stages during the Holocene have been identified in Xingyun’s catchment. A marked increase in lacustrine palaeoproductivity occurred from 11.06 to 9.98 cal. ka BP, which likely resulted from an enhanced Asian southwest monsoon and warm-humid climate. Between 9.98 and 5.93 cal. ka BP, a gradually increased lake level might have reached the optimum water depth, causing a marked decline in coverage by aquatic plants and lake productivity of the lake. This was caused by strong Asian southwest monsoon, and coincided with the global Holocene Optimum. During the period of 5.60–1.35 cal. ka BP, it resulted in a warm and dry climate at this stage, which is comparable to the aridification of India during the mid- and late Holocene. The intensifying human activity and land-use in the lake catchment since the early Tang Dynasty (~1.35 cal. ka BP) were associated with the ancient Dian culture within Xingyun’s catchment. The extensive deforestation and development of agriculture in the lake catchment caused heavy soil loss. Our study clearly shows that long-term human activities and land-use change have strongly impacted the evolution of the lake environment and therefore modulated the sediment records of the regional climate in central Yunnan for more than one thousand years.

Introduction

The Yunnan Plateau, southwest China, is located in the confluence zone of the Asian monsoon, and the climate is mainly controlled by a system comprising the Asian southwest monsoon, westerly winds and local climatic influences of the Qinghai-Tibet Plateau. Since the Cenozoic, a large number of structurally-controlled lake basins formed following the uplift of the Qinghai-Tibet Plateau [1]. Therefore, it is a key area in which to study the prehistoric Asian monsoon patterns over different time scales.

The climatic transition from the Pleistocene to Holocene changed the activity characteristics and life style of ancient people [2]. Agriculture provided the material foundation for birth of civilization and promoted an increase in population and intensity of human activity [3], [4], which has had a lasting and profound impact on the environment. China is the origin and development centers of rain-fed millet [5] and cultivated rice [6]. Early wheat remains in China emerged mainly in the Tarim Basin [7], the Hexi Corridor [8], [9], the Tianshui Basin [10], Shaanxi and Henan [11], dated at roughly in late Holocene, and the cultivated rice spread southwardly to Southeast Asia through Guangdong and Yunnan Provinces [12] at the same time.

Lake sediments play an increasingly important role in the research of global change and regional environmental evolution because they can demonstrate continuity and environmental and seasonal sensitivity, therefore providing high resolution and typically abundant environmental and climatic information [13], [14]. Whilst both natural climate change and human-influenced environmental changes are likely to be recorded in Holocene sediments of Yunnan [1], it is critical to be able to evaluate the influence of human activities on the reliability of sedimentary proxies in inferring the past climate change [15], [16]. Few researchers have investigated climate change and potentially associated human-influenced environmental change based on lake-catchment sediments, at millenial time scales.

Based on high-resolution geochemical proxy analysis of sediment core from Xingyun Lake, we aim to establish the processes and stages of the environmental change of Xingyun’s catchment, and identify the initial time and manner in which human activities influenced the receiving environment and additionally probe how Xingyun Lake responded to the interaction between climate and humans.
Study area

Xingyun Lake is located in the central Yunnan Plateau (Figure 1), about 80 km south of Kunming and 20 km east of Yuxi. It is a semi-closed shallow lake, situated at 1740 m above sea-level and is surrounded by mountains. The lake has a water surface area of 34.7 km² and catchment area of 325 km². The mean water depth is approximately 7 m. The lake joins Fuxian Lake to the north via the narrow channel of the Gehe River [17]. Mean annual temperatures recorded at regional weather stations are in the range of 12–16 °C, and the mean annual precipitation is approximately 976 mm, with more than 85% falling between May and October [18]. The climate in the catchment is dominated by the Asian southwest monsoon. The native vegetation comprises mainly broadleaved deciduous forests [16]. The small catchment area of Xingyun Lake suggests that the lake sediments will likely be reliable recorders of environmental change of the catchment, given the limited external influence thereon.

Materials and Methods

In June 2011, a sediment core 429 cm in length was recovered using a piston corer at the western part of the deep basin of Xingyun Lake in water 7.5 m deep (24°19’48.78” N, 102°45’ 47.04” E, Figure 1). No specific permissions were required for the described study, which complied with all relevant regulations. The field studies did not involve endangered or protected species and specific location can be seen below. The core was sampled in the field at 2.0 cm intervals, and sub-samples were sealed in plastic bags for transport to the laboratory.

The experimental analysis of sedimentary proxies was carried out at the Key Laboratory of Plateau Surface Process and Environment Changes of Yunnan Province. Magnetic susceptibility was measured with a Bartington MS2 magnetic susceptibility meter and mass-specific magnetic susceptibility (\( \chi_{ms} \)) was also calculated. The CaCO₃ content of the samples was measured using the calcimeter method of Bascom [20]. This involved measuring the amount of CO₂ produced after adding the HCl, and stoichiometrically calculated this into CaCO₃ content, and error of <1% was achieved during this analysis. Grain size was measured with a Mastersizer-2000 laser diffraction particle size analyzer (Malvern Instruments Ltd., UK) after treatment with \( H_2O_2 \) and HCl to remove organic matter and carbonate [21]. From this analysis, the relative standard deviation of parallel analyses for individual samples obtained was <1%. In the interest of obtaining accurate data, all of above proxies were measured three times, under the same conditions, treatment and analytical methods.

Total organic carbon (TOC), total nitrogen (TN), \( \delta^{13}C \) and \( \delta^{15}N \) isotope ratios of the samples were measured at 4.0 cm intervals at the Key Laboratory of China Geological Survey of Nanjing Center, Geological institution of the Ministry of Land and Resources, using an elemental analyzer (Flash EA1112 HT, Thermo) and mass spectrometer (MAT253). Samples were decarbonized with 0.5 mol/L HCl and then rinsed with deionized water until the filtrate was neutral, and then freeze dried. Afterwards, samples were weighed into tinfoil capsules and combusted at 1080°C in excess oxygen. The resulting material was flushed into the MAT253 with a He-carrier flow for analysis [22]. Isotope ratios are reported in \( \delta \)-notation, where \( \delta = (R_i/R_\text{std} - 1) \times 1000 \). \( R_i \) and \( R_\text{std} \) are the isotope ratios of the sample and the standard (PDB for carbon, AIR for nitrogen), respectively. Standard sample (lake sediment of the national soil standard reference material, GSS-9) with known \( \delta^{13}C \) and \( \delta^{15}N \) were measured daily to monitor analytical accuracy. The analytical precision was better than the mean: ±0.1‰ for \( \delta^{13}C \), ±0.2 ‰ for \( \delta^{15}N \), 0.1 mg g⁻¹ for TOC and 0.05 mg g⁻¹ for TN.

Results

1 Age model and chronology

Eight bulk sediment and plant macrofossil samples were collected from the organic-rich horizons of the core, and accelerated mass spectrometry (AMS) \(^{14}C \) dates were measured at the AMS Laboratory of Beijing University, China (Table 1 and Figure 2). Organic carbon was extracted from each sample and dated following the method described by Nakamura [23]. The conventional ages were converted to calibrate with IntCal13 calibration data [24]. Based on linear-fitting analysis, the uppermost sediments in the core yield an age of 1.2 ka. According to \(^{210}Pb\) dating of the core [16], the anomalously old age can be considered to result from “carbon reservoir effects” on radiocarbon dating of the Xingyun Lake sediments. To produce the age model for the core, we subtracted the reservoir age of 1.2 ka from all the ages, assuming that it is constant throughout the core (Table 1). The age models and the records of environmental proxies show a continuous sedimentation record, extending back to the last ~11 ka BP. The sedimentation rate of the upper layer (0–167 cm) is 1.25 mm/a and 1.24 mm/a, and is 0.17 mm/a and 0.27 mm/a in the lower layers (167–243 cm and 243–351 cm), respectively. The sedimentation rate in the lowest part of the core (351–429 cm) is 0.72 mm/a (Table 1). The results of sedimentation rate are in coincidence with geochronology of Xingyun Lake and other lakes in Yunnan Province [13], [25].

2 Proxy indices

The \( \chi_{ms} \) value of Xingyun Lake sediments varies from 0.9 to 30.1×10⁻⁸ m³/kg with an average value of 10.9×10⁻⁸ m³/kg, and demonstrates a substantial increase above 167 cm in the core (Figure 3-A). An average value of the \( \chi_{ms} \) from 167 cm to the top is 24.24×10⁻⁸ m³/kg. The CaCO₃ content of Xingyun Lake samples is in the range of 0–61.45% (Figure 3-B), and is hence variable and fluctuates substantially. In the 243–167 cm interval, CaCO₃ content peaks at 61.5% (213 cm), and is very low (average 0.32%) from 109 cm to the top of the core. The medium diameter (Md) is in the range of 2.88–15.11 μm, with an average of 6.63 μm. The sediment is therefore composed principally of fine grain sizes, with the finest material located between 167 cm and the top of the sediment core (Figure 3-D).

Values of TOC vary between 0.73% and 13.20% with a mean value of 6.40% (Figure 3-E), and gradually increase between 429 cm and 351 cm. The TOC content increases to a peak value from 351 cm to 243 cm although there are obvious fluctuations. The lowest value of TOC (approximately 0.3%), from 167 cm to the top of the sediment core, indicates a decrease in the abundance of plants in the catchment. The TN content is generally low, with an average of 0.33% (Figure 3-F), and is well correlated with TOC (R=0.88, Figure 4-A). The C/N ratio of the sediments varied between 6.88 and 49.07, with an average of 18.71 (Figure 3-G). The C/N ratio exceeds a value of 20 at the 429-161 cm interval of the sediment core, with the maximum value between 237 cm and 161 cm. From 109 cm to the top of the core, the C/N ratio is ≤ 10. The C/N ratio displays a positive correlation with the TOC (R=0.56, Figure 4-B), and a very weak correlation with the TN content (R=0.11). This suggests that the TOC more strongly influences the C/N ratio.

Values of \( \delta^{13}C \) vary from −24.27‰ to −7.74‰ with an average value of −18.37‰ (Figure 3-H). The highest values of \( \delta^{13}C \) were found in the 243-167 cm interval of the sediment core.
There is a demonstrable positive correlation between $\delta^{13}C$ and the C/N ratio ($R = 0.82$, Figure 4-C). Values of $\delta^{15}N$ vary between 0.07% and 5.55% with an average value of 3.11 (Figure 3-C), and the 351-243 cm interval of the sediment core is the most $^{15}N$ depleted (minimum of 0.07%). The depth profile of $\delta^{15}N$ is similar to that of TN content, and there is a good inverse correlation between $\delta^{15}N$ and TN content ($R = -0.79$, Figure 4-D).

### Discussion

1. Climatic significance of the proxy indices

   **Geochemical proxy indices.** Sources of TOC in lacustrine sediments have been suggested to be the biomass of aquatic algae, aquatic macrophytes and terrestrial plants in the lake catchment. The contribution of each of these different organic matter types to the TOC is affected by the regional climates, catchment...
Table 1. Radiocarbon dating in Xingyun Lake sediment core and age model.

| Laboratory number | AMS 14C age (14C yr BP) | Calibrated 14C (2σ, cal a BP) | Modelled age (cal a BP) | Sedimentation rate (mm/a) |
|-------------------|--------------------------|-------------------------------|-------------------------|--------------------------|
| PA06849           | 31.42                    | 1335                          | 1310–1175               | 1240                     |
| PA06850           | 26.20                    | 2485                          | 2725–2365               | 1350                     |
| PA06851           | 19.92                    | 3625                          | 4080–3840               | 2760                     |
| PA06852           | 24.02                    | 4645                          | 7200–6900               | 1.24                     |
| PA06853           | 26.46                    | 6210                          | 9250–8930               | 0.13                     |
| PA06854           | 28.20                    | 9760                          | 11250–10930             | 0.16                     |
| PA06855           | 30.84                    | 10360                         | 12230–11960             | 0.72                     |

CaCO₃, was characterized by a gradual increase in TOC, TN content, indicating are biological, and physico-chemical, such as temperature and precipitation in the lake catchment. The C/N ratio, δ¹³C and δ¹⁵N values of lake sediments can be influenced by the concentration of dissolved nitrate, nitrogen-fixing processes, bacterial decomposition, kinetic isotopic effects and climate change. The δ¹³C composition of aquatic macrophytes is complex and broad of range. The δ¹⁵N values of aquatic plants vary between −20‰ and −12‰. These plants take up carbon from HCO₃⁻ in lake water for photosynthesis, yielding higher δ¹³C values than for emergent plants (−30‰ to −24‰).

The δ¹⁵N values of lake sediments can be influenced by the concentration of dissolved nitrate, nitrogen-fixing processes, bacterial decomposition, kinetic isotopic effects and climate change [36]. The dominant factor influencing δ¹⁵N depends on the local physicochemical processes [37]. In general, large amounts of terrigenous organic matter entering the lake would cause a low δ¹⁵N value during warm-humid period and vice versa [32], [38]. Moreover, human activities can increase the δ¹⁵N value in lacustrine sediment significantly [39].

Other proxy indices. In southwest China, especially in Yunnan Province, rainfall is a grain-size determining factor. In short time-scale and high resolution studies (years to decades), it is evident that larger sediment grain-sizes become more migration during high rainfall periods in a wet climate [40]. Sediment grain size can, therefore be used to study the changes in humidity and can be distinguished from environmental indicators linked to the grain size of aeolian sediments. Moreover, the development of agricultural practices is expected to compromise the soil surface structure, and therefore increase the content of finer sediments being transported and entering lake [41].

Magnetic susceptibility is an efficient and sensitive proxy with which to study the lake environment [42]. The research results indicate that ferromagnetic material, concentrated in surface soil and detritus of the lake catchment, is one of the main sources of magnetic minerals in the lake sediments. CaCO₃ in the lake sediments is mainly composed of authigenic and allochthonous carbonates. The two main factors that induce carbonate precipitation are biological, and physico-chemical, such as temperature variations, evaporation and release of CO₂ [44].

2 Environmental evolution of Xingyun Lake

From the environmental proxies and depositional rates determined for the Xingyun lake sediments, the environmental evolution, including monsoonal and human influences, can be divided into four main stages (Figures 3 and 5), as follows:

Stage 1: 11.06-9.98 cal. ka BP (429-351 cm). This period was characterized by a gradual increase in TOC, TN content, CaCO₃, λf and fluctuating Md, indicating a period of high productivity, enhanced hydraulic conditions and increasing precipitations in the lake catchment. The C/N ratio, δ¹³C and
relatively low $\delta^{15}$N value indicate that organic matter in the lacustrine sediments was mainly derived from C4 land plants and that the climate was warm and humid. The change in environmental proxies are considered consistent with an intense influence of the Asian southwest monsoon and overall the climate shifted from cold-wet to warm-humid during this early Holocene period [45].
Stage 2: 9.98-5.93 cal. ka BP (351-243 cm). Compared with the early Holocene, this period experienced abundant rainfall and high effective moisture of the lake catchment, as represented by the high values of Md, CaCO3 and χ_lif. The high TOC and TN content, stable C/N ratio, and gradually increasing δ13C and δ15N values suggest that the organic matter was mainly derived from land and aquatic plants, and that vegetation in the lake catchment was flourishing. The low δ15N value is consistent with a climate characterized by warm and wet conditions strongly influenced by the southwest Asian monsoon.

Stage 3: 5.93-1.35 cal. ka BP (243-167 cm). Between 5.93 and 4.36 cal. ka BP, the high TOC and TN content, stable C/N and δ13C values suggest significant climatic fluctuation and a decrease in plant productivity in the lake catchment. This is consistent with the relatively high CaCO3.

Figure 4. Correlations between TOC contents, TN contents, C/N ratios, δ13C and δ15N (n = 108). The correlations were all highly significant (P<0.01).
doi:10.1371/journal.pone.0102167.g004

During this period, the warmest stage identified lies in the 8.98-6.10 cal. ka BP interval, which coincides with the global Holocene Optimum [46–50].

Stage 3: 5.93-1.35 cal. ka BP (243-167 cm). Unit 1 5.93-4.36 cal. ka BP (243-217 cm) Between 5.93 and 4.36 cal. ka BP, the high TOC, TN content, C/N ratio, the positive δ13C value and gradually increasing δ15N value indicate significant climatic fluctuation and a decrease in plant productivity in the lake catchment. This is consistent with the relatively high CaCO3.
content, overall fine grain size and lower $\chi_d$. The environmental proxies therefore denote the beginning of a temperature decrease, consistent with a climatic cold event reported from other localities in southwest China in the 6-4 ka BP interval [13]. However, there is no immediate prospect of human activities records of Xingyun Lake sediment in this period.

Unit 2 5.60-1.35 cal. ka BP (217-167 cm) The transition from Unit 1 to 2 is marked by a strong shift in environmental proxies. The highest CaCO$_3$ content and the lowest $\chi_d$ show that the temperature was comparatively warm, and the high TOC, C/N ratio, low TN content, positive $\delta^{13}$C and high $\delta^{15}$N values all suggest that organic matter entering the lake at this time was mainly derived from C4 terrestrial plants and planktonic productivity was low. The environmental proxies, and relatively slow rate of deposition, are further consistent an ecological change, decreased precipitation and intensification of evaporation within the lake catchment. The climate appeared to warm and dry at this stage, comparable to the warm and dry period of the mid- to late Holocene [51] and aridification of India [52]. Cultural relics unearthed from the Lijiashan ruins in this period depicted a deer falling prey to two leopards [53], indicating that the climate of the Xingyun catchment was warmer than presently. Meanwhile, the massive people immigrated into Yunnan Province, which coincided with the Spring and Autumn and the Warring States Period (~2.0 ka BP) of Chinese history, and it had further exacerbated the ecological environment of the lake catchment.

Stage 4:1.35 cal. ka BP to present (167-0 cm). The consistently low content of CaCO$_3$, TOC and TN reflect the low biomass of the Xingyun catchment during this stage. The fine grain-size, high rate of deposition and high $\chi_d$ suggest a heavy loss of soil from the catchment. The C/N ratio, $\delta^{13}$C and $\delta^{15}$N values are consistent with high contributions of organic matter from aquatic plant life to the lake sediments, and negligible terrestrial organic matter input. This suggests an abrupt change in the plant community, and also that intensified human activity and land-use in the catchment began from 1.35 cal. ka BP. This is consistent with the period of Dian culture established within the Xingyun catchment [54]. At this time extensive deforestation and development of agriculture in the lake catchment caused heavy loss of soil and fine-grained sediment was easily transported into the lake. In addition, the intensive agriculture would likely have led to organic matter decomposition and release of bound soil particles - as demonstrated by the increase in magnetic minerals present in the lake sediments. During the early Tang Dynasty (600 AD), local population increased in the Xingyun area, which was related to a high rate of immigration into Yunnan. This area was developed into a social and economic center of stockbreeding, irrigation, agriculture and trade [55]. Increased human activity, such as deforestation, reclaiming of land, agriculture and stockbreeding, resulted in the reduced vegetative coverage of the landscape. This inevitably led to increased erosion of surface soil and destruction of the vegetation ecology, as demonstrated by the high $\chi_d$, low TOC and TN content, and increased $\delta^{15}$N value as a result of human activity.

3 Comparison with Erhai Lake, Qunf and Dongge Cave

To better understand the regional environment change of Xingyun lake catchment, the records of the lake environment are...
compared to those with high temporal resolution records from different monsoonal regions. Erhai lake is lied on the area of southwest monsoon, which is about 300 km distant from Xingyun lake. Qunf cave (54°18'E, 17°10'N) is located in Oman experienced typical Indian monsoon climate [34], and Dongge cave (108°3'E, 23°17'N) is situated in southwest China, with local climate influenced by both India monsoon and East Asian monsoon [47].

As shown in Figure 5, the changing trend of the environmental proxies of Xingyun Lake was similar with the TOC content of Erhai Lake and the δ18O value of Qunf and Dongge stalagmite. They exhibit a similar feature of the Holocene summer monsoon variation: intensive summer monsoon in the early Holocene, a decreasing trend during the middle Holocene, and a relatively weak summer monsoon in the late Holocene. Asian monsoon intensity was found to be directly controlled by mid-July solar insolation at 30°N over the entire Holocene. The general consistency of monsoon records of Xingyun Lake with those from other continental records across Asia indicates an in-phase relationship between the Asian summer monsoon on orbital timescales over the Holocene.

The Xingyun Lake records (TOC, and δ15N isotope, grain-size, CaCO3) show a distinct weakened monsoon event during 8.3-8.1 cal. ka BP, and this 8.2-ka BP weak monsoon event is also clearly exhibited in the δ18O records in caves of Qunf and Dongge, but to a less degree in the records of Erhai Lake. Meanwhile, the Holocene Optimum of Qunf cave was terminated in 7300 a BP, which was earlier than the lake of Xingyun Lake, Erhai and Dongge cave [1], [45], [51]. This may be due to the fact that insolation-driven Intertropical Convergence Zone migrated southward and India summer monsoon began to decrease, which resulted in less precipitation and gradual influence to north direction after 7.3 cal. ka BP.

During the late Holocene, the records of TOC, TN and CaCO3 in Xingyun Lake, TOC content of Erhai Lake, the δ18O value of Qunf and Dongge cave indicate the weak summer monsoon. The abrupt changes of δ13C and fine-grained of Xingyun and Erhai Lake sediment suggest the intensive human activity and land-use since 1.35 ka BP, which wasn’t recorded in Qunf and Dongge cave. It suggests that this symbiotic human-monsoon relationship may have existed at Yunnan Plateau, southwest China. However, human activity had less influence on cave system compared to that on the lake catchment which was important for agriculture activities, and there stalagmite records can provide more faithful information on climate change.

Conclusions

Based on the application of biochemical (TOC, TN content, δ13C and δ15N isotope ratios, C/N ratios) and other environmental proxies (grain-size, δ13C, CaCO3), as well as AMS 14C dating and historical documents, we have identified four climatic stages in the Holocene as recorded in lacustrine sediments on Xingyun Lake. Furthermore, we have identified the impact of human activities during the past ~2000 years on the environmental records. The conclusions of this study can be summarized as follows:

1. A δ15N isotope record from a 429-cm sediment core from Xingyun Lake, dating back to 11.06 cal. ka BP, provides the first complete Holocene nitrogen isotope record for this area. The record reveals a long history of climate changes and human influence in the lake catchment in the latter part of this history. The Holocene climatic evolution is characterized of a shift from being dry-cold to humid-warm and finally to dry-warm. There is also evidence that the lake expansion resulted from an intensification of the Asian southwest monsoon during the early Holocene.

2. Between 9.98 and 5.93 cal. ka BP, the gradually expanded lake may have reached the optimum water depth, causing a marked decline in the coverage of aquatic plants and low planktonic productivity in the lake, again strongly influenced by the Asian southwest monsoon. This coincided with the global Holocene Optimum. Between 5.60 and 1.35 cal. ka BP the temperature was comparatively warm and precipitation decreased, thus comparable to the aridification of India in the mid- and late Holocene. Meanwhile, the massive people immigrated into Yunnan Province, which coincided with the Spring and Autumn and the Warring States Period (~2.0 ka BP) of Chinese history, and it had further exacerbated the environment of the lake catchment.

3. Human activity and land-use intensified since the early Tang Dynasty (~1.35 cal. ka BP) are corresponded well with the development of the local Dian culture. The extensive deforestation within the catchment could lead to heavy soil loss as revealed in lake sediments.

Acknowledgments

We thank the editor and reviewers for their constructive comments and suggestions for improving our paper. We also thank Luming Yang, Kunwu Yang, Jie Chen, Qinglei Li and Xiao Bai for the field work and their assistance during the laboratory work. Thanks are extended to Dr. David Smith for his assistance in checking the English of this paper.

Author Contributions

Conceived and designed the experiments: WXZ HCZ QZM ZTS. Performed the experiments: WXZ JN GLI FQC. Analyzed the data: WXZ GJC. Contributed reagents/materials/analysis tools: JN GLI. Wrote the paper: WXZ.

References

1. Shen J, Yang LY, Yang XD, Manumoto R, Tong GB, et al. (2005) Lake sediment records on climate change and human activities since the Holocene in Erhai catchment, Yunnan Province, China. Science in China (Series D) 48: 353–363.

2. Bellwood (2005) First Farmers: The Origin of Agricultural Societies. London: Blackwell Publishing.

3. Ruddiman WF, Guo Z, Zhou X, Wu H. (2008) Early rice farming and anomalous methane trends. Quat Sci Rev 27: 1291–1295.

4. Li XQ, Sun N, Dodson J, Zhou X, Dodson J, Ji M (2013) Impact of agriculture on an oasis landscape during the late Holocene: Palynological evidence from the Xintala site in Xinjiang, NW China. Quaternary International 311: 81–86.

5. Li XQ, Sun N, Dodson J, Zhou X (2012) Human activity and its impact on the landscape at the Xishaoping site in the western Loess Plateau during 4800–4300 cal yr BP based on the fossil charcoal record. J Archaeol Sci 39: 3141–3147.

6. Crawford GW (2006) East Asian plant domestication. In: Stark M T, ed. Archaeology of Asia. Malden: Blackwell Publishing.

7. Zhao KL, Li XQ, Zhou XY, Dodson J, Ji M (2013) Impact of agriculture on an oasis landscape during the late Holocene: Palynological evidence from the Xintala site in Xinjiang, NW China. Quaternary International 311: 81–86.

8. Flad R, Li SC, Wu XH, Zhao ZJ (2010) Early wheat in China: Results from new studies at Dongquishan in the Hexi Corridor. The Holocene 20: 935–965.

9. Dodson J, Li XQ, Zhou XY, Zhao KL, Sun N, et al. (2013) Origin and spread of wheat in China. Quat Sci Rev 72: 108–111.

10. Li X Q, Dodson J, Zhou XY (2007) Early cultivated wheat and broadening of agriculture in Neolithic China. The Holocene 17: 553–560.

11. Thornton CP, Schurr TG (2004) Genes, language, and culture: An example from the Tarim Basin. Oxford Journal of Archaeology 23: 83–106.

12. Yan W M (1997) The new progress on the rice origin in China. Archaeologia 9: 71–76 (in Chinese).
13. Hodell DA, Beemser M, Kanfoush SL, Curtis JH, Stoner JS, et al. (1999) Paleoclimate of southwestern China for the past 50,000 yr. inferred from lake sediment records. Quaternary Research 52: 369–380.

14. Zhang HC, Peng JL, Ma YZ, Chen GJ, Feng ZD, et al. (2004) Late Quaternary palaeolake levels in Tenger Desert, NW China. Palaeogeography, Palaeoclimatology, Palaeoecology 211: 45–58.

15. Yang DP, Brugam R (1997) Human disturbance and trophic status changes in crystal lake, McHenry country, Illinois, USA. Journal of Paleolimnology 17: 369–376.

16. Zhang HL, Li SJ, Feng QL, Zhang ST (2010) Environmental change and human activities during the 20th century reconstructed from the sediment of Xingyu Lake, Yunnan Province, China. Quaternary International 212: 14–20.

17. Yu G, Xue B, Liu J (2001) Lake Records from China and the Palaeoclimate Dynamics. Beijing: China Meteorological Press (in Chinese).

18. Shi ZT, Ming QZ and Zhang HC (2005) A study review on the modern processes and environmental evolution of the typical lakes in Yunnan. Yunnan Geographic Environment Research 17: 24–26. (in Chinese).

19. Wu WX, Liu TS (2004) Possible role of the “Holocene Event 3” in the weakening of the monsoon. The Holocene 14: 259–267.

20. Yang DP, Brugam R (1997) Comparison of laser grain size analysis and pipette analysis: A solution for the underestimation of the clay fraction. Sedimentology 44: 523–535.

21. Li X, Liu W, Xu L (2012) Carbon isotopes in surface-sediment carbonates of modern Lake Qinghai (Qinghai-Tibet Plateau): Implications for lake evolution in arid areas. Chemical Geology 300: 88–96.

22. Nakamura T, Niu E, Oda H, Reza A, Minami M, et al. (2000) The HVEE tandem AMS system at Nagoya University. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 172: 52–57.

23. Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, et al. (2013) IntCal13 and MAR13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4): 1869–1887.

24. Zhang ZK, Yang XD, Shen J, Zhu YX, et al. (2001) Climatic variations and human activities during the past 8000 a. Chinese Science Bulletin 46: 80–82.

25. Chang FQ, Zhang HC, Chen Y, Yang MS, Niu J, et al. (2008) Changes during the Late Pleistocene ofPaleolake Qurban in the Quzlan Basin. Journal of University of Science and Technology of China 19: 1–8.

26. Song L, Qiang M, Lang L, Liu X, Wang Q, et al. (2012). Changes in algal abundance and bioproductivity in the core from a shallow, eutrophic lake. Science in China (Series D) 47: 1283–1299.

27. Yu XX, Yu XQ (1987) Study on the ancient Yunnan agricultural development. Plant Physiol 1971, 47: 380–384.

28. Winston AL, Leng MJ, Mohammed MU, Lamb HF (2004) Holocene climate and vegetation change in the Main Ethiopian Rift Valley, inferred from the composition (C/N and δ13C) of lacustrine organic matter. Quaternary Science Reviews 23(7): 881–891.

29. Brown R (1991) Isotopes and Climates. London: Elsevier.

30. Smith BN, Epstein S (1971) Two categories of 14C/12C ratio for higher plants. Plant Physiol 1971, 47: 380–384.

31. Xu H, Sheng E, Lin J, Liu B, Yu K et al. (2014). Decadal/multi-decadal temperature discrepancies along the eastern margin of the Tibetan Plateau. Quaternary Science Reviews 89: 85–93.

32. Hodell DA, Schelske CL. (1998) Production, sedimentation, and isotopic composition of organic matter in Lake Ontario. Limnology and Oceanography 1998, 43(2): 200–214.

33. Watanabe T, Narazaka H, Nishimura M, Kacai T. Biological and environmental changes in Lake Baikal during the last Quaternary inferred from carbon, nitrogen and sulfur isotopes. Earth and Planetary Science Letters 2004, 222: 285–299.

34. Wu J, Shen J (2010) Paleoenvironmental and palaeoclimate changes in lake Xingkai inferred from stable carbon and nitrogen isotopes of bulk organic matter since 28 kaBP. Acta Sedimentologica Sinica 29(2): 365–372. (in Chinese).

35. Chen JA, Wang GJ, Zhang F (2004). Environmental records of lacustrine sediments in different time scales: Sediment grain size as an example. Science in China (Series D) 47: 934–940.

36. Vannière B, Bossuet G, Walter-Simonnet AV, Gauthier E, Barral P, et al. (2003) Land use change, soil erosion and alluvial dynamic in the lower Doubs Valley over the 1st millennium AD (Neublaus, Jura, France). Journal of Archaeological Science 30: 1283–1299.

37. Hu SY, Deng CL, App E, Veroush KL (2002) Environmental magnetic studies of lacustrine sediments. Chinese Science Bulletin 47: 613–616.

38. Pius MA, Postma G, Weltje G (2000) Controls on the terrigenous sediment supply to the Arabian Sea during the late Quaternary. The Makran continental slope. Marine Geology 169: 351–371.

39. Chen JA, Wan GJ, Wang FS (2002) Research of the Carbon Environment Records in the Lake Modern Sediments. Science in China (Series D) 32: 73–80.

40. Wang YJ, Cheng H, Edwards RL, He YQ, Kong XG, et al. (2005) The Holocene Asian monsoon: links to solar changes and North Atlantic climate. Science 308: 834–857.

41. Sirocko F, Sarnthein M, Erkeneker H, Lange H, Arnold M, et al. (1993) Century-scale events in monsoonal climate over the past 24,000 year. Nature 323: 48–50.

42. Sirocko F, Garbe-Schönberg D, Mckintyre A, Molfinho B (1996). Teleconnections between the subtropical monsoons and high-latitude climates during the last deglaciation. Science 272: 526–529.

43. Thompson LG, Yao TD, Davis ME, K. Henderson A, Thompson EM et al. (1997) Tropical Climate Instability: The Last Glacial Cycle from a Qinghai-Tibetan Ice Core. Science 276: 1821–1825.

44. Sirocko F, Battarbee R, L. Giosan TI, Eglinton DQ, Fuller JE, Johnson P, et al. (2012) A high-resolution Holocene aridification of India. Geophysical Research Letters 39(3), L03704.

45. Ponton C, L. Giosan TI, Eglinton DQ, Fuller JE, Johnson P, et al. (2012) Holocene and Asian monsoon: links to solar changes and North Atlantic climate. Science 300: 1737–1739.

46. Sirocko F, Garbe-Schönberg D, McIntyre A, Molfinho B (1996). Teleconnections between the subtropical monsoons and high-latitude climates during the last deglaciation. Science 272: 526–529.

47. Thompson LG, Yao TD, Davis ME, K. Henderson A, Thompson EM et al. (1997) Tropical Climate Instability: The Last Glacial Cycle from a Qinghai-Tibetan Ice Core. Science 276: 1821–1825.

48. Wang YJ, Cheng H, Edwards RL, An ZS, Wu JY, et al. (2001) A high-resolution Holocene organic carbon isotope record of lacustrine palaeoproductivity and climatic change derived from varved lake sediments of Lake Holmaar, Germany. Quaternary Science Reviews, 22(5): 569–580.

49. Meyers PA (2003) Applications of organic geochemistry to paleolimnological reconstructions: A summary of examples from the Laurentian Great Lakes. Organic Geochem 34: 261–289.

50. Routh J, Meyers PA, Hjorth T, Baskaran M, Hallberg R (2007) Sedimentary geochemical record of recent environmental changes around Lake Middle Marviken, Sweden. J Palaeolimn 37: 529–545.

51. Krishnamurthy RV, Bhattacharya SK, Kusumgar S (1986) Palaeoclimatic changes deduced from 13C/12C and C/N ratios of Karewa lake sediments, India. Nature 323: 48–50.

52. Meyers PA, Lalfer VE (1999) Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. Journal of Paleolimnology 21: 345–372.

53. Lamb AL, Leng MJ, Mohammed MU, Lamb HF (2004) Holocene climate and vegetation change in the Main Ethiopian Rift Valley, inferred from the composition (C/N and δ13C) of lacustrine organic matter. Quaternary Science Reviews 23(7): 881–891.