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A 150-year record of recent changes in human activity and eutrophication of Lake Wushan from the middle reach of the Yangtze River, China

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ABSTRACT

In order to determine baseline conditions (pre-impact) and recent changes to lakes on the middle reach of the Yangtze River, China, a lake sediment core was extracted from Lake Wushan covering the last ca *150 years. Detailed chemical, biological (subfossil chironomids), and physical analyses of the lake sediments were undertaken. The data showed consistent trends of increased productivity since the early 1920s, notably significant changes in the chironomid fauna which were associated with changes in the sedimentological and stable isotope proxies. More typically eutrophic chironomid taxa first appeared around this time that had not been present in the lake since at least the 1860s. Further increases in productivity occurred around the 1950s which coincided with the local decline and extirpation of some chironomid taxa, particularly macrophyte associated taxa, which had been present in the lake since at least the late 19th Century. A chironomid-inferred water total phosphorus (CI-TP) reconstruction produced accurate levels of water TP compared with contemporary measurements (207.4 µg L^{-1} TP), and suggested that levels for the late 19th Century were relatively low (50-60 µg L^{-1} TP). These reconstructions illustrate the baseline levels that existed pre-impact and provide potential targets for restoration, but they also show the magnitude of human impact in this region, which has increased the nutrient content of Lake Wushan fourfold within the last* ca *100 years.*

Key words: lake sediment, eutrophication, human activity, stable isotopes, subfossil chironomids

1. INTRODUCTION

The deteriorating quality of terrestrial freshwater sources has been one of the largest and most widespread environmental problems in the world, especially in developing countries such as China (Liu & Diamond 2005). Eutrophication is a particularly severe problem for lakes in the middle and lower reaches of the Yangtze River, China (Qin & Zhu 2006). Formalized efforts to halt or reverse the rate of eutrophication have been established across the Lower Yangtze region. Targets for each site have been established based on pre-disturbance baseline conditions defined using nutrient load models driven by palaeolimnological datasets (e.g., Hall & Smol 1999; Jordan *et al*. 2001; Smol 2002; Ramstack *et al*. 2004). For regionally unique and highly altered systems, the approach of using the palaeolimnological record to define 'pre-disturbance' conditions is often the most reliable (Engstrom *et al*. 2006).

Lake Wushan is located in the middle reach of the Yangtze River and has a complex and highly altered hydrological system. The lake-catchment system has been heavily affected by both agricultural and industrial activity and widespread urbanization, the combined impact of which has led to a marked decline in water quality reflected by increased eutrophication of the lake. There is no long-term water quality data for the site and as such it is unknown what is driving these changes, how fast they occurred or at what point in time the system began to change. Defining the nature of the pre-impact limnological system is therefore impossible using current datasets. To address these issues a multi-proxy palaeolimnological study of the recent sediments was undertaken the results of which are outlined in this paper.

2. METHODS

2.1. Site description

Wushan Lake (N29°53'~29°57', E115°31'~115°37') is a hypereutrophic lake in the middle part of the Yangtze floodplain (Fig. 1). Its surface area was decreased from 42.5 km^2 to the present 16.1 km^2 because of land reclamation programmes during 1950-70s (Wang & Dou 1998). The lake has a maximum depth of 4.7 m and a mean depth of 3.1 m. The lake has a drainage area of 469.0 km^2, with inflows from the northern hillocks and it drains into Taibai Lake to the East. Presently there are no macrophytes in the open water (Jian *et al*. 2001). Water quality investigations in July 2001-April 2003 indicated that the annual average TP concentration was high (207.4 µg L^{-1}), suggesting that the lake is now hypereutrophic (Yang *et al*. 2008). Since 1987 the establishment of several chemical factories on the lakeside has led to increased pollution of the lake (Jian *et al*. 2001), speeding up the eutrophication process and the

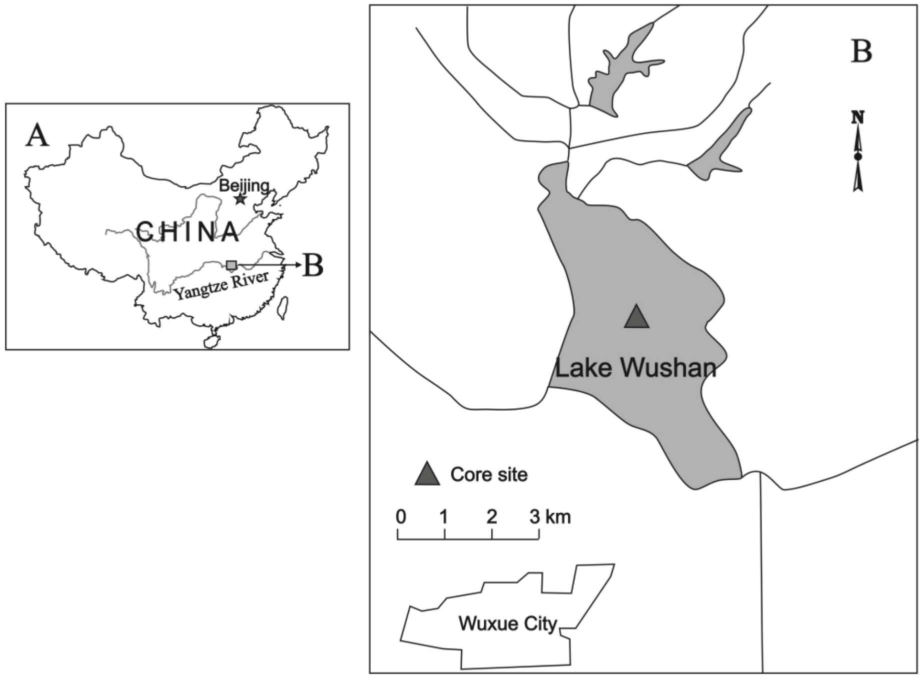

Fig. 1. Map of Lake Wushan and the location of sampling site.

deterioration of the lake ecosystem (Wuxue committee for compilation of local chronicles, 1994). This situation was exacerbated even further with the introduction of commercial fish stocking in the lake at this time (Jian *et al*. 2001; Yang *et al*. 2002).

2.2. Coring and subsampling

In April 2007, a 50-cm sediment core was collected from the centre of Wushan Lake (water depth: 4 m) using a Kajak gravity corer with a 60-mm-diameter coring tube. The sediment core was sub-sampled at 1 cm contiguous intervals and refrigerated at 4 °C prior to analysis.

2.3. Chronology

Sediment samples were dated using ^{210}Pb and ^{137}Cs by non-destructive gamma spectrometry (Appleby & Oldfield 1992). Samples were counted on 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. Sediment chronologies were calculated using a composite model (Appleby 2001). ^{137}Cs was used to identify the 1963 nuclear weapons peak, which was then used as part of a constant rate of supply (CRS) model to calculate a ^{210}Pb chronology for the core. The CRS model was chosen due to the complexity and heavily impacted nature of the hydrological system at Wushan.

2.4. TOC, TN, $\delta^{13}C$ and $\delta^{15}N$

Bulk carbon samples were prepared for contiguous 1 cm samples, which were prepared by placing 2 g of wet sediment overnight in 50 mL of 5% hydrochloric acid to remove carbonates. The samples were then washed with deionised water, oven dried at 40 °C, ground into a fine powder and sieved at 80 µm. TOC and TN analyses were performed by combustion using a FlashEA1112 Elemental Analyser linked to a Thermo Delta^{Plus} Advantage mass spectrometer. δ^{13}C values were calculated to the VPDB scale and δ^{15}N calculated to the AIR scale. Analytical precision was 0.1‰ for organic carbon and 0.15‰ for nitrogen isotope ratios. TOC and TN were determined by reference to standard samples, and replicate analyses of well-mixed samples indicate a precision of ±0.1% (1 SD).

2.5. Sediment phosphorus species

The chemical speciation of phosphorus in the sediment was determined following the SMT protocol (Ruban *et al*. 2001). This operationally defined sequential extraction scheme defined the Phosphorus into three species; NaOH-extractable P (NaOH-P, P bound to Al, Fe and Mn oxides and hydroxides), HCl-extractable P (HCl-P, Ca-bound P) and organic P (OP). The sum of these was then expressed as TP. During the sequential extraction analysis, parallel samples were analysed for accuracy control. The maximum relative standard deviation was lower than 10%.

2.6. Magnetic susceptibility

Freeze dried sub-samples were packed into pre-screened 10 mL polystyrene sample pots and the analysed using a dual frequency (470 Hz =χLF, 4700 Hz =χHF) Bartington Instruments MS2 sensor (e.g., Evans & Heller 2003).

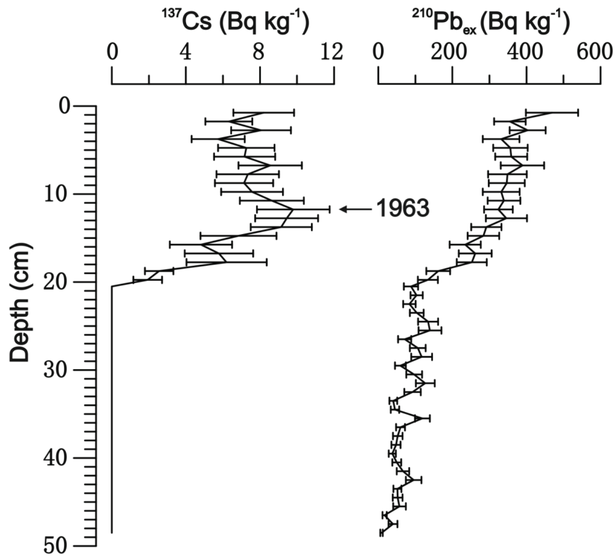

Fig. 2. Variation of ^{137}Cs and ^{210}Pb activities in the core sediment of Lake Wushan.

2.7. Subfossil chironomid analysis and lake water TP reconstruction

Sediment samples were analysed for chironomids by following standard methods (Brooks *et al*. 2007). Deflocculate sediments in 10% KOH in water bath at 75 °C for 15 minutes. The samples were then sieved with 212 µm and 90 µm meshes and the residue was examined under a stereo-zoom microscope at 25×. All the head capsules found were mounted on microscope slides in a solution of Hydromatrix®. The chironomid head capsules were identified mainly following Oliver & Roussel (1983), Wiederholm (1983), Rieradevall & Brooks (2001), and Brooks *et al*. (2007).

Lake water TP for the Wushan Core was calculated using a chironomid-TP inference model by applying an optimal two-component WA-PLS model which provides a high jack-knifed coefficient of prediction for conductivity $r^2_{jack} = 0.76$, with a low root mean squared error of prediction ($RMSEP_{jack} = 0.13$) (Zhang *et al*. 2006). The water TP reconstruction was undertaken using the program C2 (Juggins 2003). Minimum variance cluster analysis was performed using CONISS (Grimm 1987), implemented by the programs TILIA and TILIGRAPH (Grimm 1991) to identify the major zones in species composition.

3. RESULTS

3.1. Chronology and mass accumulation rate

The 1963 spike in ^{137}Cs associated with the peak in atmospheric nuclear weapons testing (Appleby 2001) is clearly evident in the core at 12 cm (Fig. 2). The ^{210}Pb$_{exc}$ profile shows a continuous increase from the bottom to the top of the core, but no exponential distribution (Fig. 2). When compared to the 1963 ^{137}Cs speak, the ^{210}Pb data was found to be too old, reflecting a decrease in sedimentation rates linked to reservoir construction in the upper reaches of Wushan lakes catchment during the early 1960s. The ^{137}Cs data was therefore used to constrain the ^{210}Pb data and produce a composite age model. Calculated mass accumulation rates (MAR) are seen to vary markedly over the last 150 years (Fig. 3). From 1860s to the mid 20th Century, they rise rapidly peaking in the early 1950s after which point they decline through to the top of the core.

3.2. TOC, TN, C/N, $\delta^{13}C$ and $\delta^{15}N$

TOC is seen to decline from *ca* 6% to 1% between the years 1860s and the middle 1920s (Fig. 4). From the middle 1920s to the present day the values increased steadily to *ca* 3%. The TN curve produces a similar trend as TOC but with lower values, which decreased from *ca* 0.4% to 0.1% between 1860s and the middle 1920s, and increased again to present day value (*ca* 0.4%). C/N ratios were calculated to examine the relative importance of autochthonous and allochthonous sources of organic material within the Lake Wushan sediments (Meyers 1994; Meyers and Teranes 2001). C/N ratios vary between 10 and 12 before the early 1900s (38 cm depth), after which point they decreased gradually to 8.

δ^{15}N values for the core were generally low, but values increasing steadily until the early 1920s, after which point they plateau. Following this stable period until the middle 1950s, δ^{15}N increased through to the present day. In contrast δ^{13}C values oscillated between 1860s and the middle 1920s on a decreasing trend before stabilizing from the middle 1920s to the 1940s. From the 1940s through to the middle 1950s values decreased again after which point they stabilized through to the top of the core.

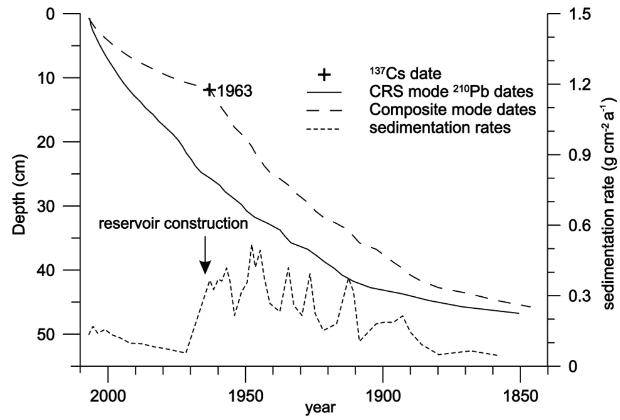

Fig. 3. Chronology and sedimentation rate of Lake Wushan.

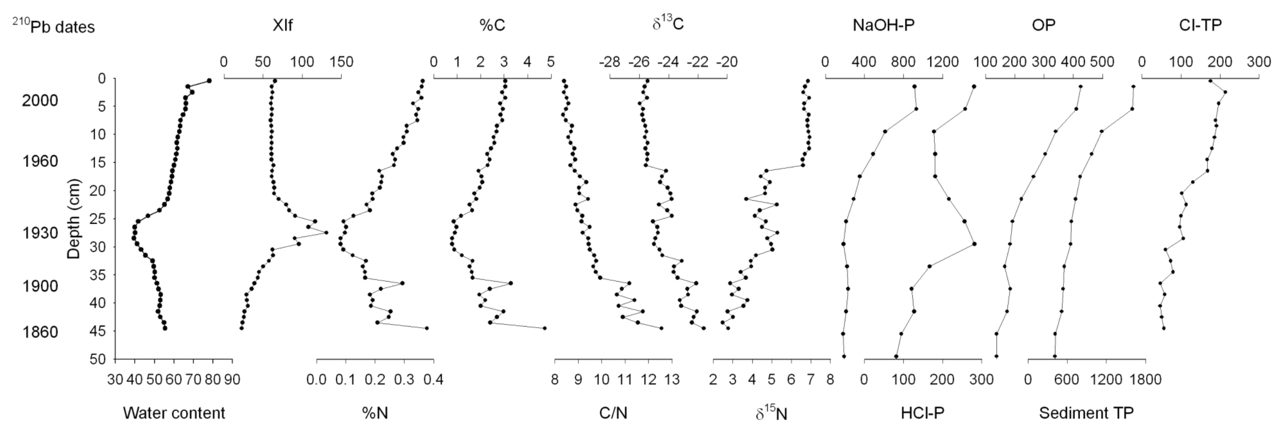

Fig. 4. Depth profiles of the geochemical proxies (water content (%), χLF (10^{-8} m^3 kg^{-1}), TN (%), TOC (%), C/N, $\delta^{13}C$ (‰ *vs* VPDB), $\delta^{15}N$ (‰ *vs* air N_2), NaOH-P (mg kg^{-1}), HCl-P (mg kg^{-1}) OP (mg kg^{-1}) Sediment TP (mg kg^{-1}) CI-TP (μg L^{-1})) in the Wushan core.

3.3. Sediment phosphorus species

Total phosphorus (TP) values range from 412 to 1620 mg kg^{-1} (Fig. 4). Values were relatively low and constant before the middle 1920s, after which they gradually increased. The highest concentrations were recorded in recent years. The concentrations of NaOH-P and OP range from 182-914 mg kg^{-1}, and 138-426 mg kg^{-1} respectively. In contrast peak concentrations of HCl-P occur between the middle 1920s and the middle 1950s.

3.4. Magnetic susceptibility

χLF values (Fig. 4) increase steadily from 1860s, reaching a peak from the middle 1920s to the middle 1950s. After which values decrease gradually to the top of the core.

3.5. Chironomid assemblages

A total of 34 chironomid taxa were identified in the core. Within the taxa, *Microchironomus tabarui* and *Propsilocerus akamusi* do not occur in the identification guides this paper used. *Microchironomus tabarui* can be differentiated from other *Microchironomus* taxa as the 3 outermost lateral teeth of the mentum are not arranged in a distinct cluster and the lateral teeth gradually descend from the first to the sixth. *Propsilocerus akamusi* can be identified as it has 9-10 pairs of lateral teeth. Three zones were identified using CONISS analysis (Fig. 5). Zone 1: 45-29 cm (~1860s-the middle 1920s) is dominated by *Paratanytarsus penicillatus*-type, *Polypedilum nubeculosum*-type, *Microchironomus* and *Cricotopus intersectus*-type. In zone 2a (the middle 1920s-the middle 1950s), these taxa decline as *Microchironomus tabarui*, *Procladius*, *Propsilocerus akamusi* and *Tanypus* begin to increase. Zone 2b (the middle 1950s-2007) shows an almost complete dominance of the same taxa that increase in zone 2a, but with associated decreases and/or local extirpations of many of the other taxa previously present in the lake.

3.6. Chironomid-inferred water TP

A chironomid-inferred record of mean annual lake water TP (CI-TP) for the period 1860s - 2007, was calculated for the Wushan Core by applying a WA-PLS

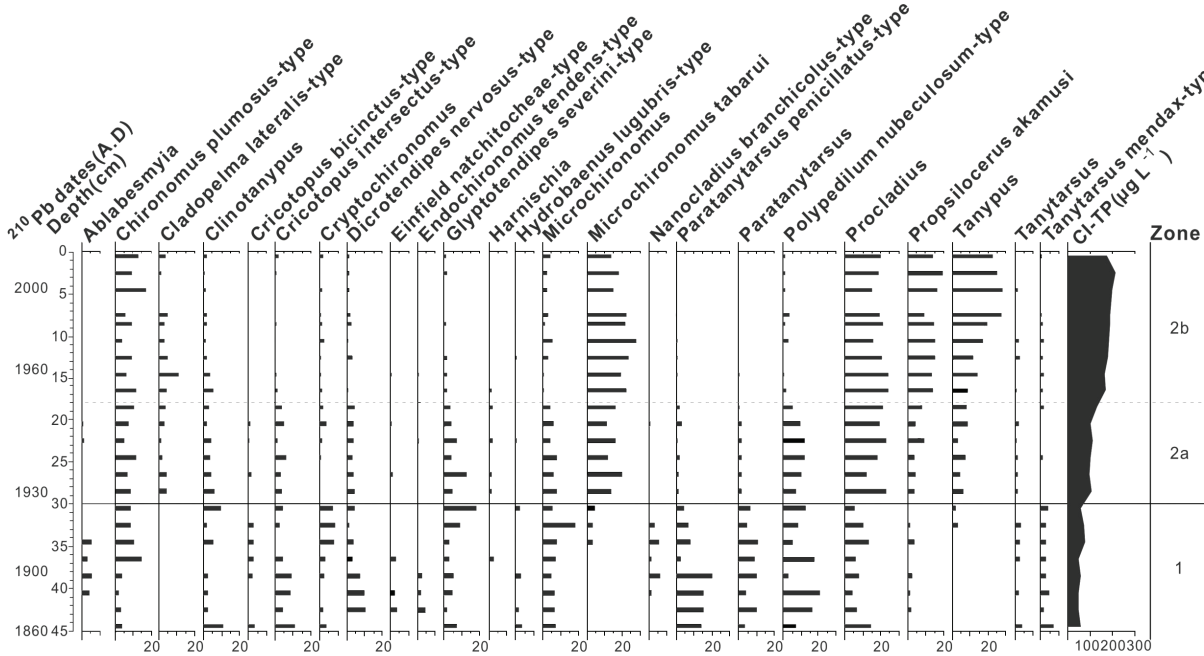

Fig. 5. Selected chironomid taxa in percentage abundance (%), CI-TP for Lake Wushan, covering the period 1860s to 2007.

model (Zhang *et al*. 2006), to the fossil chironomid assemblage data (Fig. 4). CI-TP values are relatively low at the base of the core (50-60 µg L^{-1} TP), rising gradually to 100 µg TP L^{-1} by the middle 1920s. CI-TP then remains relatively stable until the middle 1940s, before increasing to ~160 µg L^{-1} TP. After this point values are seen to rise rapidly, reaching 210 µg L^{-1} TP by the top of the core (2007). This CI-TP concentration for the surface sediment sample (210 µg L^{-1} TP) was in good agreement with modern values for total phosphorus concentration in the lake water (207.4 µg L^{-1} TP) sampled in 2001-2003 (Yang *et al*. 2008).

4. DISCUSSION

Analysis of the multi-proxy data set for Wushan indicates that the lake has experienced significant increased nutrient loading over the last 150 years. Over the last 50 years the situation has become particularly acute, leading to a major shift in lake status from mesotrophic to more eutrophic conditions.

Within the subfossil chironomid record the changing water quality is characterised by a clear shift in fauna commencing around the middle 1920s. Taxa which dominated pre-the middle 1920s, in zone 1, such as *Paratanytarsus*, *Dicrotendipes* and *Polypedilum nubeculosum*-type are indicative of relatively clear water conditions with a reasonable macrophyte density and/or species richness from lakes in NW Europe (Davidson *et al*. 2010; Langdon *et al*. 2010). Their co-occurrence here, pre-impact and pre-eutrophication, suggest that their general ecologies (in terms of subfossil genera and taxon morphotypes) are similar to the studies from the Palaearctic although further ecological data from Chinese lakes would help to confirm this. These taxa, which showed stability from the mid 19th Century to the start of the 20th Century, are either reduced or almost lost completely from the fauna post-the middle 1920s, as taxa such as *Microchironomus tabarui*, *Procladius*, *Propsilocerus akamusi* and *Tanypus* either increase in concentrations significantly and/or become part of the local fauna for the first time in the current record. *Chironomus plumosus*-type also increases in abundance around this time and is a well known eutrophic/anoxic indicator (Brooks *et al*. 2007). This clear change in fauna occurs over a period of *ca* 20 years, indicating that either increased loadings were substantial over this time and/or a threshold was crossed within the lake functioning leading to, for example, a regime shift within the lake ecosystem (cfr. Carpenter 2003). The chironomid data would indicate that this change was accompanied by a decline in macrophyte-dwelling taxa, a phenomenon often associated with increased eutrophication. The CI-TP reconstruction also suggests the lake has become increasingly more productive. Values for CI-TP were relatively low in the late 19th and early 20th Century (50-60 µg L^{-1} TP). These values are comparable to the diatom-inferred TP concentration from shallow lakes in middle and lower reaches of Yangtze River (Dong *et al*. 2008; Yang *et al*. 2008). The CI-TP record shows clear increases in productivity post the middle 1920s and further increases post the middle 1950s. A similar trend is also recorded at Taibai Lake and Longgan Lake, that lie within the same catchment (Yang *et al*. 2002, 2008; Wu *et al*. 2008).

Studies suggest that the anthropogenic input of phosphorus from the wastewater contributes primarily to the NaOH-P component, whereas HCl-P is derived mainly from the terrestrial sources (Correll 1998; Zhang & Shan 2008). The contribution of OP can be from either terrestrial or aquatic sources, a proportion of which could be decomposed and released to the water. The increased contribution of NaOH-P and OP since the middle 1920s further supports the inference of an increase in lake productivity over this time.

C/N ratios of 8-12 suggest that submerged macrophytes and/or aquatic algae were the main source of carbon to the lake prior to the early 1900s, which supports the inference from the chironomid data. The decline in values recorded after the middle 1920s points to an increased contribution of algal material (Meyers 1994; Meyers & Teranes 2001). This is not reflected in the $\delta^{13}C_{org}$ record, which trends in the opposite direction, suggesting an increased contribution of terrestrial plant material. This apparent discrepancy may reflect subtle changes in the contribution of organic matter from macrophyte and/or phytoplankton sources accompanied by shifts in the degree of fractionation (Popp *et al*. 1999; Neumann *et al*. 2002; Vuorio *et al*. 2006). A range of palaeolimnological studies have shown that changes in primary productivity do not always yield linear shifts in $\delta^{13}C$ values (Brenner *et al*. 1999; Benson *et al*. 2008). A similar situation has been observed in the sediment record from Lake Taihu in Jiangsu province (Wu *et al*. 2006).

The changes observed in the sediment core from Lake Wushan are typical of an area experiencing elevated nutrient input from urban and agricultural sources. This interpretation is confirmed by the recent land use history of the area, which highlights several phases of significant anthropogenic activity in the catchment over the time period covered by the core. Widespread deforestation and frequent flooding were commonplace in the catchment before 1950s, which can be linked to increased erosion of the catchment and an increased flux of terrestrial material into the lake (Wuxue committee for compilation of local chronicles, 1994). After 1949, a series of water conservancy measures were implemented within the Wushan catchment, and the lake was partly drained for agricultural land reclamation during the 1950-70s (Wuxue committee for compilation of local chronicles, 1994). During this time the lake decreased in area from 42.5 km^2 to the present 16.1 km^2 (Wang & Dou 1998). The decline in the hydrological storage capacity of the lake, combined with the increased use of chemical fertilizer across the catchment would have significantly increased levels of primary production in the lake. The χLF peak period from the middle 1920s-1950s and a coarsening of particle size combined with a higher HCl-P content in the sediment further supports the inference of an increase in terrestrial sediments to the lake over this period, and increasing TP levels.

The high use of N-P-K fertiliser in the catchment over the last 30 years has had a major impact on the lake system at Wushu and is likely to be responsible, at least in part, for the observed rise in TP. Such an interpretation is supported by the $\delta^{15}N$ signature, changes in which would be expect to be in proportion to the quantity of N fertiliser applied, regardless of the initial signature of fertiliser (Leavitt *et al*. 2006; Bunting *et al*. 2007). The abrupt jump in $\delta^{15}N$ around 1950 is most likely to be linked to the introduction of chemical fertilisers into the catchment.

5. CONCLUSIONS

Analysis of the recent sedimentary record from Lake Wushan clearly indicates that the site has been heavily impacted by anthropogenic activity over the last 150 years. The long-term impact on the lake ecosystem has been a shift in status from mesotrophic to eutrophic. This change is due primarily to the introduction and high use of fertilisers, increased industrial activity and accelerated urbanisation. Based on the CI-TP record, the relatively low water phosphorus concentration (50-60 $\mu g\ L^{-1}$ TP) recorded for the lake in the late 19th Century and the early 20th Century suggests this period could be targeted as a likely reference period for future remediation efforts.

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