Long term dynamics of ecosystem services in typical Yangtze shallow lakes (China)

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Abstract Understanding the dynamics of ecosystem services (ESs) is crucial for sustainable resource management. Palaeolimnological records have a great potential to reveal long-term variation and dynamic interactions in ESs, especially supporting/regulating services, which are less easily quantified by documentary records. To elucidate the variations among eight important ESs in shallow lake ecosystem, we combined documentary records with palaeolimnological proxies (covering the past 100 years) from two typical lakes (Lakes Taibai and Zhangdu) in the Yangtze River basin. Although all supporting services and part of the provisioning services have increased, the regulating services of the two lakes have markedly declined, in particular since the 1950s. Human activities, including hydrological intervention, nutrient input and land use, were identified as the main factors controlling of the observed variations. Both in Lake Taibai and Zhangdu, services in primary productivity and biodiversity maintenance increased (synergies) whereas services in water-purification and climate regulating decreased significantly (tradeoffs) since 1950s, when local people are seeking higher desired services (land/fish ESs) by human “modification” on lake ecosystem. By long-term records, temporal perspectives on such dynamic tradeoffs and synergies relationship among various ESs under the context of different types resource utilization over time have significant implications for management initiatives.

1. Introduction

Ecosystem services (ESs) are the benefits that people derive from ecosystems (Millennium Ecosystem Assessment, 2005). In the past several hundred years, humanity has made substantial efforts to maximize the provision of desired ESs (benefits) in a cheap and stable way (Millennium Ecosystem Assessment, 2005; Ouyang et al., 2016). However, interactions among ESs can results in tradeoffs (the provision of one service is enhanced at the cost of another) or synergies (multiple services are enhanced simultaneously) due to the complex mechanisms of the socio-ecological systems, leading to unintended changes in other services (especially massive loss of regulating services produced by tradeoffs) (Bennett et al., 2009; Rodríguez et al., 2006). As reported in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), the net benefits of actions to

increase desired ESs have always been smaller than initially believed when their interactions (tradeoffs) are taken into account. Although dramatic changes in ESs have motivated recent studies into interactions, current work has revealed the risk of drawing incorrect conclusions due to the use of routine inferences based on spatial relationships without regard for interactions over time (Tomscha et al., 2016). Yet, information on these is essential to understand the dynamic mechanisms behind socio-ecological behaviors (Dallimer et al., 2015; Renard et al., 2015; Tomscha and Gergel, 2016).

Long-term records (decadal to centennial time scales) have increasingly been employed to improve our temporal perspective on ESs (Carpenter et al., 2009; Dearing et al., 2012; Jeffers et al., 2015; Xu et al., 2014). Over the past decade, knowledge of long-term ES variation has rapidly expanded through the use of various historical datasets: more than 50 different paleoenvironmental proxies have been mapped to a wide range of ES categories and subcategories, and the effectiveness of these in assessing the persistence of, especially supporting/regulating services across a variety of time scales, has been substantiated (Dearing et al., 2012; Jeffers et al., 2015). Furthermore, with historical topographical maps/document records, temporal variations of individual ESs (30-60 years) have been reconstructed for some urban areas and this empirical evidence has also demonstrated changes in the relationships among ESs across time scales (Dallimer et al., 2015; Renard et al., 2015; Tomscha and Gergel, 2016). Despite it being increasingly acknowledged that temporal approaches are important, in-depth examination of the long-term dynamics of ESs is impeded by factors such as scarcity of ESs data in many ecosystems, practical challenges in using proxy records for direct reconstruction of historical ESs, and the limitation of temporal scales available to reflect the dynamics in ESs as time lags in socio-ecological systems are not captured (Dallimer et al., 2015; Renard et al., 2015; Rodríguez et al., 2006; Swetnam et al., 1999; Tomscha et al., 2016).

Shallow lakes are vitally important ecosystems of great heritage, ecological, and aesthetic value. They sustain the livelihoods of the people inhabiting their catchments by providing services such as freshwater, food, flood and drought regulation, and biodiversity maintenance (Millennium Ecosystem Assessment, 2005; Wang and Dou, 1998). The middle and lower reaches of the Yangtze River basin (MLYB) are one of the most developed areas in China and are rich in shallow lakes with substantial ESs. However, in recent decades, growing pressures including habitat fragmentation, eutrophication, and heavy metal pollution caused by natural or human-induced factors, have resulted in severe ecosystem degradation and biodiversity loss (He et al., 2014; Qin et al., 2013; Yi et al., 2010; Yi et al., 2011). The current ES development patterns under regional ecosystem modification across the MLYB have proved to be unsustainable (Ouyang et al., 2016; Xu et al., 2014; Zhang et al., 2015). However, the real state of ESs in local MLYB lake ecosystems as well as the dynamic responses to complex environmental changes or ecosystem modifications are topics that remain to be elucidated. Knowledge of these aspects is, however, crucial for future lake management and the well-being of the local population.

We selected eight typical ESs – food, freshwater, land, primary productivity, biodiversity, climate regulating, water purification-I, and water purification-II – to represent the major services provided by shallow lake ecosystems by the combination of two sets of records (documentary records for provisioning services and palaeolimnology data for supporting/regulating services) on two typical MLYB-located lakes. Our aim was to elucidate the long-term dynamics of ESs and their relationship with human activities in coupled socio-ecological systems. Two lakes, Lake Taibai and Lake Zhangdu with different catchment characteristics and various types of disturbances over the 100 years, were chosen for comparison of the responses of ESs patterns with different ecosystem modification/management measures. Our focus was directed at revealing: 1) long-term changes in lake ESs and their driving factors; 2) dynamic relationships (tradeoffs or synergies) among ESs relevant to catchment

background and type of resource usage over the past 100 years; 3) ES patterns within the context of different types resource utilization of socio-ecological systems and the significance for adaptive lake management. We also provided a discussion of the effectiveness and possibility of paleolimnological proxies in reflecting the historical dynamics of ES variations in lakes and the dynamic responses of multiple services to external drivers.

2. Materials and methods

2.1. Study site.

MLYB (Fig.1) is located in the south-east region of China; it covers a total area of 18,400 km² and exhibits more than 600 lakes over 1 km². The area is affected by the East Asian monsoon, and it is cold and dry in winter and hot and wet in summer, with an average annual temperature of 14-18°C and an annual precipitation of 1000-1600 mm (Wang and Dou, 1998).

Fig.1. Location of Lake Taibai and Lake Zhangdu within the Yangtze River Basin.

Lake Taibai (Fig.1, Tab.1) is situated north of Yangtze River and south of Dabie Mountain that borders the Wuxue and Huangmei counties of Huanggang city, Hubei province. The rivers Jingzhu and Kaotian in the north flow into Lake Taibai and drain into the Yangtze River by Lake Longgan in the southeast and Lake Wushan in the west (Liu et al., 2007). In 1951-1955 AD the Meiji sluice was built to control the water from Lake Longgan, and in 1958-1963 AD the Jingzhu, Kaotian and Xianrenba reservoirs were constructed to protect the upstream water supply. In 1976 AD, the Tongsipai sluice gate was constructed to retain the water from Lake Wushan, implying a further blocking of the water connection between Lake Taibai and Yangtze River (Liu et al., 2012). Lake Taibai was formerly much larger than today, diminishing in size from 69.2 km² in the 1930s to 25.1 km² today due to extensive land reclamation during the 1950s-1970s (Liu et al., 2012). There is a long tradition of agricultural activity in the area and grain crops are grown and fishing conducted at the local state-run farms built in the 1950s. However, following the agricultural intensification and transformation of aquaculture to enable higher production in the 1980s and 1990s, respectively, as well as the rapid industrialization and urbanization, Lake Taibai has become eutrophic with consequent resilience loss and extensive deterioration of ecological functions (Liu et al., 2012; Zhao et al., 2016).

Lake Zhangdu (Fig.1, Tab.1) is a typical shallow lake in the Xinzhou district of Wuhan city, Hubei province, situated 1 km to the north of Yangtze River. The main inflow rivers of Lake Zhangdu include the Jushui in the west and the Daoshui in the north, and the outflow drains into the Yangtze River in the south (Wang and Dou, 1998). In the late 1950s AD, with the construction of the Wagou sluice gate, Lake Zhangdu lost its natural connection with Yangtze River, and with the river improvement project conducted at Jushui and Daoshui in the 1970s, Lake Zhangdu was transformed into a reservoir under human control. Together with the construction of water conservancy facilities, more than 100 km² of Lake Zhangdu were reclaimed as land in the 1950s-1970s, leading to a two-thirds reduction of the lake area (Qin et al., 2009). Historically, Lake Zhangdu was rich in natural resources and acted as a traditional transfer place for many rare and valuable migratory birds (Wang and Dou, 1998). However, in recent decades, detrimental impacts from aquaculture, farming and urbanization have accelerated the degradation of the local lake ecosystem with increasing environmental problems as a result. In order to restore the lake and protect wetland resources, the Lake Zhangdu catchment area has been preserved by WWF since 2002 and seasonally reconnected with Yangtze River for nature conservation since 2005 (Yu et al., 2009).

Table 1 Selected lake catchment characteristics of Lakes Taibai and Zhangdu.

	Lake Taibai	Lake Zhangdu
Longitude/latitude	29°56'–30°10'N;115°46'–115°50'E	30°37'–30°42' N;114°40'–114°48'E
Lake area (km ²)	25.1	35.2
Catchment area (km ²)	960	514
Mean lake depth (m)	2.5	1.2
Regional annual precipitation (mm)	1273	1462
Mean temperature (°C)	16.7	16.3
Lake water quality	Hypereutrophic	Eutrophic
Lake core depth (cm)	80	45
Land use/cover	~60% cultivated land in lowlands; ~25% oak forest and secondary pine forest in mountains	~60% cultivated lands; ~8% urbanized land; 3% forests and ~1% wetlands near the lake

2.2. Records on lake ecosystem services.

2.2.1. Documentary records.

We used available documentary records from published papers, fishery farms, and local hydrographic offices to show changes in the provisioning services of Lake Taibai and Zhangdu. Changes have occurred in 1) fishery production – fish provisioning service; 2) water volume – fresh water provisioning service; 3) reclamation history – land provisioning service (see Appendix Tab.A1).

2.2.2. Palaeolimnological records.

We used palaeolimnology records to trace variations of regulating and supporting services of Lake Taibai and Zhangdu. Two sediment cores, TN (80 cm) and ZD (45 cm), were taken with a piston corer in the deepest part of the lakes in 2006 and 2011, respectively (Fig.1). The upper 50 cm of the cores were subsampled with 0.5 cm resolution for both lakes and with 1 cm resolution from 50-80 cm for Lake Taibai. All subsamples were sealed in

plastic bags and transported to the laboratory for further analysis, including ^{210}Pb and ^{137}Cs chronology, physical-geochemical proxies (TOC, DMAR, heavy metals), and bio-identification (diatoms, cladocerans), using standard methods ³⁰⁻³². Five proxies from the two sediment cores were used to describe the major supporting and regulating services of the two lakes: 1) total organic carbon in sediment (TOC) to describe lake primary productivity (supporting service); 2) average values of the diatom and cladoceran (Shannon) biodiversity index after standardization (supporting service); 3) carbon storage (climate regulating service); 4) diatom-inferred TP (water purification-I (regulating) service); and 5) the potential risk index by heavy metals (water purification-II (regulating) service) (see Appendix Tab.A1).

2.3. Environmental parameters.

Climate change and human impacts were extracted to reveal possible impacts of external drivers. As significant external drivers did not exist until the founding of new China in the 1950s, only data covering the recent 50 years were extracted. Instrumental annual climate data (precipitation and temperature) for the past 50 years were collected from the nearest meteorological stations of the two lake basins via the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>). Socio-economic data were collected from statistical yearbooks and documental records (Liu, 2012; Statistics Bureau of Hubei Province 2014; Zeng, 2000), including: GDP, agricultural and industrial output (value), population, grain yields, fertilizer input, arable lands, and information of water conservation facilities in the Taibai and Zhangdu lake basins (see Appendix Fig.A2). Due to incomplete symmetry in chronology between the palaeolimnological proxies and environmental parameters, we downscaled the annual environmental data to match the palaeolimnological proxies in chronology when combining the two for further analysis with mitigating error.

2.4. Data analysis.

In order to show the overall variation of all kinds of ESs, we aggregated the curves of fish/land/freshwater services, primary productivity/biodiversity services, and climate/water purification-I/water purification-II services according to mean values into indexes of provisioning services (PES), supporting services (SES), and regulating services (RES), respectively. Due to the different units and orders of magnitude of each ES, all proxy data for ESs were standardized $((X-X_{\min})/(X_{\max}-X_{\min}))$, to be 0-1) and some data points removed from the aggregated curves in case of lack of temporally matching data. Besides, the median values of standardized ESs in specific periods characterized by different disturbances were extracted to reflect the ES patterns relative to various types of resource utilization over time.

RDA (Redundancy analysis) (Borcard et al., 1992) was used to explore the possible forcing factors (external drivers) leading to the ES changes in Lakes Taibai and Zhangdu. Eight ESs were used as ‘response’ variables and environmental factors (external drivers, including 10 proxies for climate and socio-economic change, dam construction coded as 1-‘before’/0-‘after’ dummy variable) as ‘predictor’ variables. All proxy data were $\log_{10}(x)+3$ transformed prior to ordination analyses to eliminate negative numbers. A gradient length of 0.8 and 0.6 standard deviation (SD) units in Lakes Taibai and Zhangdu suggested that linear-modal methods were suitable for ordination analysis. The explanatory variable with the highest variable inflation factor (VIF) was eliminated until all VIFs were <5 to identify a minimum subset of significant explanatory variables. Monte Carlo permutation tests ($n = 999$ unrestricted permutations) were used to test the significance of each variable. The ordination was performed using the R 3.2.5 (Vegan 2.3-5 package) (Oksanen et al., 2007).

To reveal the variance of ES relationships (tradeoffs and synergies) relative to different kinds of disturbance and resource use, Pearson-correlation analyses between ESs were conducted using R 3.2.5 (Corrplot 0.77 package) (Wei and Simko, 2016).

3. Results

3.1. Variations in ecosystem services in Lake Taibai and Lake Zhangdu during the past 100 years.

Marked changes have occurred in all ESs in the two lakes over the past 100 years (Fig.2). In Lake Taibai, no significant changes in ESs took place in the period 1900-1950, which was characterized by a relatively high level of regulating services and a low level of supporting services/freshwater provisioning services. Subsequently, in 1950-1980, i.e. the “new China” period, substantial changes occurred in most ESs. The provision of land services increased markedly with a pronounced reduction of freshwater provisioning services; all supporting services increased significantly, whereas climate/water purification-II regulating services declined notably. After 1980, the “opening-up” period with reforms, further changes occurred in ESs – the changes in land/freshwater services abated, whereas the provision of fish service increased significantly and water purification services continued to

Fig.2. Changes in ecosystem services in (a) Lake Taibai and (b) Lake Zhangdu during the past 100 years. Dots represent actual values of each proxy and solid lines are curves fitted with Loess Fits at 0.5.

decline. Significant changes in water purification-I services and supporting services were observed, and climate regulating services increased slightly. The changes continued after 2000, with more pronounced trends, not least reflected by increasing fish provision and severely declining water purification-I services.

Overall, Lake Zhangdu showed a relatively similar ES trends as Lake Taibai. In 1900-1950, despite some fluctuations, regulating and freshwater/fish services were relatively high, while supporting services remained low. After 1950, ESs exhibited significant changes. Thus, fish/freshwater/climate/water purification-II services declined, followed by a marked increase in land services, and supporting services increased despite decreasing biodiversity during the last part of the period. In 1980-2000, ES variety tended to decrease – the provision of fish service still exhibited a slight decrease and the changes in land/freshwater services tended to be slow, supporting services increased at a more moderate rate, and there was a sharp decline in water purification-I services. In contrast, the climate regulating services started to increase. After 2000, with the exception of the continued decline in water purification-I services, other ESs tended to be relatively stable.

As to the combined changes in ESs, however, a sustained downwards trend in RES and an upwards trend in SES occurred in both lakes, whereas PES increased in Lake Taibai but declined in Lake Zhangdu due to the differences in fish provisioning services. Besides, although ES changes were insignificant until the 1950s, the variations are not synchronous in time or amplitude in the two lakes. In 1950-1980, the change rates in SES/RES in the two lakes were almost identical, excepting a stronger decline in PES in Lake Zhangdu, but in 1980-2000 the variations in ESs were smaller in Lake Zhangdu than in Lake Taibai (also in PES). After 2000, ESs in Lake Zhangdu were relatively stable with only a slight decline in RES, while more dramatic changes occurred in Lake Taibai.

3.2. The relationship between lake ecosystem services.

In both lakes, a significant correlation between ESs can be traced in the whole time series (Fig.3) and in each specific time period as well (see Appendix Fig.A1). In general, with the exception of a negative correlation between regulating services and freshwater services in both lakes, regulating services correlated negatively with provisioning/supporting services in Lake Taibai, while significant negative relationships were found only for regulating services and supporting services in Lake Zhangdu. For each service, land/primary productivity services correlated negatively with freshwater/water purification-I/water purification-II services in both lakes. Furthermore, a significant negative relationship was traced between fish and water purification-I services in Lake Taibai but not

Fig.3. Correlation analysis of ecosystem services in (a) Lake Taibai and (b) Lake Zhangdu during the recent 100 years; each grid with colored background shows significance at 0.95.

in Lake Zhangdu.

3.3. Factors influencing lake ecosystem services.

RDA ordination revealed the relationship between ESs and human activities in both lakes. In Lake Taibai, five out of 10 available proxies, all with $VIF < 5$, including temperature and precipitation in the past 50 years, fertilizer input, per area grain output, and dam construction, explained 64.1% of total ES. Deleting the two redundant variables, four environmental factors - dam construction, fertilizer input, temperature in the past 50 years, and per area grain output, reflecting the impacts of hydrodynamics, nutrient input, climate change, and the intensity of agriculture, respectively - formed the minimal group of significant variables ($P < 0.01$), capturing 59.0% of the cumulative ES variance (Fig.4a).

In Lake Zhangdu, three of the 10 available proxies, all with $VIF < 5$, including fertilizer input, dam construction, and croplands, explained 67% of total ES variance after significant testing ($P < 0.01$) (Fig.4b). As in Lake Taibai, fertilizer input and dam construction, indicating, respectively, the nutrient input and the change in hydrodynamics, played the key role in ES variation; however, unlike Lake Taibai, croplands influenced by land use change also exerted an important impact on the Lake Zhangdu ESs.

Fig.4. RDA analysis of ecosystem services and forcing factors for (a) Lake Taibai and (b) Lake Zhangdu.

4. Discussion

Following the relatively stable conditions prior to 1950s, major changes occurred in both Lake Taibai and Lake Zhangdu with sudden increases in SES (and PES) in Lake Taibai and pronounced degeneration of regulating services (and PES) in Lake Zhangdu (Fig.2). Most lakes in the Yangtze River basin, being the fastest growing area in China, have exhibited similar development as our two study lakes. Services such as land (in lakeshore)/food (fish)/stable freshwater have been overexploited to meet the growing demand of social development and poverty alleviation through pronounced alterations of lake ecosystems, accompanied, though, by a sharp decline of other, especially regulating, services (Dearing et al., 2012; Xu et al., 2014; Zhang et al., 2015). This development is not unique for China; thus, there are plenty of examples in other regions of the world of a decline or even collapse of ESs following overexploitation of desired lake ESs (Costanza et al., 2014; Jones, 2010; Lade et al., 2015; Peterson et al., 2003; Verschuren et al., 2002).

Our results provide evidence that intensified human activities were the principal forces driving the increased variations in ESs in the two lakes during the past 50 years (Fig.4,5). Firstly, changed hydrology was revealed to be a key driver of ES change in both lakes. In the 1950s-1970s, water conservancy projects were common in China, and almost ~50,000 dams were constructed throughout the Yangtze River basin, and these weakened the historical patterns in hydrodynamics and disconnected most lakes from the Yangtze River (Yang et al., 2011). However, the construction of the Meiji/Tongsipai sluice in Lake Taibai and the Wagou sluice in Lake Zhangdu during this period led to improved primary productivity/biodiversity (services) by promoting the rooting and photosynthesis of aquatic vegetation (Scheffer et al., 1993), while at the same time undermining water purification-II services due

the reduced input of suspended material into the Yangtze River as well as higher sedimentation of heavy metals (Rose et al., 2010; Xue and Yao, 2011). Owing to water conservancy projects, vast lake shore areas were reclaimed for agricultural purposes to improve the provision of land services, and this probably deteriorated the water purification-II services due to increasing soil erosion. Furthermore, fish (in Lake Zhangdu), freshwater, and climate regulating services declined due to the largely diminished lake size (Dong et al., 2012; Du et al., 2011). Secondly, enhanced human-produced nutrient input was another important factor causing variation in ESs. Since the founding of “new China”, and especially the “reform and opening-up” policies in the 1980s, increased fertilizer use due to agricultural intensification, coupled with point and non-point source pollution from industrialization and urbanization (see Appendix Fig.A2), have greatly increased the nutrient input to lakes (Carpenter et al., 2005; Qin et al., 2013), leading to enhanced primary productivity services and sharply declining water purification-I services. It is worth mentioning that also land use change had significant effects on ESs. After 2000, wetland conservation, including ‘returning farmland to lakes’ in Lake Zhangdu, mitigated the deterioration of its regulating services by introducing buffer strips to trap nutrients; however, water purification-I services still declined due to the nutrient surplus caused by intensive agriculture and aquaculture.

Fig.5. ES patterns from (a) Lake Taibai and (b) Lake Zhangdu relative to varied human “modification” of the socio-ecological systems over time.

The temporal changes in ESs in both lakes over the past 100 years confirms significant interactions (tradeoffs or synergies) between ESs (Fig.3). In Lake Taibai, the fulfilled objective of increased land/fish services has markedly modified the lake ecosystem with enhanced provision of primary productivity/biodiversity services

(synergies) but dramatically declining freshwater and regulating services (tradeoffs). In Lake Zhangdu, however, increased land services have deteriorated not only the regulating services but also the fish/freshwater services (tradeoffs). Our analyses further show the dynamic ESs patterns through time in response to four stages of different human disturbances in Lakes Taibai and Zhangdu (Fig.5). Prior to 1950, lake ESs were in a relatively natural state due to low human disturbance, with a high level of regulating services/freshwater provisioning services and a low level of land provision/supporting services. In this period, although freshwater services were sufficient, a less pronounced variation of freshwater services were expected due to frequent severe flooding and drought events. During 1950-1980, multiple water conservancy facilities were constructed followed by large-scale land reclamation of Lake Taibai and Zhangdu. Freshwater services were thus less fluctuating but its provision reduced, while land provisioning services increased to the benefit of the local population, creating a certain increase in supporting services. However, a severe reduction of freshwater provisioning/climate regulating/water purification-II services (tradeoffs) took place. In 1980-2000, the central government encouraged an expansion of human activities seen in the light of the prior 'successful modification', with the goal of boosting the economy and lifting hundreds of millions of people out of poverty. With the intensified agriculture and industrialization, the tradeoffs between water purification services and land/primary productivity increased due to the massive nutrient inputs affecting a chain of ecological processes. Since 2000, utilization of resources in the two lakes has differed. As to Lake Taibai, the relatively poorly developed economy has led to overexploitation of the lake for agricultural and aquacultural purposes, resulting in increasing fish provisioning services and a high level of supporting services but declining regulating services. In contrast, in Lake Zhangdu, the booming economy (see Appendix Fig.A2-per capita GDP) and the environmental degradation led to a call for improving the lake environment, and lake restoration initiatives have been introduced (including wetland conservation and 'seasonal reconnection with the Yangtze River'). This restoration has slowed down the degradation of most ESs; however, water purification-I services have not recovered, as otherwise expected, due to the severity of the degradation.

The examples provided by Lake Taibai and Lake Zhangdu of heavy exploitation of ESs within the recent 100 years show that improved understanding of the dynamic relationship (tradeoffs and synergies) among multiple lake ESs within the socio-ecological system is crucial to optimize the provision of ESs – and this has significant implications for the decisions to be made by lake managers. Due to the dynamic relationships between ESs influenced by human activities in space and time, and their reversibility, all ESs must be considered when developing policies or undertaking 'domestication' to prevent degradation (Rodríguez et al., 2006). For example, failure to prevent the degradation of climate regulating services (carbon storage) may not significantly affect the current wellbeing of the local population but may enhance regional warming with future adverse effects (Chhatre and Agrawal, 2009; Dong et al., 2012). Furthermore, in Lake Taibai, the construction of water facilities created less fluctuating but reduced freshwater services, and the enhanced nutrient input from fertilization in catchments/aquaculture gradually impaired the nutrient cycling due to the time lag in the socio-ecological system. The degradation of water purification-I services lasted until the 1980s and restoration has proved extremely difficult due to resilience loss (Zhao et al., 2016).

The robustness of palaeolimnological data in revealing long-term variance of ecosystem services has been increasingly acknowledged, as has the use of records of sub-fossil chironomids (Howard et al., 2010), diatom fossils (Dearing et al., 2012) and fossil pollen (Macias-Fauria and Willis, 2013) as indicators of water supply, water purification, and important species services. Potential limitations of using palaeolimnological proxies to reconstruct variations in ecosystem services exist, though. Firstly, although multiple palaeolimnological indicators exist, their driving factors are non-unique (Birks and Birks, 2006), and despite the improvement of modern dating methods, dating sediment cores from shallow lakes using ^{210}Pb can be difficult (Appleby, 2001). This implies that

temporal fine-resolution sampling may not suffice to identify ES variation (Likens, 2010). Moreover, the ESs inferred from palaeolimnological indicators cannot be accurately interpreted without knowledge of their geographic background (Birks and Birks, 2006). Despite these shortcomings, palaeolimnological approaches are without doubt a useful complementary tool to contemporary indicators for determining long-term dynamics of ESs.

5. Conclusions

Palaeolimnological and documentary records were combined in this study to reveal long term variance of ecosystem services in two typical Yangtze shallow lake ecosystems. Significant ecosystem services variation of the lakes started in 1950s with gradually increased SES and most PES, while decreased RES. Human impacts, including the change of hydrology and nutrient input, were the main driving factors of the ESs variation in both lakes. When maximize the desired land and fish (in Lake Taibai) services by human “modification” on lake ecosystem, synergies occurred in primary productivity and biodiversity maintenance services, whereas tradeoffs occurred in water-purification I,II and climate regulating services, rendering varied ES patterns with time. Long-term ecosystem service reconstruction based on instrumental and lake sediment records identified relationships between ESs and their response to social-ecological behavior, which may have significant implication for future lake management in the two lakes and their catchments, and beyond.

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References

- Appleby PG. Chronostratigraphic Techniques in Recent Sediments. In: Last WM, Smol JP, editors. Tracking Environmental Change Using Lake Sediments: Basin Analysis, Coring, and Chronological Techniques. Springer Netherlands, Dordrecht, 2001, pp. 171-203.
- Bennett EM, Peterson GD, Gordon LJ. Understanding relationships among multiple ecosystem services. *Ecology Letters* 2009; 12: 1394-404. <http://dx.doi.org/10.1111/j.1461-0248.2009.01387.x>.
- Birks HH, Birks HJB. Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany* 2006; 15: 235-251. <http://dx.doi.org/10.1007/s00334-006-0066-6>.
- Borcard D, Legendre P, Drapeau P. Partialling out the Spatial Component of Ecological Variation. *Ecology* 1992; 73: 1045-1055. <http://dx.doi.org/10.2307/1940179>.
- Carpenter SR, Mooney HA, Agard J, Capistrano D, Defries RS, Diaz S, et al. Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proc Natl Acad Sci U S A* 2009; 106: 1305-12. <http://dx.doi.org/10.1073/pnas.0808772106>.
- Carpenter SR, Pingali PL, Bennett EM, Zurek MB. *Ecosystems and Human well-being: scenarios*, volume 2. 2005.
- Chhatre A, Agrawal A. Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. *Proceedings of the national Academy of sciences* 2009; 106: 17667-17670. <http://dx.doi.org/10.1073/pnas.0905308106>.

351 Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, et al. Changes in the global value
 352 of ecosystem services. *Global Environmental Change* 2014; 26: 152-158.
 353 <http://dx.doi.org/10.1016/j.gloenvcha.2014.04.002>.
 354 Dallimer M, Davies ZG, Diaz-Porras DF, Irvine KN, Maltby L, Warren PH, et al. Historical influences on the
 355 current provision of multiple ecosystem services. *Global Environmental Change* 2015; 31: 307-317.
 356 <http://dx.doi.org/10.1016/j.gloenvcha.2015.01.015>.
 357 Dearing JA, Yang X, Dong X, Zhang E, Chen X, Langdon PG, et al. Extending the timescale and range of
 358 ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin. *Proc*
 359 *Natl Acad Sci U S A* 2012; 109: E1111-20. <http://dx.doi.org/10.1073/pnas.1118263109>.
 360 Dong X, Anderson NJ, Yang X, chen X, Shen J. Carbon burial by shallow lakes on the Yangtze floodplain and its
 361 relevance to regional carbon sequestration. *Global Change Biology* 2012; 18: 2205-2217.
 362 <http://dx.doi.org/10.1111/j.1365-2486.2012.02697.x>.
 363 Du Y, Xue H, Wu S, Ling F, Xiao F, Wei X. Lake area changes in the middle Yangtze region of China over the
 364 20th century. *Journal of environmental management* 2011; 92: 1248-1255.
 365 <http://dx.doi.org/10.1016/j.jenvman.2010.12.007>.
 366 He Q, Bertness MD, Bruno JF, Li B, Chen G, Coverdale TC, et al. Economic development and coastal ecosystem
 367 change in China. *Scientific Reports* 2014; 4: 5995. <http://dx.doi.org/10.1038/srep05995>.
 368 Howard LC, Wood PJ, Greenwood MT, Rendell HM, Brooks SJ, Armitage PD, et al. Sub - fossil Chironomidae as
 369 indicators of palaeoflow regimes: integration into the PalaeoLIFE flow index. *Journal of Quaternary*
 370 *Science* 2010; 25: 1270-1283. <http://dx.doi.org/10.1002/jqs.1409>.
 371 Jeffers ES, Nogu S, Willis KJ. The role of palaeoecological records in assessing ecosystem services. *Quaternary*
 372 *Science Reviews* 2015; 112: 17-32. <http://dx.doi.org/10.1016/j.quascirev.2014.12.018>.
 373 Jones B. *Economic Value of Lake Ecosystem Services*. spring 2010; 22.
 374 Lade SJ, Niiranen S, Hentati-Sundberg J, Blenckner T, Boonstra WJ, Orach K, et al. An empirical model of the
 375 Baltic Sea reveals the importance of social dynamics for ecological regime shifts. *Proceedings of the*
 376 *National Academy of Sciences* 2015; 112: 11120-11125. <http://dx.doi.org/10.1073/pnas.1504954112>.
 377 Likens GE. *Lake Ecosystem Ecology: A Global Perspective*: Academic Press, 2010.
 378 Liu E, Yang X, Shen J, Dong X, Zhang E, Wang S. Environmental response to climate and human impact during
 379 the last 400 years in Taibai Lake catchment, middle reach of Yangtze River, China. *Science of the Total*
 380 *Environment* 2007; 385: 196-207. <http://dx.doi.org/10.1016/j.scitotenv.2007.06.041>.
 381 Liu Q. Ecological response of Taibai Lake to natural and anthropogenic forcing during the last 200 years. *Physical*
 382 *geography*. Doctor. Graduate School of Chinese Academy of Sciences, 2012.
 383 Liu Q, Yang X, Anderson NJ, Liu E, Dong X. Diatom ecological response to altered hydrological forcing of a
 384 shallow lake on the Yangtze floodplain, SE China. *Ecohydrology* 2012; 5: 316-325.
 385 <http://dx.doi.org/10.1002/eco.222>.
 386 Macias-Fauria M, Willis KJ. Landscape planning for the future: using fossil records to independently validate
 387 bioclimatic envelope models for economically valuable tree species in Europe. *Global Ecology and*
 388 *Biogeography* 2013; 22: 318-333. <http://dx.doi.org/10.1111/j.1466-8238.2012.00781.x>.
 389 Millennium Ecosystem Assessment. *Ecosystems and Human Well-being: Synthesis*. In: Assessment ME, editor.
 390 Island Press, Washington, DC, 2005.
 391 Oksanen J, Kindt R, Legendre P, Hara BO, Henry M, Stevens H. The vegan package. *Community Ecology*
 392 *Package* 2007.
 393 Ouyang Z, Zheng H, Xiao Y, Polasky S, Liu J, Xu W, et al. Improvements in ecosystem services from investments
 394 in natural capital. *Science* 2016; 352: 1455-1459. <http://dx.doi.org/10.1126/science.aaf2295>.

395 Peterson GD, Beard Jr TD, Beisner BE, Bennett EM, Carpenter SR, Cumming GS, et al. Assessing future
 396 ecosystem services: a case study of the Northern Highlands Lake District, Wisconsin. *Conservation*
 397 *Ecology* 2003; 7: 1.
 398 Qin B, Gao G, Zhu G, Zhang Y, Song Y, Tang X, et al. Lake eutrophication and its ecosystem response. *Chinese*
 399 *Science Bulletin* 2013; 58: 961-970. <http://dx.doi.org/10.1007/s11434-012-5560-x>.
 400 Qin Y, Booth RK, Gu Y, Wang Y, Xie S. Testate amoebae as indicators of 20th century environmental change in
 401 Lake Zhangdu, China. *Fundamental and Applied Limnology/Archiv für Hydrobiologie* 2009; 175: 29-38.
 402 <https://doi.org/10.1127/1863-9135/2009/0175-0029>.
 403 Renard D, Rhemtulla JM, Bennett EM. Historical dynamics in ecosystem service bundles. *Proceedings of the*
 404 *National Academy of Sciences* 2015; 112: 13411-13416. <http://dx.doi.org/10.1073/pnas.1502565112>.
 405 Rodríguez JP, Beard TD, Bennett EM, Cumming GS, Cork SJ, Agard J, et al. Trade-offs across space, time, and
 406 ecosystem services. *Ecology and society* 2006; 11: 28. <http://dx.doi.org/10.2307/2390206>.
 407 Rose NL, Morley D, Appleby PG, Battarbee RW, Alliksaar T, Guilizzoni P, et al. Sediment accumulation rates in
 408 European lakes since AD 1850: trends, reference conditions and exceedence. *Journal of Paleolimnology*
 409 2010; 45: 447-468. <http://dx.doi.org/10.1007/s10933-010-9424-6>.
 410 Scheffer M, Hosper S, Meijer M, Moss B, Jeppesen E. Alternative equilibria in shallow lakes. *Trends in ecology &*
 411 *evolution* 1993; 8: 275-279. [http://dx.doi.org/10.1016/0169-5347\(93\)90254-M](http://dx.doi.org/10.1016/0169-5347(93)90254-M).
 412 Statistics Bureau of Hubei Province Statistical Yearbook of Hubei Province 2014. Beijing: China Statistics Press,
 413 2014.
 414 Swetnam TW, Allen CD, Betancourt JL. Applied historical ecology: using the past to manage for the future.
 415 *Ecological applications* 1999; 9: 1189-1206.
 416 [http://dx.doi.org/10.1890/1051-0761\(1999\)009\[1189:AHEUTP\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(1999)009[1189:AHEUTP]2.0.CO;2).
 417 Tomscha SA, Gergel SE. Ecosystem service trade-offs and synergies misunderstood without landscape history.
 418 *Ecology & Society* 2016; 21. <http://dx.doi.org/10.5751/ES-08345-210143>.
 419 Tomscha SA, Sutherland IJ, Renard D, Gergel SE, Rhemtulla JM, Bennett EM, et al. A Guide to Historical Data
 420 Sets for Reconstructing Ecosystem Service Change over Time. *BioScience* 2016; 66: 747-762.
 421 <http://dx.doi.org/10.1093/biosci/biw086>.
 422 Verschuren D, Johnson TC, Kling HJ, Edgington DN, Leavitt PR, Brown ET, et al. History and timing of human
 423 impact on Lake Victoria, East Africa. *Proc Biol Sci* 2002; 269: 289-94.
 424 <http://dx.doi.org/10.1098/rspb.2001.1850>.
 425 Wang SM, Dou HS. *Lakes in China*. Beijing: Science press, 1998.
 426 Wei T, Simko V. Package ‘corrplot’. *Statistician* 2016; 56: 316-324.
 427 Xu X, Tan Y, Chen S, Yang G. Changing patterns and determinants of natural capital in the Yangtze River Delta
 428 of China 2000-2010. *Sci Total Environ* 2014; 466-467: 326-37.
 429 <http://dx.doi.org/10.1016/j.scitotenv.2013.07.043>.
 430 Xue B, Yao S. Recent sedimentation rates in lakes in lower Yangtze River basin. *Quaternary International* 2011;
 431 244: 248-253. <http://dx.doi.org/10.1016/j.quaint.2011.01.003>.
 432 Yang SL, Milliman JD, Li P, Xu K. 50,000 dams later: Erosion of the Yangtze River and its delta. *Global and*
 433 *Planetary Change* 2011; 75: 14-20. <http://dx.doi.org/10.1016/j.gloplacha.2010.09.006>.
 434 Yi Y, Yang Z, Zhang S. Ecological influence of dam construction and river-lake connectivity on migration fish
 435 habitat in the Yangtze River basin, China. *Procedia Environmental Sciences* 2010; 2: 1942-1954.
 436 <http://dx.doi.org/10.1016/j.proenv.2010.10.207>.

437 Yi Y, Yang Z, Zhang S. Ecological risk assessment of heavy metals in sediment and human health risk assessment
 438 of heavy metals in fishes in the middle and lower reaches of the Yangtze River basin. *Environ Pollut*
 439 2011; 159: 2575-85. <http://dx.doi.org/10.1016/j.envpol.2011.06.011>.
 440 Yu X, Jiang L, Li L, Wang J, Wang L, Lei G, et al. Freshwater management and climate change adaptation:
 441 Experiences from the central Yangtze in China. *Climate and Development* 2009; 1: 241-248.
 442 <http://dx.doi.org/10.3763/cdev.2009.0023>.
 443 Zeng F. *Water resources annals (Hubei Province)*. Beijing: China Water Power Press, 2000.
 444 Zhang K, Dearing JA, Dawson TP, Dong X, Yang X, Zhang W. Poverty alleviation strategies in eastern China
 445 lead to critical ecological dynamics. *Science of The Total Environment* 2015; 506-507: 164-181.
 446 <http://dx.doi.org/10.1016/j.scitotenv.2014.10.096>.
 447 Zhao Y, Wang R, Yang X, Dong X, Xu M. Regime shifts in Taibai Lake's ecosystem during the last century.
 448 *Journal of Lake Sciences* 2016; 28: 1381-1390. <http://dx.doi.org/10.18307/2016.0624>.

449

Appendix A

Table A1. Quantified lake ecosystem services explaining temporal variations.

Ecosystem service		Proxies		Data source/Interpretation
		Documentary records	Palaeolimnological proxies	
Provisioning services	Fish	Fish production per year		Data sources: public papers (Li-Yin et al., 2006; Li-Yin et al., 2006) and aquaculture reports from Lake Taibai and Lake Zhangdu fishing farms (<i>unpublished data</i>).
	Freshwater	Water volume		Data source: local hydrographic offices, water resources yearbooks (Zeng, 2000).
	Land	Lake area by reclamation		Data source: public papers (Liu, 2012; Wang et al., 2005), Huangmei county annals (Huangmei local government, 1985), Wuhan local chronicles (Zou, 1992).
Supporting services	Primary productivity		Total organic carbon in sediment	Relatively high values signify high primary production (Castañeda et al., 2011).
	Biodiversity		Average of diatom and cladoceran Shannon-diversity	Relatively high values signify high diversity of diatoms (Dearing et al., 2012) and cladocerans (Jeppesen et al., 2001).
	Climate		Carbon storage per year	The extent of carbon burial in lakes acts as a proxy of climate regulation; relatively high values signify high ability of climate regulation (Dong et al., 2012; Jeffers et al., 2015).
Regulating services	Water purification-I		Total phosphorus inferred from diatoms	Using transfer function, past TP concentrations in lake water can be inferred from sedimentary pigments and used as an indicator of the water purification regulating ability; high values reflect relative loss of water purification-I (Anderson et al., 1993; Dearing et al., 2012).
	Water purification-II		Potential risk of heavy metal pollution	Heavy metal concentrations in sediments in consequence of human contamination are important proxies reflecting potential risk of water purification loss; high values reflect relative loss of water purification-II (Liu et al., 2012; Renberg, 1986).

Fig.A1. Correlation analysis of ecosystem services of (a) Lake Taibai and (b) Lake Zhangdu over time; each correlation coefficient is significant at $p=0.05$ (large dots = higher significance). Gray grid indicates lack of data.

Fig.A2. Climate and socio-economic records showing the external drivers of (a) Lake Taibai and (b) Lake Zhangdu; data from statistical yearbooks and documental records in Huangmei County and Wuhan City (alternatively from Xinzhou County) within the recent 50 years (1949-2014AD), respectively.

Appendix A References

- Anderson NJ, Rippey B, Gibson CE. A comparison of sedimentary and diatom-inferred phosphorus profiles: implications for defining pre-disturbance nutrient conditions. *Hydrobiologia* 1993; 253: 357-366.
- Castañeda IS, Werne JP, Johnson TC, Powers LA. Organic geochemical records from Lake Malawi (East Africa) of the last 700 years, part II: Biomarker evidence for recent changes in primary productivity.

467 Palaeogeography, Palaeoclimatology, Palaeoecology 2011; 303: 140-154.
 468 <http://dx.doi.org/10.1016/j.palaeo.2010.01.006>.

469 Dearing JA, Yang X, Dong X, Zhang E, Chen X, Langdon PG, et al. Extending the timescale and range of
 470 ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin. Proc
 471 Natl Acad Sci U S A 2012; 109: E1111-20. <http://dx.doi.org/10.1073/pnas.1118263109>.

472 Dong X, Anderson NJ, Yang X, chen X, Shen J. Carbon burial by shallow lakes on the Yangtze floodplain and its
 473 relevance to regional carbon sequestration. Global Change Biology 2012; 18: 2205-2217.
 474 <http://dx.doi.org/10.1111/j.1365-2486.2012.02697.x>.

475 Huangmei local government. Huangmei county annals. Wuhan: Hubei People's Publishing House, 1985.

476 Jeffers ES, Nogu S, Willis KJ. The role of palaeoecological records in assessing ecosystem services. Quaternary
 477 Science Reviews 2015; 112: 17-32. <http://dx.doi.org/10.1016/j.quascirev.2014.12.018>.

478 Jeppesen E, Leavitt P, De Meester L, Jensen JP. Functional ecology and palaeolimnology: using cladoceran
 479 remains to reconstruct anthropogenic impact. Trends in Ecology & Evolution 2001; 16: 191-198.

480 Li-Yin LI, Zhao-Hui NI, Yun-Feng LI, Hui-Bi WU, Peng GY. Investigation of wetland protection and optimized
 481 fishery production model of Zhangdu Lake. Resources & Environment in the Yangtze Basin 2006; 15:
 482 366-371.

483 Li-Yin LI, Zhao hui NI, Yun feng LI, Hui-Bi WU. An Investigation on the Fishery Resource and Fish Diversity of
 484 Zhangduhu Lake. Freshwater Fisheries 2006.

485 Liu E, Birch GF, Shen J, Yuan H, Zhang E, Cao Y. Comprehensive evaluation of heavy metal contamination in
 486 surface and core sediments of Taihu Lake, the third largest freshwater lake in China. Environmental Earth
 487 Sciences 2012; 67: 39-51. [10.1007/s12665-011-1478-x](https://doi.org/10.1007/s12665-011-1478-x).

488 Liu Q. Ecological response of Taibai Lake to natural and anthropogenic forcing during the last 200 years. Physical
 489 geography. Doctor. Graduate School of Chinese Academy of Sciences, 2012.

490 Renberg I. Concentration and annual accumulation values of heavy metals in lake sediments: Their significance in
 491 studies of the history of heavy metal pollution. Hydrobiologia 1986; 143: 379-385.

492 Wang LM, Hui-Jian HU, Wang D. Ecological impacts of disconnection from the Yangtze on fish resources in
 493 Zhangdu Lake. Resources & Environment in the Yangtze Basin 2005; 14: 287-292.

494 Zeng F. Water resources annals. Beijing: China Water Power Press, 2000.

495 Zhou, XW. Wuhan local chronicles. Wuhan: Wuhan University Press, 1992.

Documentary record

Sedimentary Proxies

Palaeolimnological record

Assessment on Long-term Ecosystem Services

Before 1950 → 1950-1980 → 1980-2000 → 2000-2010s

Ecosystem service type

V1-Food provision

V4-Primary productivity

V7-Water purification-I

V2-Land provision

V5-Biodiversity

V8-Water purification-II

V3-Freshwater provision

V6-Climate regulating