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RESEARCH ARTICLE

The effects of soil erosion on chironomid assemblages in Lugu Lake over the past 120 years

Enlou Zhang [1], *Hongqu Tang* [2], *Yanmin Cao* [1], *Peter Langdon* [3], *Rong Wang* [1,3], *Xiangdong Yang* [1] *and Ji Shen* [1]

[1] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China
[2] Research Center of Hydrobiology, JiNan University, Guangzhou, China
[3] School of Geography, University of Southampton, Southampton, UK

Lakes in Yunnan Province, SW China, have been subjected to increased environmental stress over the last century. In order to assess the impacts of these stresses on the biota, a sediment core was collected from Lugu Lake covering the past 120 years, and detailed chemical, biological (subfossil chironomids), and physical analyses of the lake sediments were undertaken. The analyses indicated consistent trends of increased soil erosion since the early 1970s associated with significant changes in chironomid assemblages, which occurred simultaneously with the sedimentological proxies. A redundancy analysis (RDA) using a range of sedimentary proxies indicated that the shifts in the chironomid communities were mainly attributable to soil erosion. Constant soil erosion caused dramatic reductions in the available organic materials and large increases in fine sediments, leading to changes in the chironomid fauna and reduced chironomid abundance. The chironomid succession revealed that *Procladius*, the likely top predator in the chironomid community food chain, decreased in abundance under the impact of soil erosion, whereas the proportion of small forms of filter feeders, represented by *Tanytarsus mendax*-type, increased rapidly. Due to the loss of suitable habitats, the population of some bottom collector-gatherers (e.g., *Polypedilum nubeculosum*-type) decreased sharply. The results of this study suggest that increased catchment soil erosion may seriously impact benthic communities and potentially alter ecosystem functioning.

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1 Introduction

Aquatic ecosystems are directly influenced by terrestrial soil erosion, and excessive sediment loading constitutes a significant, widespread, and pervasive form of aquatic pollution [1, 2]. Modern ecological studies have revealed that excesses in both suspended and deposited sediment can lead to reduced species richness in the benthos [1]. Further, it exerts an impact on the lake ecosystem as a whole, which is likely to be determined by the relative interactions among the numerous physical, chemical, and biotic factors (see the review by Donohue and Molinos [3]). As one of the dominant components of benthic communities in freshwater lakes, chironomids are sensitive to environmental change. Chironomid head capsules are typically well-preserved in lake sediments [4, 5], allowing them to be used as paleolimnological proxies in long-term studies of environmental change. Such proxies are needed in order to understand historical relationships between environmental variables and ecosystem components, and where no monitoring data exist they can be the only method of providing reference

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Correspondence: Prof. Enlou Zhang, State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
E-mail: elzhang@niglas.ac.cn
Fax: 0086 25 5771 4759

Abbreviations: DCA, detrended correspondence analysis; **LOI**, loss-on-ignition; **RDA**, redundancy analysis; **TOC**, total organic carbon conditions for such relationships. Recent studies have indicated that chironomid subfossils have become the ideal indicator for past environmental changes of lakes caused by a variety of human activities [5–8]. Soil erosion, an important processes caused by anthropogenic activities, plays an important role in catchment ecosystems as it alters sedimentation rates which impacts benthic communities such as chironomids. This has been observed in the sediment record, as increased soil erosion has been found to have significant alterations to chironomid taxonomic composition [9]. However, few studies have examined the effects of soil erosion on the chironomid fauna over a long time period, especially for lakes in China.

Lugu Lake is an alpine graben lake in Northwest Yunnan Province, which is mainly influenced by the Indian Summer Monsoon. Lugu Lake is recognized as an ideal site for long-term paleolimnology studies due to its continuous sedimentation, lack of industrial pollution and low population density in the catchment. However, Lugu Lake is facing multiple pressures due to increased tourism and mechanized agriculture in recent years [10]. Since the foundation of P. R. China in 1949, human activities intensified near Lugu Lake, mainly consisting of agricultural intensification and large-scale deforestation. Indeed, large-scale deforestation has occurred twice around Lugu Lake catchment: once at the beginning of the 1970s and the other between 1980 and 1992 [11]. However, the impacts from these human activities on the lake's ecosystem state are currently unknown. In this study, a sediment core obtained from Lugu Lake was analyzed to understand the effects of key environmental processes on the chironomid fauna over the last century.

2 Methods

2.1 Study site and sampling

Lugu Lake (27°41′–27°45′N, 100°45′–100°50′E, 2690 m asl) is located in Ninglang County, Yunnan Province, on the southeast margin of the Tibetan Plateau (Fig. 1). It is a semi-closed, deep graben lake with a maximum depth of 93.5 m and a mean depth of 40.3 m, a water area of 48.45 km^2, and a drainage area of 171.4 km^2 [12]. Lugu Lake is affected by the Indian Monsoon Current, and the climate in this region is temperate with distinct dry and wet seasons. Approximately 80–90% precipitation happens between May and October. The mean annual air temperature is approximately 12.8°C, and the annual precipitation is approximately 1000 mm. The lake is mainly charged by Karst groundwater and by precipitation, and is located in the catchment of the Yalong River, which is a tributary of the Yangtze River. The most common rock types in the catchment are limestone, mudstone, and sandstone. Major soil types include Alfisols, Oxisols, Entisols, and Mollisols [12]. Lugu Lake is currently clear and oligotrophic with a secchi depth of 11 m and total phosphorus (TP) concentration of 18.5 μg L^{-1}. Terrestrial vegetation in the catchment consists mainly of conifers *Pinus yunnanensis* var. *faranch* and *Pinus tabuliformis*.

In July 2007, a 30-cm sediment core was collected from the center of Lugu Lake (water depth of 64 m) using an UWITEC gravity corer with a 60-mm-diameter coring tube (Fig. 1). The sediment core was sub-sampled at 0.5 cm contiguous intervals and refrigerated at 4°C prior to analysis.

2.2 Chronology

The sediment core was dated using ^{210}Pb and ^{137}Cs by non-destructive gamma spectrometry [13]. The samples were counted using an Ortec HPGe GWL series well-type coaxial low-background intrinsic germanium detector to determine the activities of ^{210}Pb, ^{226}Ra, and ^{137}Cs. The chronology was calculated based on ^{210}Pb but using a composite model [14]. ^{137}Cs was used to validate and calibrate the ^{210}Pb chronology under a constant rate of supply model (CRS) based on the 1963 peak value of global nuclear testing.

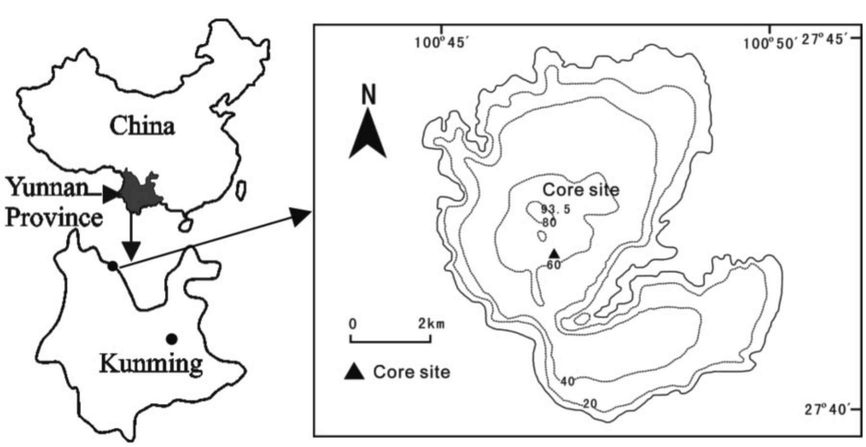

Figure 1. Lake location and sampling site.

2.3 Sediment proxy analyses

Elemental concentrations (Al, Ca, Fe, K, and Mn) were measured using inductively coupled plasma-atomic emission spectrometry (ICP-AES). Magnetic susceptibility (χ_{lf}) was measured at 0.47 kHz using a Bartington MS2 Meter (e.g., [15]). Grain size compositions of the samples were measured using a Malvern Instruments Mastersizer-2000. Total organic carbon (TOC) and TN analyses were performed by combustion using a Euro 3000 Elemental Analyzer. Organic matter as loss-on-ignition (LOI) was estimated using a sample size of approximately 1 g of dry sediment. The sediment was dried at 105°C for 12 h and then ignited in an oven at 550°C for 2 h [16]. All these analyses were performed on each 0.5 cm sample.

2.4 Chironomid analysis

Chironomid samples (freeze dried sediments ranging from 0.8 to 5 g, with mean weight of 1.6 g) were placed in a solution of 10% KOH and heated to approximately 75°C for 15 min. The samples were then sieved through a 90 μm mesh, and the residues were examined under a stereo-zoom microscope at 25× magnification. Given the low concentration of head capsules in the upper 8 cm of sediments, the chironomid analyses were conducted at 1 cm intervals, while, 0.5 cm intervals were used for sediments below 8 cm. All head capsules were mounted in a solution of Hydromatrix. The subfossils were identified following Wiederholm [17], Oliver and Roussel [18], Rieradevall and Brooks [19], and Brooks et al. [20].

2.5 Statistical analysis

A detrended correspondence analysis (DCA) was applied to the fossil chironomid percentage data to explore the temporal patterns of species changes. Datasets containing "predictor" (i.e., geochemical indicators, grain size, and magnetic susceptibility) and "response" (chironomid taxa) variables were created for the samples to investigate the forcing factors that led to the change in chironomids. Geochemical proxy data were $\log_{10}(x + 1)$ transformed, and the grain size data were square-root transformed prior to the ordination analyses. The DCA of the chironomid data showed that the gradient length of axis 1 was 1.39 standard deviations, indicating that a linear method (redundancy analysis, RDA) was more appropriate for the ordination analysis [21]. A series of RDAs were performed for sequentially eliminating the explanatory variable with the highest variable inflation factor (VIF) until all of the VIFs were <20 [22]. Down-weighting of rare species was employed during the process of ordination analysis. Automatic selection was used to identify a minimum subset of significant explanatory variables. Monte Carlo permutation tests ($n = 499$ unrestricted permutations) were used to test the significance of each variable. A series of partial RDAs were also performed to calculate the marginal and conditional effects of each significant variable in explaining the chironomid data. The ordinations were performed using the CANOCO version 4.5 program package [21]. The constrained incremental sum of squares (CONISS) analysis was used to identify the chironomid zones in the sediment core, which were based on the square-root transformed species data [23].

3 Results

3.1 Chronology

Although there were extensive variations in the sequence of $^{210}Pb_{ex}$, a logarithmic decrease was observed with depth (Fig. 2). The CRS dating model was employed for the chronology calculations [14]. There is a large increase in ^{137}Cs which roughly peaks at 9 cm (Fig. 2), which is assumed to correspond to the 1963–1964 maximum fallout in atmospheric nuclear bomb testing [14]. The ^{137}Cs date of 1963 AD was used for the corrections of the ^{210}Pb-based chronology following the procedure described by Appleby [14]. The calculated chronology over the past 120 years is also presented in Fig. 2.

3.2 Sediment indicator changes

Selected paleolimnological indicators from Lugu Lake are presented in Fig. 3. Organic matter content in the lake sediment is exemplified by both TOC and LOI. The percentage of total organic carbon (TOC%) remained stable below 14.5 cm (c. 1950), dropped slightly up to 7 cm (c.1970). Thereafter, it declined rapidly until 3 cm (c. 1995) from where it increased to the top of the section. Compared to the TOC, LOI increased gradually from the bottom of the core to about 12 cm (mid 1950s), where the value was around 17%. Above 12 cm, LOI gradually declined to around 10% at 3 cm from where it increased sharply. The magnetic susceptibility was stable up to 14.5 cm (c. 1950), after which it gradually increased until around 1–2 cm from where it decreased slightly. Al and K showed similar trends, which gradually increased from the base to ~25 cm, then decreased until 15 cm (c. 1950). Both elemental values increased again from 15 cm to around 3 cm, and then declined. The concentration of Ca declined from the bottom to 25 cm, and then increased up to 15 cm. From 15 to 7 cm, the values remained constant, and then rapidly decreased after 7 cm. The median grain size decreased above 14.5 cm, and the particles <4 μm increased over the same interval. The median grain size and <4 μm particles

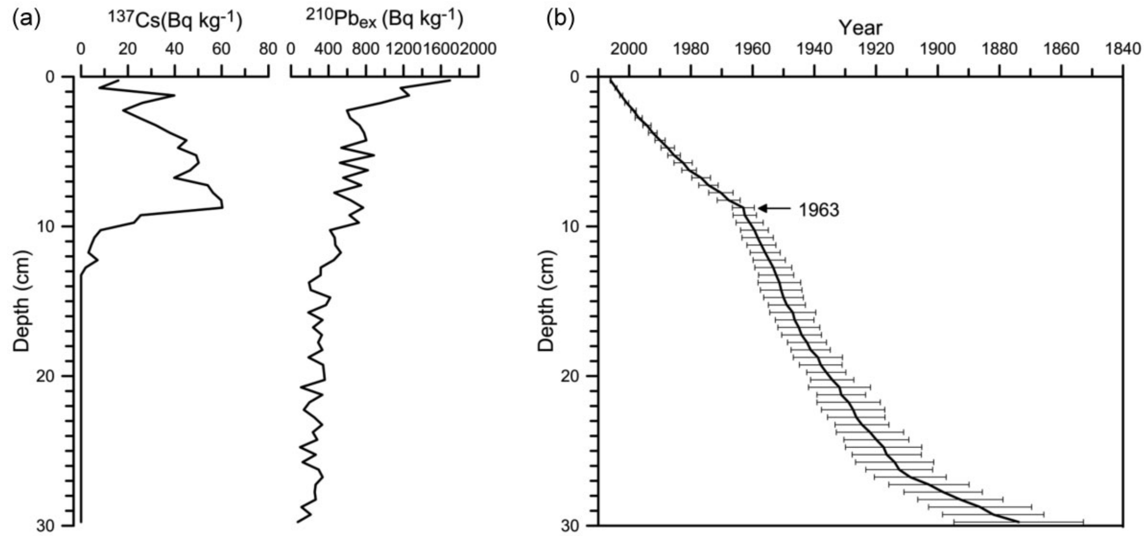

Figure 2. Variation of (a) ^{137}Cs and ^{210}Pb activities and (b) chronology of Lugu Lake core.

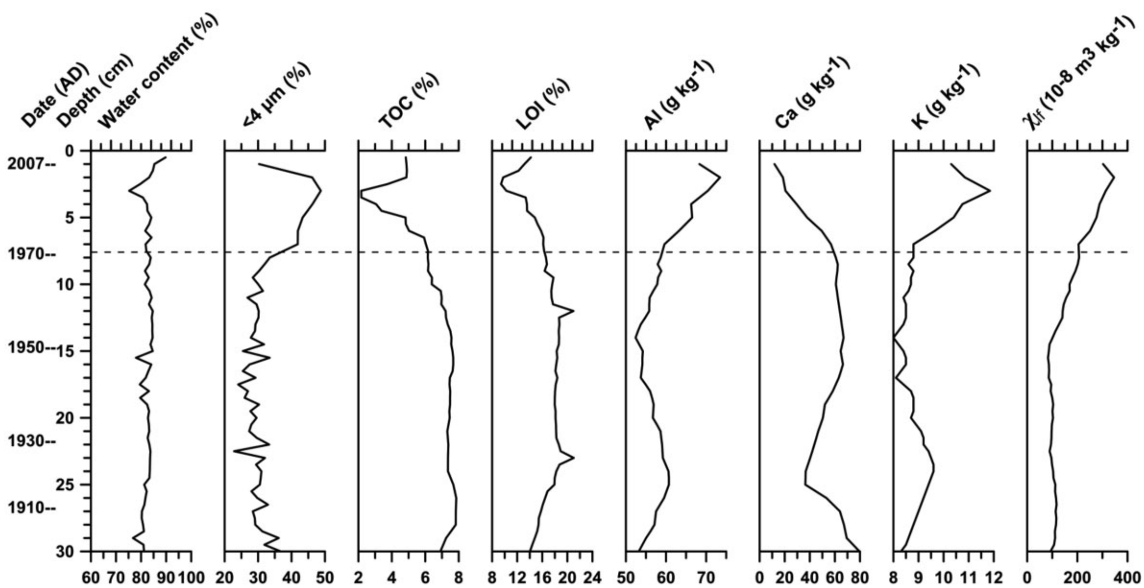

Figure 3. Depth profiles of the selected physical and chemical proxies in the Lugu core. χ_{lf}: magnetic susceptibility; <4 μm (%): percentage of clay and fine silt sediments; TOC, total organic carbon; LOI, organic matter as loss-on-ignition; Al, Ca, and K refer to chemical elements.

show that more fine particles are deposited in the lake after 1970.

3.3 Chironomid stratigraphy

A total of 26 chironomid taxa were identified from the core, mostly belonging to subfamilies Chironomidae and Tanypodinae (Fig. 4). The count sum of head capsules per sample (hcs) ranged from 35.5 to 110, with an average of 58 hcs. The largest number of specimens was recovered from sample 23.5 cm whereas the fewest were from 7.0 to 0.5 cm. The abundance of heads per gram dry sediment showed a clear trend throughout the core, as high values occurred below 14.0 cm, with a clear transition between 14.0 and 7.0 cm, then a decline above 7 cm with a value of <14 head capsules per gram dry sediment. Cluster analysis yielded two faunal zones in the chironomid stratigraphy. Zone 1 (below 7 cm; before 1970 AD)

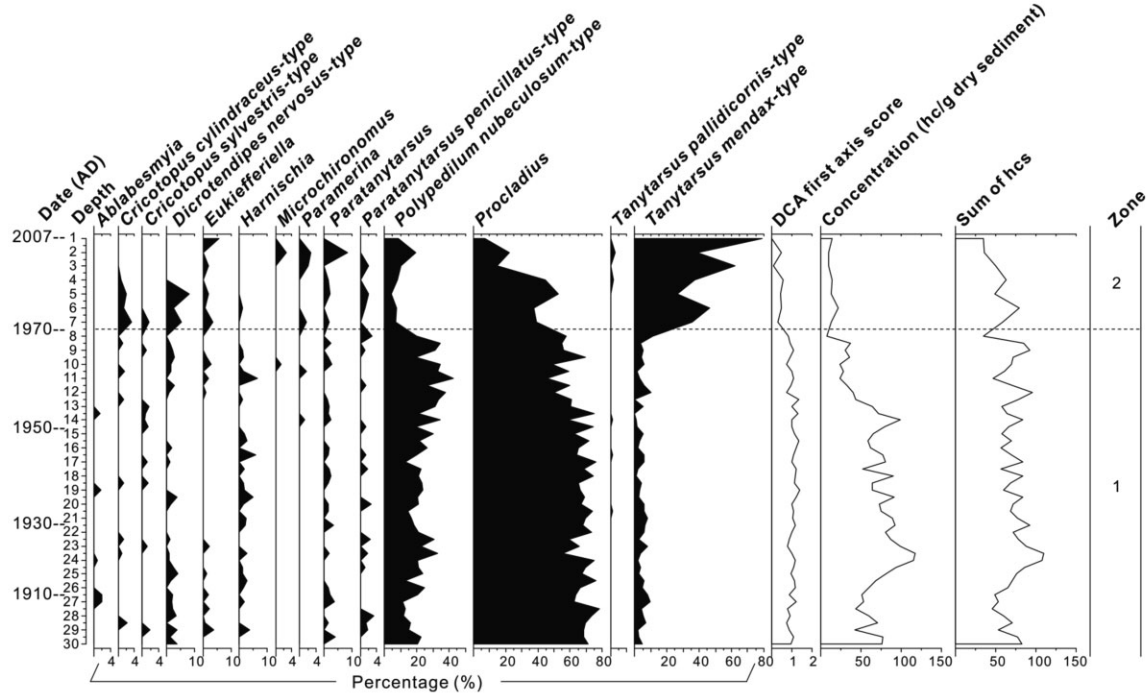

Figure 4. Selected chironomid taxa in percentage abundance (%) for Lugu Lake (panels with black shading, left side) as well as DCA first axis score, concentrations of head capsules (hc), and sum of head capsules per sample (hcs; panels with solid line, right side).

was dominated by *Procladius*, with an abundance of approximately 60%, and *Polypedilum nubeculosum*-type, with percentages that varied between 20 and 40%. Zone 2 (above 7 cm, after 1970 AD) was significantly different from Zone 1, with a marked expansion in *Tanytarsus mendax*-type, which replaced the dominance of *Procladius* in the chironomid community, showing an abundance that increased from 5 to 80%. A clear decrease from 7 to 5 cm was simultaneously observed in the percentage of *P. nubeculosum*-type, which then increased and reached a maximum at 2 cm. Other taxa, such as *Harnischia*, *Paratanytarsus*, *Cricotopus*, *Dicrotendipes*, *Eukiefferiella*, *Microchironomus*, *Ablabesmyia*, and *Paramerina* also appeared in the core. Despite their relatively low abundance ($<5\%$), some of these taxa changed in abundance near the zone boundary. For example, the percentage of *Dicrotendipes*, *Eukiefferiella*, and *Cricotopus cylindraceus*-type increased around 7 cm, while *Harnischia* disappeared in Zone 2.

The predatory midges includes two main types, the *Harnischia* complex members and Tanypodinae genera, which show different trends in the sequence. Even in the same *Harnischia* complex, the distributions of *Harnischia* and *Microchironomus* are not the same. The abundance of *Harnischia* remained fairly stable up to 11 cm then reduced rapidly in abundance to 5 cm, after which it was extirpated locally. Conversely, *Microchironomus* did not occur in the sediment until 10.5 cm, then disappeared again briefly, but increased again in abundance in the top 3 cm. Two Tanypodinae genera which occurred in relatively low abundances, such as *Ablabesmyia* and *Paramerina* showed different records as the two taxa only co-occurred at 13–14 cm; before that only *Ablabesmyia* was present in the lake sediment, while after 13 cm (13–1 cm), only *Paramerina* occurred with a peak abundance in the top 3 cm.

3.4 Ordination analysis

The first two DCA axes explained 16.9 and 10.4% variance of chironomid data, respectively, while 42.8 and 6.0% variance were captured by the first and second axis of RDA. The relationship between the environmental factors and the chironomid assemblages revealed by the RDA ordination are shown in Fig. 5. After the deletion of redundant variables (TN, K, Ca, Fe, Mn, median grain size (MD)), automatic forward selection in the RDA indicated that the content of clay and fine silt (<4 μm), Al, χ_{lf}, and TOC acted as the significant variables ($p<0.05$) and explained approximately 45.2% of the variance of the total chironomid data. The variance independently explained by each environmental variable ranged from 2.3 (χ_{lf}) to 4.3% (the clay and fine silt content). RDA (Fig. 5) clearly divided the samples into two groups: the samples in the top 7 cm,

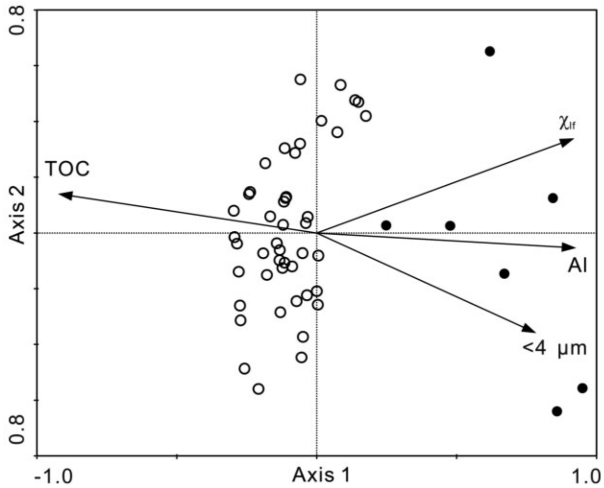

Figure 5. Sample-environmental variable plot of RDA between fossil chironomids and sedimentary proxies in Lugu Lake core. Black circles represent samples above 7 cm and open circles are samples below 7 cm in the core from Lugu Lake. χ_{lf}: magnetic susceptibility, $<$4 µm: percentage of clay and fine silt sediments; TOC, total organic carbon; Al, concentration of aluminum.

which were highly influenced by clay and fine silt fractions of sediments, magnetic susceptibility and Al concentration, and samples below 7 cm which were mainly affected by organic content.

4 Discussions

4.1 Soil erosion in the catchment of Lugu Lake

The increase in human activities after the foundation of P. R. China in 1949, including changing agricultural practices and deforestation, had a considerable effect on Lugu Lake. In particular, debris-flow clay and fine silt from catchment erosion entered the streams that flowed into the lake. From 1980 to 1990 siltation, due to the frequent deforestation, had advanced 100 m into the lake in the mouth of Da Yu Ba River alone [11]. The proxy indicators in the lake sediment have been used to record the characteristics of the erosion. Magnetic susceptibility has been shown to be an effective indicator of soil erosion occurring in lake catchments [24, 25]. In Lugu Lake, magnetic susceptibility increased markedly from 1950 onwards, particularly after 1970 (Fig. 3), which can be interpreted as documenting increasing erosion in the watershed. Although, the evidence from both documentary sources and magnetic susceptibility suggest increasing erosion in the catchment, grain size analyses suggest erosion decreased after the 1970s. Typically, the enhancement of erosion will correspond to an increasing particle size in the lake sediment. However, grain size values will decrease when more clay and fine silt particles are eroded from the catchment. Our results suggest that the catchment deforestation provides more clay and fine silt particles for erosion, and that the hydrodynamics did not increase significantly. As a response to intensified human impacts on the lake system, there were additional changes in the lakes geochemistry, which shows a range of elemental values reached their peaks or minima during the 1990s (around 3 cm depth). Simultaneously, the accumulation of eroded minerals diluted the concentration of organic matter, reducing the TOC and LOI values to reach their historical minima in the 1990s.

4.2 The effects of soil erosion on chironomid fauna

The concentration of midge head capsules declined from circa 1950s and decreased sharply after 1970s. This coincided with the increase of sediment fine fractions, associated with large-scale deforestation in the watershed. The elimination of many individuals of the dominant species also indicates that the entire chironomid community was altered by the sediment composition changes. The RDA results demonstrated that the chironomid community also changed rapidly after the 1970s. Figure 6 shows the DCA scores of the chironomid samples against an indicator of erosion (i.e., magnetic susceptibility), which suggests a high linear relationship ($r = -0.78$, $p<0.001$) between chironomid communities and soil erosion. It confirms the assumption that the soil erosion is a main driver causing the chironomid community changes. One hypothesis for the community change is that the increasing soil erosion enhanced the trophic status of the lake. However, both TOC and LOI indicate that the lake's

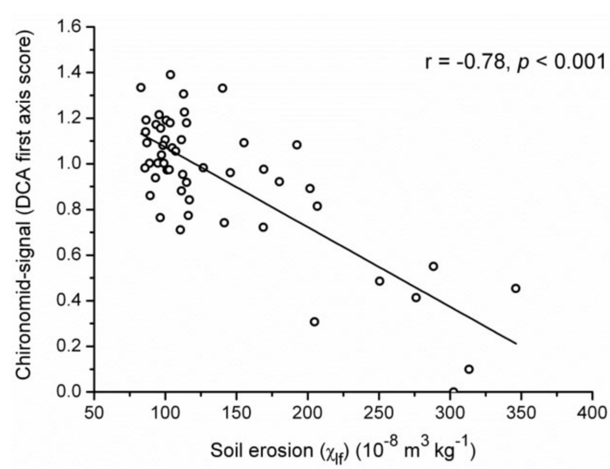

Figure 6. The relationships between chironomids (first axis score of DCA for fossil chironomid data in the core) and soil erosion (χ_{lf}).

primary production showed a relative decrease after 1970s, thus the lake's nutrient status is not likely to have increased. Constant or severe soil erosion can affect the community structure of Chironomidae, resulting in reduced density and alterations of the relative dominance among species [26]. The hcs concentrations declined sharply from the 1950s, which is consistent with the intensified human activities and soil erosion. This is because soil erosion can lead to food scarcity, which will directly hinder chironomid growth and even survival. Meanwhile, the induced disappearance of diverse microhabitats and shelter and/or substrate variations makes the invertebrates more vulnerable to frequent attack and predation by other consumers [4, 9].

The impact of fine sediment has been found to have a negative impact on both the survivorship and growth rates of benthic invertebrates [27, 28]. The increased fine sediment may decrease oxygen concentrations in the bottom of the lake as the increase in fine sediment caused by soil erosion is likely to clog the interstices in the lakebed sediments. This can reduce oxygen penetration, alter biogeochemical and microbial processes and negatively affect bioturbators, with consequent indirect effects on other benthic organisms [29–31]. In the case of Lugu Lake, since the 1950s, and especially after the early 1970s, our data suggest soil erosion caused large decreases in the available organic matter and greatly increased the fine sediments (Fig. 3). Under the pressure of microhabitat changes, the population of some Tanypodinae, such as *Procladius*, as the top predator in the chironomid community food chain decreased either dying due to limited food resources or escaping from the affected areas [32]. In contrast, some small forms of filter feeders, represented by *T. mendax*-type, most likely were able to adapt to new habitats, yielding a relatively higher proportion. Thus, the relative dominance in the chironomid community was altered from *Procladius* type to Tanytarsini. The loss of favorable habitats (for collector-gathers, as the difficulty in entering the substrate would result in a high possibility of predation) is probably the reason why the populations of some bottom collector-gathers (e.g., *Polypedilum*) decreased sharply. Meanwhile, the less dominant collectors, such as the deposit-feeders (e.g., *Cricotopus*, *Dicrotendipes*, *Eukiefferiella*) generally showed the same trends as *T. mendax*-type due to the increase in both the fine sediment component and food availability. Two taxa of *Harnischia* complex, namely *Harnischia* and *Microchironomus*, showed different trends in the sequence. Larvae of *Harnischia* are obligate predators, which have been mainly reported from the relatively sandy substrates [33–35]. Conversely, *Microchironomus* favors the muddy-sand habitat, often fine grain dominated sediments, where the consumed food is not obligate. If small zoobenthos are available, *Microchironomus* will prey on it, otherwise it could also feed on zooplankton, diatoms, and detritus [36, 37]. Thus, under enhanced soil erosion and an increasing fine sediment component, the population of *Harnischia* decreased after the 1970s while the concentration of *Microchironomus* increased in recent years.

5 Conclusion

The sediment record from Lugu Lake indicated that increased soil erosion after the 1970s had a clear impact on the lake ecosystem. The increase in fine sediment in wash may have caused a decrease in organic production. The chironomid succession revealed that the excess sedimentation was correlated with changes in the faunal composition, altering the relative dominance among species and possibly reducing the density of chironomids. This research provides a case study to improve our understanding of the ecological effects of soil erosion on the benthic communities of other lakes that have experienced similar impacts in China.

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