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Chironomid-inferred environmental change over the past 1400 years in the shallow, eutrophic Taibai Lake (south-east China): Separating impacts of climate and human activity

Yanmin Cao,[1,2] Enlou Zhang,[2] Peter G Langdon,[3] Enfeng Liu[2] and Ji Shen[2]

Abstract

A sediment core from Taibai Lake, a shallow and eutrophic lake (SE China), was analysed for chironomids to track environmental changes in the lake. Nutrient dynamics over the past 1400 years were traced based on subfossil records and a regional chironomid-inferred total phosphorus (CI-TP) transfer function. Between AD 600 and 1370, the coexistence of several macrophyte-related taxa such as *Dicrotendipes, Paratanytarsus* and *Endochironomus* reflected a clear-water state with flourishing plants, and total phosphorus (TP) reconstructions ranged from 40 to 60 μg/L. For the time span from AD 1370 to 1650, the prevalence of *Paratanytarsus penicillatus*-type indicated a slight decline of TP to lower than 50 μg/L, but CI-TP increased to previous levels between AD 1650 and 1940. Since the 1950s, *Chironomus plumosus*-type dominated the chironomid community, which illustrated that the lake suffered from high nutrient loadings and CI-TP increased from 80 to 140 μg/L. The results suggest that 50–60 μg/L of TP concentration is the reference condition for Taibai Lake, and ~80–110 μg/L might be considered as the nutrient threshold range between the plant-dominated and algal-dominated status. Variance partitioning analysis (VPA) was used to determine the relative influence of climate and human factors on the lake ecosystem. The analyses revealed that long-term climate change appeared to be the main determinant regulating the chironomid assemblages; however, the impact of human activities on the aquatic ecosystem prevailed over that of climate factors since the 1950s. This study improves our understanding of complex trajectories of aquatic ecosystem development at centennial to millennial timescales, which are influenced by both anthropogenic and climatic factors in a densely populated region. The main finding also provides reference for sustainable management in this lake and other analogous floodplain lakes.

Keywords

anthropogenic disturbance, chironomids, climate change, nutrient, the Yangtze floodplain, variation partitioning

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Introduction

Lowland floodplain lakes are strongly influenced by multiple stressors (flood pulses, wind pressure, morphology and climate warming; Chen et al., 2013; Schiemer et al., 2006). Ecological degradation in these lakes has focused the efforts of freshwater scientists worldwide to determine their functional process, as external forcing factors (e.g. nutrient inputs) can degrade the ecosystem services that the lakes are able to provide (Dearing et al., 2012). Hence, it is urgent to understand the key processes (e.g. biotic community changes) of lake ecosystem responses to external stressors, such as anthropogenic nutrient inputs and climate warming (Hall et al., 1999).

In the absence of long-term monitoring data, an effective and widely accepted approach to understand lake development on long timescales can be obtained through the analyses of lacustrine sediment archives (Battarbee and Bennion, 2011; Sayer et al., 2010). Floodplains have long been subjected to anthropogenic disturbances, and hence, coupled climate–human effects enhanced the complexity of biotic response to environmental changes within lowland lakes (Tockner et al., 2000). It is important to disentangle the individual effects of climate and human impacts on limnological functions to forecast the potential response of lakes to environmental changes (McGowan and Leavitt, 2009).

One proxy that can help improve understanding of past lake functioning is chironomids, as they are sensitive to climate changes (especially temperature variations), nutrient inputs and other nutrient-mediated factors such as macrophytes and hypolimnetic oxygen conditions (Langdon et al., 2006; Walker et al., 1991). Relationships between chironomid assemblages and contemporary total phosphorus (TP) have previously been quantified (Brooks et al., 2001; Lotter et al., 1998; Zhang et al., 2006) in

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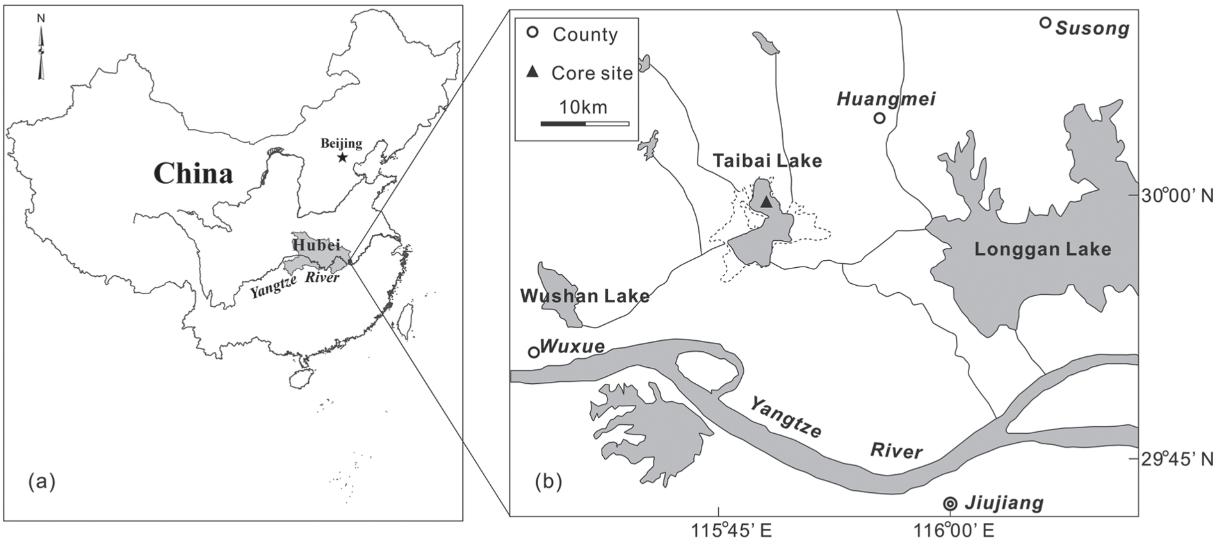

Figure 1. (a) Location of Taibai Lake in Hubei Province, China and (b) the position of the core site in Taibai Lake. The dashed line in (b) displays the surface area in mid-1950s (according to Liu et al. (2007)).

order to track lake development history in both stratified deep lakes (Sæther, 1980) and shallow lakes (Langdon et al., 2006; Stewart et al., 2013, 2014), despite the indirect relationships noted above.

The middle and lower Yangtze floodplain possesses one of the largest groups of freshwater lakes in China (Yang et al., 2010). Archaeological and palaeoecological evidence has already detected long-term human perturbations on the floodplain, initially from 7000 yr BP (Huang, 2003; Sun et al., 1981). Most lakes in this region have experienced serious cultural eutrophication during the last three decades (Yang et al., 2010). However, little long-term information is available concerning relative impacts of human and climate factors on these lake ecosystems over centennial to millennial timescales (Chen et al., 2013). A long-term perspective on lake development influenced by changes in climate–human interactions will benefit the understanding of complex changes within lakes. Thus, it can promote sustainable management for these lakes (Hall et al., 1999; McGowan and Leavitt, 2009).

This study utilizes a chironomid record to quantify the influence of climate change and anthropogenic impacts on a shallow lake in the Middle Yangtze Basin via the variance partitioning approach (Borcard et al., 1992), to provide insight into the mechanism driving changes in midge communities. Partial redundancy analysis (RDA) is employed to calculate the effects of objective variable groups (climatic and anthropogenic variable groups) in different time periods. The aims of this study are to (a) reconstruct nutrient dynamics and lake development in Taibai Lake in the past 1400 years using sedimentary chironomid data and compare the results with diatom records and (b) to quantify the contribution of climatic and anthropogenic factors to variations in midge composition during different time periods since AD 1400.

Study area

Taibai Lake (29°56′–30°01′N, 115°46′–115°50′E) is located across Huangmei and Wuxue Counties, Hubei Province, the middle reach of the Yangtze River in China (Figure 1). The irregular-shaped lake has a maximum width of 5.2 km, an average length of 10.8 km and a maximum water depth of 3.9 m. The drainage area of Taibai Lake is 960 km^2, and water volume is 0.08 km^3. The surface area has reduced gradually from 69.2 to 25.1 km^2 due to the extensive reclamation and human disturbance since the 1950s. The Taibai Lake catchment is characterized by a subtropical monsoon climate with a mean annual temperature of 16.7°C, a precipitation of 1270 mm and an evaporation of 1040 mm. The lake is slightly alkaline with pH values between 7.4 and 8.0, and the seasonal average concentration of hypolimnetic dissolved oxygen is 7.7 mg/L (Wang and Dou, 1998). Yellow brown soil and paddy soil on the floodplain are the dominant catchment soils with occasionally vermiculated red soils (China National Agricultural Atlas, 1989). Farmland surrounds the lake, and vegetation is mainly dominated by secondary pine forest (China National Agricultural Atlas, 1989).

Extensive land reclamation around Taibai Lake has led to the decline of surface area and enrichment of nutrients in the lake basin. Further activities include industrial development (from the late 1980s), which affected the water quality directly as a result of sewage input, and aquaculture (started in the 1950s) with extensive fish cage cultures, as the fish stocking rate reached 3.85×10^3 kg/km^2 in 1999 (Jian et al., 2001). The excessive fishery practices and fertilizer use contributed to the accumulation of nutrients within the lake and the deterioration of water quality. The average annual concentration of TP reached 125 µg/L (ranging from 82 µg/L in April to 203 µg/L in July during 2001–2003), and the lake has been hypereutrophic and algal dominated since 2001 (Yang et al., 2008). The majority of submerged macrophytes, which had previously been extensive, vanished from the 1980s onwards, and two species (*Vallisneria denseserrulata* and *Potamogeton crispus*) with low coverage were the remaining dominant macrophytes restricted to the northern part of the lake until 2000 (Jian et al., 2001).

Materials and methods

Sampling and laboratory analyses

A 143-cm-long sediment core named TN5 was collected from the centre of northern Taibai Lake (29°59.717′N, 115°48.45′E; Figure 1) in a water depth of 1.5 m using a UWITEC piston corer in May 2007. The core lithology gradually changed from soft brown silt clay in the uppermost 20 cm into grey clay silt in sediments below 30 cm. The core was extruded at 0.5 cm intervals in the field, and samples were stored at 4°C until analysed. Another parallel short sediment core was recovered nearby, using a Kajak gravity corer, and sampled at 1 cm resolution for ^{210}Pb and ^{137}Cs measurements (Zhang et al., 2012).

Detailed chronologies for the upper 42.5 cm sediments were constructed using ^{210}Pb and ^{137}Cs analyses, and the age–depth

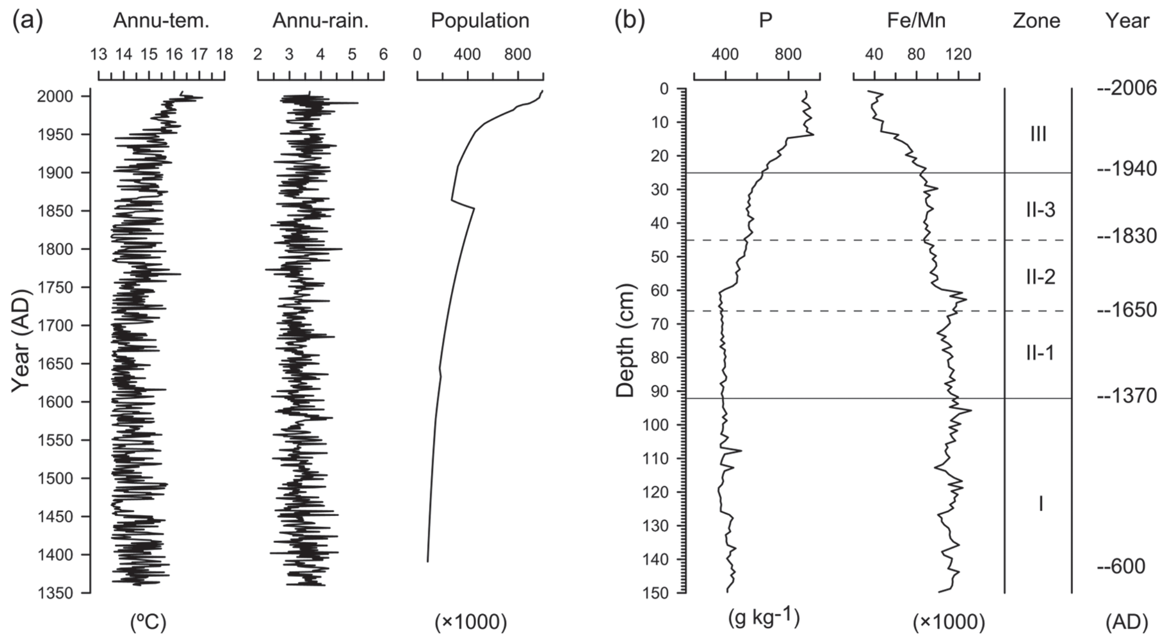

Figure 2. Diagrams of (a) simulated annual temperature (Annu-tem.) and annual rainfall (Annu-rain. anomalies; supplied by Liu et al., unpublished data), historical population in Huangmei County (Zou, 2011), and (b) sediment proxies (total phosphorus and the ratio of Fe-to-Mn; Liu et al., personal communication). Annual temperature increased since AD 1850 and rose substantially from AD 1950 while the rainfall was higher before 15th century and after the early 20th century. The population decreased sharply around 1860s because of a series of peasant uprisings represented by the Taiping Heavenly Kingdom. Sediment records are zoned according to chironomid assemblages.

relationship was calculated using a constant rate of supply (CRS) model. Two accelerator mass spectrometry (AMS) ^{14}C dates were obtained from plant macrofossil remains at sediment levels of 101 and 136 cm. The chronology between the oldest ^{210}Pb date and radiocarbon dates across the entire 143 cm sediments was extrapolated based on a second-degree polynomial function. The core covered the past 1400 years. A detailed sediment chronology has already been shown by Liu et al. (2012) and Xiao et al. (2013).

Sediment samples for chironomid analysis were prepared according to standard techniques (Brooks et al., 2007) at 0.5 cm intervals in the upper 30 cm sediments, and 1 cm for the lower 113 cm sediments. An average weight of 15 g wet sediment samples were deflocculated in 10% KOH in a water bath at 75°C for 15 min and then sieved through 212 and 90 µm meshes. The residue was transferred to a grooved perspex sorting tray and examined manually under a stereo-zoom microscope at 25× magnification with fine forceps. Head capsules were permanently mounted on slides using Hydromatrix®, ventral side uppermost, and subsequently identified at 100×–400× magnification using the taxonomy of Brooks et al. (2007), with reference to Wiederholm (1983), Oliver and Roussel (1983), Rieradevall and Brooks (2001) and Yan and Wang (2006). A minimum of 50 identifiable whole head capsules from each sample is expected to be representative of the extant fauna (Quinlan and Smol, 2001).

Collection of historical data

Six meteorological variables (January temperature and rainfall, July temperature and rainfall and annual temperature and rainfall; supplied by Liu et al., unpublished data), which were simulated via the global atmosphere–ocean coupled climate model (ECHO-G) employed by Liu et al. (2005) and Kuang et al. (2009), were used to trace climatic change since AD 1360. The precipitation and temperature data were estimated at annual resolution (Figure 2) and were used as climate categories in order to assess the variance of natural (climatic) impacts on past midge communities.

Historical records of population and arable land area in Huangmei County (AD 1391–2006) were taken from Zou (2011) and Zou (personal communication), respectively. Annual estimates of population (Figure 2) and arable land area (not shown) were calculated by linear interpolation between census years.

Numerical analyses

Species richness was calculated as the raw number of chironomid taxa encountered in samples. Rarefaction analysis (Birks and Line, 1992) using the program Primer 5.0 (Clarke, 1993) was used to estimate the expected number of taxa $E(Sn)$ in samples of different counting sizes, where n is the smallest total count ($n = 50$ here). The chironomid percentage data were generated using Tilia 2.0.b.4 and plotted using Tilia-Graph 2.0.b.5 (Grimm, 1993).

All ordination analyses of chironomid assemblages were based on percent abundances and included 38 chironomid taxa with ≥2% abundance in at least two samples. Constrained incremental sum of squares (CONISS) facility (within TILIA) was used to identify the midge zones in the core sequence. The significant number of stratigraphical zones and subzones was assessed using the broken-stick model (Bennett, 1996).

Past TP concentrations were reconstructed using the fossil chironomid data and a chironomid-based transfer function, which has been developed from 51 lakes in the middle and lower reaches of the Yangtze River with a TP gradient ranging from 30 to 290 µg/L. The applied weighted average (WA) inverse deshrinking model performed well with a high r^2_{jack} (0.68) low root mean squared error of prediction (RMSEP; 0.45 µg/L) and low mean and maximum bias (Zhang et al., 2012). An analogue matching technique was used to evaluate the reliability of the reconstruction. A squared chord distance between every fossil sample and the modern calibration set was calculated as a dissimilarity measure in the program C2 (Juggins, 2007). Fossil samples with minimum dissimilarity coefficient in the extreme 10% dissimilarity of the calibration set were determined to have a poor modern analogue (Laird et al., 1998).

Variance partitioning analysis (VPA) was used to quantify relationships between recovered midge fossils and diverse stressors, including climate (simulated meteorological data), human

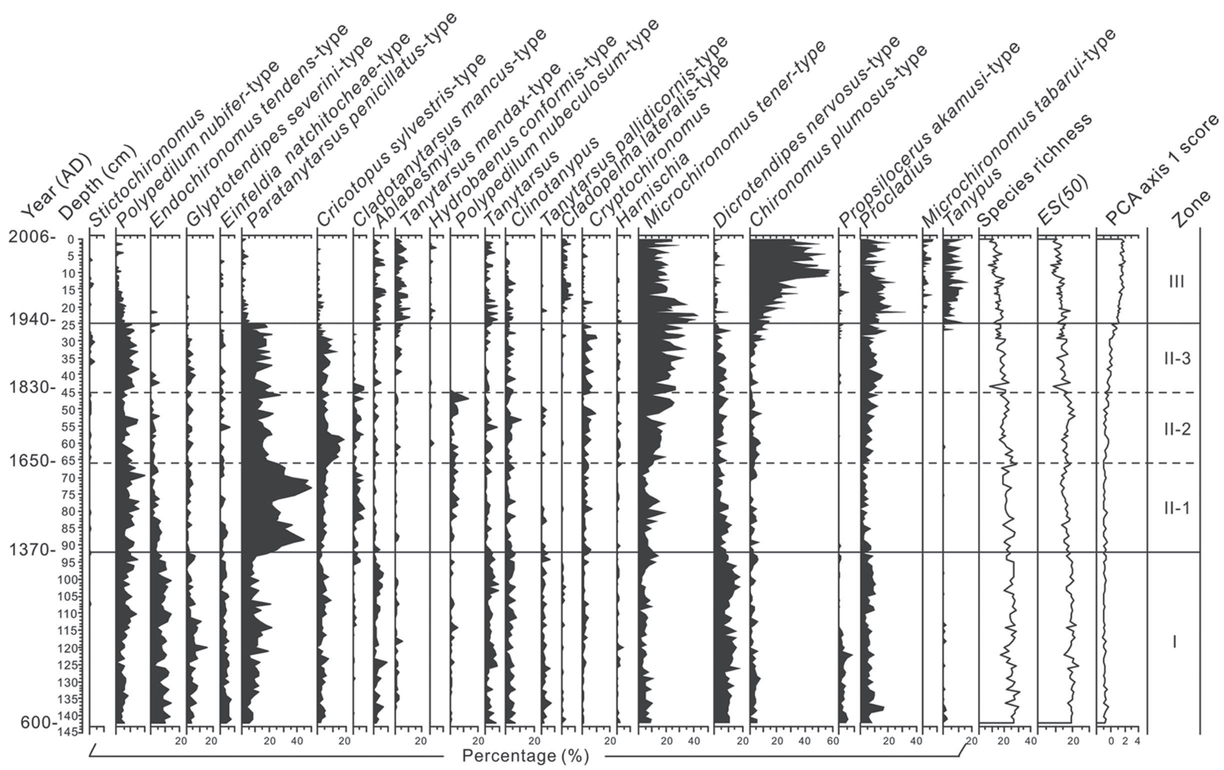

Figure 3. Diagrams of relative abundances for main chironomid taxa, species richness, rarefaction diversity (ES(50)) and first axis scores of PCA for Taibai sediment core. The taxa were arranged left to right according to increasing TP optimum concluded by Zhang et al. (2006).
PCA: principal component analysis; TP: total phosphorous.

activity (population and arable area) and their combined effects, which regulate nutrient dynamics within the lake. Given the availability of population documents, simulated and historical data from AD 1400 were averaged according to the years contained in each centimetre of sediment and used in the subsequent ordination analyses. Additionally, to avoid bias in VPA, four sediment proxies (sedimentary P, Al, Cu and frequency-dependent susceptibility), cited in unpublished data by Liu et al. (personal communication) and Wu et al. (personal communication), were selected as proxies for human activities to ensure that the number of variables was similar to that of the climate drivers. The enrichment of metals (e.g. Al and Cu) and nutrients (P) in the sediment profiles can reflect anthropogenic erosion inputs from the watershed (Eilers et al., 2004; Kemp et al., 1978; Mihelčić et al., 1996). All the sedimentary proxy and historical data were $\log_{10}(x + 1)$ transformed to standardize the variance. Chironomid data were analysed using detrended correspondence analysis (DCA) to determine the gradient length. DCA results showed that the axis 1 gradient length was 1.9 standard deviations, indicating that linear analysis was appropriate for the subsequent ordination analyses (Birks, 1995). Principal component analysis (PCA) was subsequently employed to identify the distribution of taxa along the primary ordination axis, and RDA was suitable for variance partitioning to estimate the fraction of chironomid variance explained by anthropogenic and climatic factors. To eliminate the collinearity among variables, a series of partially constrained RDAs were performed to sequentially eliminate the explanatory variable with the highest variable inflation factor (VIF) until all VIFs were <20 (Hall et al., 1999). Monte Carlo permutation tests (499 unrestricted permutations) were used to test the significance of variables, and automatic selection was employed to determine the minimum subset of significant variables. Significant explanatory variables were then assigned to one of the two categories (i.e. climatic and anthropogenic factors). VPA was carried out to evaluate the relative importance of each explanatory category and their explanatory power at different key periods. As the simulated and historical data began from AD 1400, the period from AD 1400 to 2006 was first examined by VPA; then given that both climate (precipitation and temperature) and population have changed since the early 20th century, VPA was also performed for the period from AD 1990 to 2006; since the 1950s, the impacts of human activities have grown unprecedentedly in China, and hence, the post-1950 analysis was performed. All analyses were performed using Canoco v. 4.5 (ter Braak and Šmilauer, 2002).

Results

Chironomid stratigraphy and inferred TP

Three major zones within the chironomid stratigraphy were distinguished by cluster analysis and verified using a broken-stick model (Figure 3). In basal zone I (143–92 cm, *c.* AD 600–1370), *Dicrotendipes nervosus*-type and *Paratanytarsus penicillatus*-type were the two dominant species with average percentages of ~12% and 10%, respectively. Subdominant species, such as *D. nervosus*-type, *Endochironomus tendens*-type (mean percentage around 9%), *Glyptotendipes* (average ~5%) and *Einfeldia* (average ~3%) were at their highest abundances throughout the whole core in this zone. In this period, the taxon richness was higher than that at any stage in the sequence (Figure 3).

Zone II (92–25 cm, *c.* AD 1370–1940) was separated into three subzones according to the fluctuations of the main taxa. The main difference in zone II-1 (92–66 cm, *c.* AD 1370–1650) is the high abundance of *P. penicillatus*-type (average percentage ~33%), which is indicative of macrophyte-dominated and clear-water conditions (Langdon et al., 2010; Ruiz et al., 2006), and the decline of trophic-related macrophyte indicators, for example, *D. nervosus*-type (average ~6%) and *E. tendens*-type (average ~3%), accompanied by the slight increase of another aquatic plant-related taxon *Polypedilum*. An increase of *Microchironomus tener*-type occurred in zone II-2 (66–45 cm, *c.* AD 1650–1830), which was associated with a reduction in *P. penicillatus*-type to a relatively lower level (average ~16%), but still higher than that in zone I. Another characteristic in this period was the peak of *Cricotopus sylvestris*-type, which is an epiphytic species that can be found in high abundances in more turbid lakes (Langdon et al., 2010), but can also live on emergent macrophytes (Ruiz et al., 2006). Compared with zone II-2, there were no remarkable changes of chironomid composition in zone II-3 (45–25 cm, *c*. AD 1830–1940) except for the higher abundance of *M. tener*-type (average ~24%) and eurytopic *Procladius* (average ~9%), with the final loss of *Polypedilum nubeculosum*-type. Eutrophic indicators such as *Chironomus plumosus*-type and *Tanypus* appeared and started to increase in abundance in the uppermost samples of this zone.

The notable shifts in zone III (25–0 cm, *c*. AD 1940–2006) were the sharp increases of *C. plumosus*-type, *Tanypus* and *Microchironomus tabarui*-type, and simultaneously the rapid decline of *P. penicillatus*-type from the average percentage around 14% to merely 1%. Most macrophyte-related species, such as *Polypedilum nubifer*-type, *D. nervosus*-type, *E. tendens*-type, *Glyptotendipes severini*-type, *C. sylvestris*-type and *Einfeldia* (Berg, 1950; Brodersen et al., 2001), became less abundant or were extirpated. *M. tener*-type reached its peak at 22 cm and then maintained high abundances until the top of the sediment core. The taxon richness index declined to the lowest values in this zone compared with those in the former two stages.

A PCA ordination confirmed the three main temporal zones, which clustered along axis 1 and 2 (Figure 4). The first PCA axis had an eigenvalue of 0.256, and captured 25.6% of the total variance within the chironomid data. Axis 1 aligned fauna along a gradient from hypereutrophic status to macrophyte-dominated and clear-water status. Chironomid species related to high water quality such as *P. penicillatus*-type and *P. nubifer*-type were plotted to the left of axis 1 (Figure 4). In contrast, eutrophic chironomid taxa characterized by positive scores plotted on the right of axis 1 (Figure 4). The eigenvalue of the second axis of PCA was 0.116, accounting for a further 11.6% of the total variance. Taxa closely related with PCA axis 2 are those with relatively low percentages, and mostly are mesotrophic, such as *Stictochironomus, Ablabesmyia, Proposilocerus* and *Chironomus* undiff.

The chironomid-inferred total phosphorus (CI-TP) concentrations demonstrated a significant nutrient enrichment in Taibai Lake since *c*. AD 1940 (around 25 cm; Figure 5). The TP values before *c*. AD 1370 (92 cm) fluctuated around 54 µg/L (45–62 µg/L); after a slight decrease (41–50 µg/L, mean 46 µg/L) in zone II-1, TP values increased in zone II-2. The nutrient concentrations increased strongly from the later stages of zone II-3, concurrent with the rise in *C. plumosus*-type and *Tanypus*. Then, nutrient enrichment rose in zone III, where the CI-TP reached a peak of ~140 µg/L in the uppermost samples. Analogue matching analysis indicated that most fossil samples in the top 45 cm of sediment had a good analogue with the calibration samples, except for six samples at the depths of 3, 8, 9.5, 28, 43.5 and 44.5 cm. Most samples in sediments below 45 cm, particularly below 92 cm, had poor analogues, as the chironomid communities were distinct from those in the modern data set.

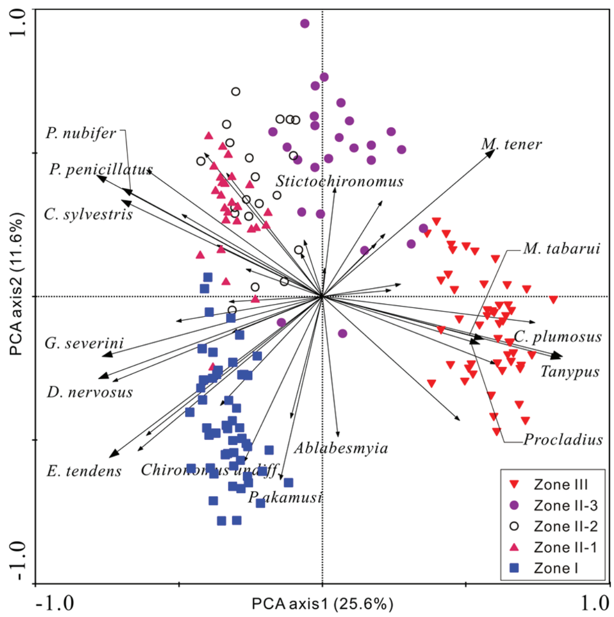

Figure 4. PCA plot for sediment samples and chironomid taxa (only the names of the most abundant taxa are shown) for Taibai Lake. The ecological trajectory within the lake was indicated by the distribution of samples from different groups along the primary ordination axis.
PCA: principal component analysis.

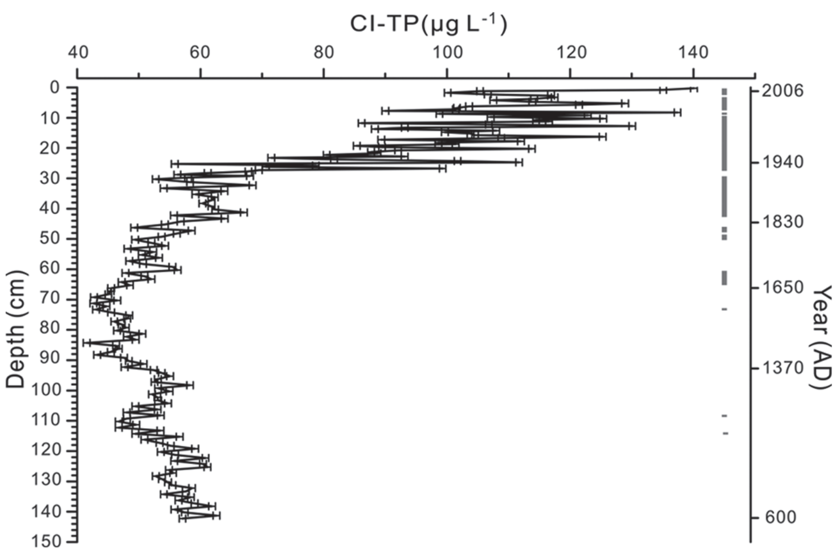

Figure 5. CI-TP values in past 1400 years for Taibai Lake. Filled boxes represent good analogues between fossil and modern chironomid assemblages.
CI-TP: chironomid-inferred total phosphorus.

Table 1. Significant variables explaining chironomid compositions in variance partitioning analyses of different time periods.

Time period	Significant variable	
	Climate	Human activity
Post-1400	July temperature	Population
	Annual temperature	
	Annual rainfall	Arable land area
Post-1900	Annual temperature	Population
	January rainfall	Arable land area
Post-1950	–	Population

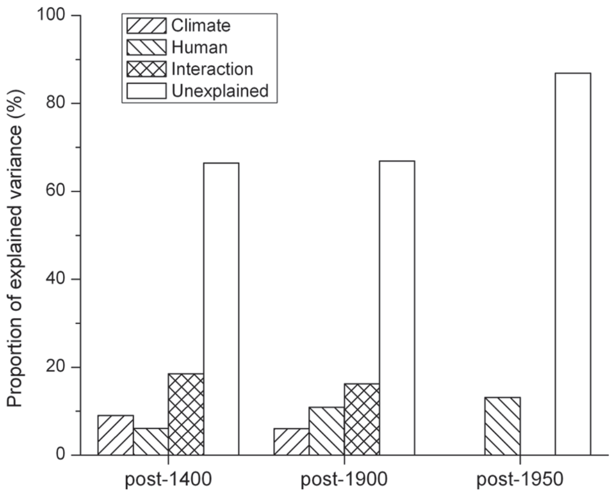

Figure 6. Proportions of chironomid variance explained by climate change and human activity in different study durations for Taibai Lake using variance partitioning analyses.

Variation partitioning analysis

VPA revealed that historical changes in climatic and anthropogenic disturbances mostly explained significant ($p < 0.05$) amounts of variance in past midge community compositions. Five variables for post-1400 (AD 1400–2006; total number of samples in the period: $n = 90$) analysis, assigned to two explanatory categories, comprised the minimum subset of significant variables capturing 33.6% of the total fossil chironomid variance. For the post-1900 (AD 1900–2006; $n = 38$) analysis, four significant variables (Table 1) explained 33.1% of the variance. VPA has been considered to be highly sensitive to the period of study (Hall et al., 1999). Although the total explained variance showed insignificant change between the two time periods, the relative importance of each category altered notably. In the post-1400 partition, the sole effects of both climatic (9%) and human (6.1%) factors explained much less variance in chironomid data than their combined effect (18.5%; Figure 6). In comparison, a larger amount of fossil variance in the post-1900 analysis was captured by the sole effect of human activities (10.9%) than that of climatic factors (6.0%), and their joint impact was slightly lower (16.2%) than that in the post-1400 period. In the post-1950s period, climatic factors were not significant in influencing the chironomid community, while human population size was the only significant variable, explaining 13.1% variance of chironomid data.

In the post-1400 analysis, all the significant explanatory variables were positively correlated with RDA axis 1 and samples before AD 1900 were mostly distributed along RDA axis 2 (Figure 7a and c). In the post-1900 analysis (Figure 7b and d), however, both the human activities and mean annual temperature were negatively correlated with the first RDA axis. January precipitation showed a weak and positive correlation with RDA axis 1 and a positive relationship with axis 2. All samples before 1950 were scattered along the axis opposite to the direction of human variables (population and arable land area). The RDA, combined with VPA results, indicated that anthropogenic disturbances were relatively weak before 1950, while the midge community after 1950 was influenced considerably by climate warming and enhanced human activities. Interestingly, the post-1950 analysis highlighted the importance of human impact, demonstrating that the effect of climate change is compounded by powerful anthropogenic disturbance in this period.

Discussion

Chironomid tracked trophic history

The environment in the Yangtze floodplain, incorporating a flat terrain and mild climate, supports a high human population and has encouraged a long history of human activity. Agricultural activities combined with humid climate-enhanced land erosion have enriched the lake, contributing to the high natural background levels of nutrients in the Yangtze floodplain lakes, as shown by several reconstructions from biological fossils (Chen et al., 2011; Dong et al., 2008; Zhang et al., 2010).

The chironomid stratigraphy changed considerably in response to temperature, lake productivity and development of aquatic plants. Prior to AD 1370, the CI-TP concentrations ranged between 40 and 60 μg/L. Relatively mild temperatures between AD 600 and 1370 (Zheng et al., 2002) favoured the increase in *D. nervosus*-type and *E. tendens*-type, which are typically associated with warm climates (Brooks et al., 2007). The relatively high abundances of other macrophyte-related taxa (e.g. *P. penicillatus*-type, *Einfeldia, G. severini*-type and *C. sylvestris*-type) are indicative of a mesotrophic status with clear water and flourishing aquatic plants (mainly submerged type).

The period during zones II-1 and II-2 (AD 1370–1830) was the ‘Little Ice Age’ in central China (Wang et al., 2007). In zone II-1, the inferred nutrient concentrations in Taibai Lake declined slightly (less than 50 μg/L), but rebounded in zone II-2. *M. tener*-type has a TP optimum of 89 μg/L in the current training set, and its increase led to the slight elevation of CI-TP in zone II-3, similar to the level pre-AD 1370. Changes in Fe/Mn ratios in mid-zone II-2 (Figure 2) also indicated altered redox conditions and nutrient enrichment, which impacted benthic invertebrate habitats.

After AD 1940, the lake suffered from high nutrient loadings and CI-TP values ranged from ~80 to 140 μg/L. Eutrophic indicators such as *C. plumosus*-type dominated the faunal assemblages. *C. plumosus*-type is a typical nutrient-tolerant species with a TP optimum of 101 μg/L, and is abundant in many nutrient-rich lakes all over the world (Brooks et al., 2001; Quinlan and Smol, 2001). Increased CI-TP values since AD 1940 were concomitant with the presence of eutrophic taxa *M. tabarui*-type and *Tanypus*. They have TP optima of >135 μg/L (Zhang et al., 2006), and can tolerate heavily polluted conditions (Gong et al., 2001; Grodhaus, 1963). *Tanypus* can withstand some extremely polluted lakes, where *C. plumosus*-type even fails to survive (Cao et al., 2012). Thus, 50–60 μg/L TP, as inferred pre-AD 1940, would be appropriate as a target for lake restoration and ecosystem rehabilitation.

Since AD 1940 climate warming and enhanced human activities have imposed significant pressures on the lake ecosystem. The Fe/Mn indicated strengthened oxidization potential at the water–sediment interface, and chironomid compositions altered as shown by the PCA scores. From the 1940s to the 1970s, the chironomid fauna experienced a major change, concurrent with a rapid increase in CI-TP from 80 to 110 μg/L. Additionally, the apparent decline of submerged macrophytes (indicated by the reduced macrophyte-related chironomids, such as *P. nubifer*-type)

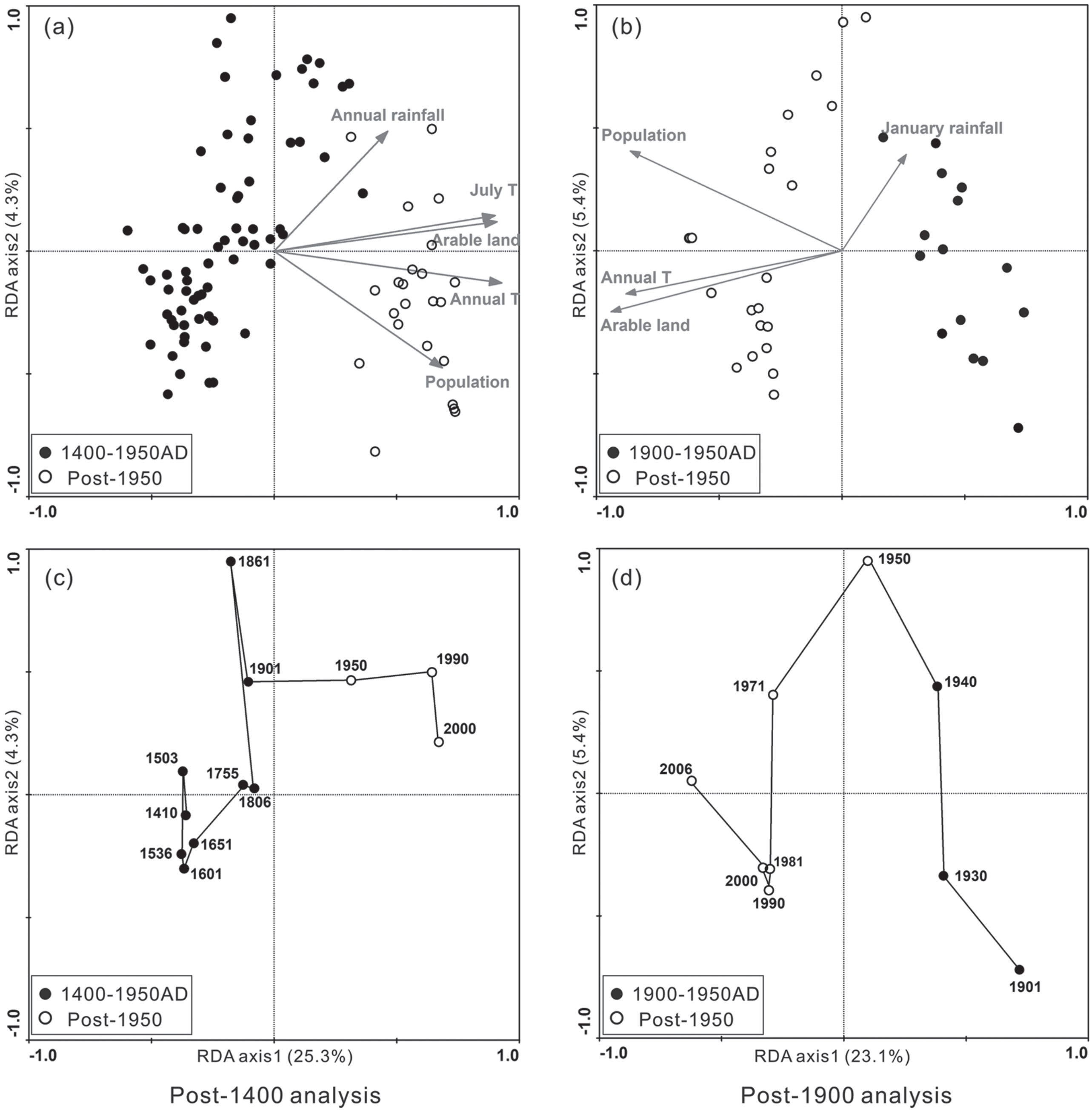

Figure 7. Relationships between environmental variables and variations in chironomid assemblages during different periods revealed by redundancy analyses: (a) post-1400 analysis and (b) post-1900 analysis, and the main evolution trajectory in chironomid community in Taibai Lake: (c) post-1400 analysis and (d) post-1900 analysis. All samples were plotted in (a) and (b), but some were omitted in (c) and (d).

led to the degradation of an important regulator in biological structure (Jeppesen et al., 1990). This transformation from macrophyte-dominated clear-water status to algal-dominated turbid water status started in AD 1940 in Taibai Lake. A TP concentration of ~80–110 µg/L might be the threshold range between the two contrasting lake regimes.

There was a relatively poor fit between chironomid assemblages in sediment samples below 45 cm and those in the modern data set. This is probably because modern lakes in the calibration data set with relatively low TP concentrations generally support abundant *Cricotopus* communities (Zhang et al., 2012), but low percentages of this taxon occurred in the sediment core. Sediment samples with relatively abundant *Cricotopus* (61–65 cm), however, showed good fits with the modern calibration set. Additionally, *Dicrotendipes, Endochironomus* and *Polypedilum* co-occur in sediments below 45 cm but are scarce in the calibration set, and this also contributed to the poor fit. Nevertheless, *Paratanytarsus* is abundant in both data sets, which helps to reduce reconstruction errors (around ±0.53 µg/L, shown in Figure 5).

Comparisons with diatom reconstructions

Both chironomid and diatom sedimentary records have revealed that lakes adjacent to the Yangtze River have high nutrient levels (Chen et al., 2011; Dong et al., 2008; Zhang et al., 2012). Reconstructions using diatom assemblages were also performed for Taibai Lake by Yang et al. (2008). These results also suggest that TP concentrations before the 1940s were around 50 µg/L. This agrees well with the chironomid inferences. Moreover, Yang et al. (2008), studying diatom assemblages, found a similar critical nutrient range (~80–110 µg TP/L in the period 1953–1970) as inferred by chironomids in this study. Jeppesen et al. (1990) analysed the relationships between P concentration and biological composition through whole-lake experiments in Denmark and revealed that aquatic plants would disappear and lake regimes would change when the nutrient concentrations exceed 80–150 μg TP/L. This means that measures should be taken to keep the nutrient concentrations less than the critical range (~80–110 μg TP/L) for Chinese shallow lakes. From a palaeolimnological perspective, chironomids can give some information on plant loss and a shift away from a macrophyte-dominated system in lakes.

Factors influencing chironomid assemblage composition

VPA was sensitive to the time duration of the investigation (Hall et al., 1999). In this study, both human pressures and climatic changes exerted significant influence on the chironomid community in both the post-1400 analyses and the post-1900 analyses. However, their sole effects in regulating chironomid assemblages were different in the two time periods studied. The results indicated that anthropogenic impacts were stronger than climatic effects on the chironomid community at the decade-scale in the post-1950 analysis.

The most important explanation for chironomid faunal variations since AD 1400 appears to be broadscale climatic changes, particularly temperature variability. Temperature could affect the chironomids directly through life cycle impacts, such as altering generation times, but could also affect chironomid assemblages indirectly through altering lake productivity and hence the quality and quantity of food. Temperature is the most significant environmental variable controlling the long-term temporal compositions of midge communities (Eggermont and Heiri, 2012). Generally, climate is the main driver in the absence of other strongly influential variables. In training sets where climate has a short or non-existent environmental gradient, other factors such as nutrients, hypolimnetic oxygen or macrophyte abundance are typically the main explanatory variables in terms of understanding chironomid distributions (e.g. Brooks et al., 2001; Langdon et al., 2006, 2010). Following the human population increase around Taibai Lake over the past few centuries, the effect of climate change on chironomids was not significant. Although the simulated annual mean temperature had an average increase of 1.03°C (n = 647, R = 0.381, p < 0.001) from AD 1360 to 2006, the effect of nutrient enrichment on chironomid communities has overwhelmed that of climate warming.

The effects of human activities and climate changes interacted in most periods. Their combined effects (18.5% and 16.2%) on chironomid assemblage composition explained more variance than the unique effects of each category (6–11%) in both the post-1400 and the post-1900 time periods. It illustrated that the influence of climatic and human variables on chironomids was important, but long-term impacts of climate change on chironomids would be mainly mediated through strengthened anthropogenic interference and vice versa. Besides direct influence on the ecosystem, climate could control biotic structure indirectly through vegetation and other human-induced processes. Ecosystems typically respond to a range of environmental variables acting in concert. The results of McGowan et al. (2005) suggested that TP changes alone were unimportant to algal community composition during ecosystem state change, but when together with fish and macrophytes, they were significant in explaining algal changes. The controlling factors of biotic communities differ temporally, and the sole effects of variables and their interactions change subsequently (Anderson et al., 2008).

However, some important factors might be ignored in the variance partitioning, as only a low proportion of chironomid variance was explained by the analysed variables and more than 60% of the variation was unexplained. One reason for the low explanatory variance might be attributed to the scarcity of information about the catchment and the lake, such as sewage drainage volume from the catchment and the use of the lake as a fishery resource. Additionally, some bias might exist between the real and simulated climatic data, which was used in the analyses. Moreover, while only the external regulators were taken into consideration in the present analyses, internal relationships within the ecosystem are likely significant for community succession (predator–prey relationship and competition; Scheffer, 1998). For example, Langdon et al. (2010) surveyed 39 shallow lakes across United Kingdom and Denmark and found that the impact of species richness and density of aquatic macrophytes on midge assemblages was more significant and direct than nutrient status alone, as the increase in plant density promotes the biomass of the periphyton which is a direct food source for chironomids. Figure 7 also indicates that chironomids were regulated by the environmental variables (e.g. rainfall and hydrological conditions) represented by the RDA axis 2. Before AD 1950, the lake trajectory was scattered along the second axis, whereas the majority of the analysed variables correlated well with the first RDA axis. Although climatic and human factors are considered to be important to midge assemblages after 1950 in this study, most of the responses at this time align on axis 2 (Figure 7d). This all demonstrates that some important parameters (e.g. related to precipitation and hydrological conditions) represented by the second RDA axis were not included in our analyses. Most scores of PCA axis 2 are positive from AD 1400 to 1950 (not shown), and it has been shown that there were more floods than droughts in Hubei Province, China, during this period (Zhou and Gao, 2003). Since the 1950s, intensified land reclamation and flood management disconnected the lake from the Yangtze River, and the hydrological regime changed within Taibai Lake (Liu et al., 2012). Chironomid assemblages likely responded to this change in negative scores of PCA axis 2 post-1950. But more data are still needed to verify this and explain better the variation along axis 2. However, by comparing with the reconstructions based on diatoms, this work has further confirmed the pristine nutrient state (50–60 μg TP/L) in Taibai Lake which should be a goal for sustainable management, assuming that other background conditions and environmental gradients also remain unchanged. Biological changes suggest a sharp increase in TP concentration from the 1940s to the 1970s. Thus, if efforts are not made to reduce nutrient inputs, further deterioration in Taibai Lake will likely take place.

Conclusion

In summary, the aquatic development of Taibai Lake experienced three main stages in the past 1400 years according to chironomid records. From AD 600 to 1370, clear water and macrophyte-associated species dominated the chironomid assemblages, and midge species richness was the highest across the whole historical period within the lake. The CI-TP oscillated between 40 and 60 μg/L, and the ecosystem was probably in a relatively ‘natural’ clear-water macrophyte-dominated status. The second zone was from AD 1370 to 1940/1950. During this period, human activities increased, causing a gradual reduction in primary forest and intensified soil erosion. The nutrient loading in Taibai Lake (both sedimentary P and CI-TP) rose slightly, although the water quality was still relatively good. From AD 1940/1950 onwards, within-lake nutrient enrichment led to algal blooms. Chironomids associated with submerged macrophytes gradually reduced, eutrophic species dominated the chironomid assemblages and chironomid species diversity decreased. The CI-TP reached ~140 μg/L. The sharp increase in nutrient level from 80 to 110 μg TP/L and decline of aquatic plants occurred from 1940 to 1970s in Taibai Lake. Our results suggest that 50–60 μg TP/L might be determined as reference conditions for lake restoration.

Climate change appeared to be the most important factor regulating the chironomid assemblages prior to AD 1900. However, the impacts of human activities were more important than that of climate change after AD 1900. In spite of their change in relative importance, the combined effects of climatic and anthropogenic variables explained a much higher proportion of chironomid variance than their sole effects. Post-1940, however, the anthropogenic pressure was relatively much stronger than climate change and overwhelmed the impact of climate on the aquatic ecosystem. The effects of long-term climate change and anthropogenic disturbance on shallow lake ecosystems, and most importantly being able to distinguish between the two, is an important step towards better understanding sustainable management of aquatic ecosystems.

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