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Using palaeolimnological data and historical records to assess long-term dynamics of ecosystem services in typical Yangtze shallow lakes (China)

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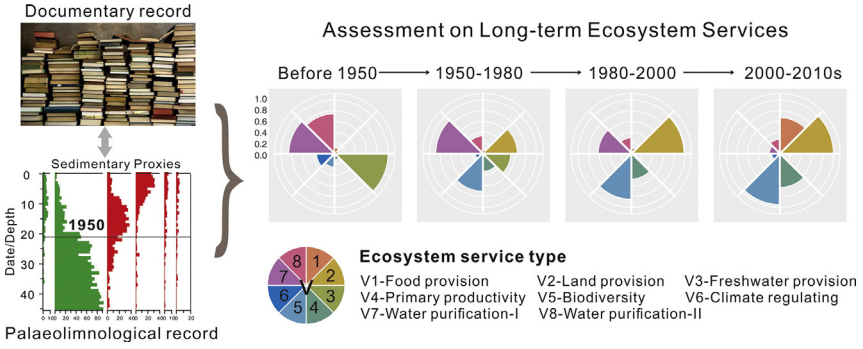
HIGHLIGHTS

- Long-term patterns of lake ecosystem services (ESs) are crucial for lake management.
- Both palaeolimnological and documentary records revealed ES variations in Yangtze lakes.
- Provisioning and regulating services have exhibited both tradeoff and synergy since 1900s.
- Human activities were the main drivers of the long-term changes of lake ESs.

GRAPHICAL ABSTRACT



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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 variations and dynamic interactions in ESs, especially supporting/regulating services, which are not easily quantified by documentary records. To elucidate the variations between eight important ESs in shallow lake ecosystems, we combined documentary records with palaeolimnological proxies (covering the past 100 years) from two typical lakes (Lakes Taibai and Zhangdu) of the Yangtze River basin. Although all supporting services and some 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 change, were identified as the main factors behind the observed variations. Both in Lake Taibai and Zhangdu, primary production and biodiversity (supporting services) have increased (synergies), whereas climate and water purification (regulating services) have significantly decreased (tradeoffs) since the 1950s when attempts were made by the local population to reach a higher land/fish ESs level. By considering long-term records, dynamic tradeoff and synergy relationship between various ESs relative to different types of human "modification" in a temporal perspective, we suggest valuable information can be gained in future lake management initiatives.

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1. Introduction

Ecosystem services (ESs) are the benefits that people derive from ecosystems, including provisioning services (PES, the products obtained from ecosystems), supporting services (SES, those that are necessary for the production of all other ecosystem services), regulating services (RES, the benefits obtained from the regulation of ecosystem processes) and culture services (CES, the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences) according to their function (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 result 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 (Liu, 2012; 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 these 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: >50 different palaeoenvironmental proxies have been mapped to a wide range of ES categories and subcategories, and the effectiveness of these in assessing the persistence of, especially, SES/RES across a variety of time scales has been substantiated (Dearing et al., 2012; Jeffers et al., 2015). Furthermore, with historical topographical maps/documentary 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 (Dallimer et al., 2015; Renard et al., 2015; Tomscha and Gergel, 2016). Despite the fact that it is 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 on many ecosystems, practical challenges in using proxy records for direct reconstruction of historical ESs, and the limitation of temporal data available to reflect the dynamics in ESs since 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), and ecosystem modification across the MLYB have promoted unsustainable development patterns (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.

In our study we aimed 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 during a 100-year period, were chosen for comparison of the responses of ESs to different ecosystem modification/management measures. We selected eight typical and major ESs services obtained from shallow lakes – fish provisioning service, freshwater provisioning service, land provisioning service, primary productivity supporting service, biodiversity supporting service, climate regulating service, water purification-I regulating service, and water purification-II regulating service – and combined two sets of records (documentary records for PES and palaeolimnological data for SES and RES) to document the development patterns in these two typical MLYB-located lakes (Assessment, 2005; de Groot et al., 2012). 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 relative to catchment characteristics and various types of disturbances over the past 100 years; 3) ES patterns within the context of ecosystem modification and the implementation of these in adaptive lake management. We also discussed the effectiveness and possibility of using palaeolimnological proxies to detect 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 km^2 and holds >600 lakes over 1 km^2. 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 (Renberg, 1986; Wang and Dou, 1998).

Lake Taibai (Fig. 1, Table 1) is situated north of Yangtze River and south of the 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., 2012b). Lake Taibai was formerly much larger than today, diminishing in size from 69.2 km^2 in the 1930s to 25.1 km^2 today due to extensive land reclamation during the 1950s–1970s (Liu et al., 2012b). 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., 2012b; Zhao et al., 2016).

Lake Zhangdu (Fig. 1, Table 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

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