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Detection of regime shifts in a shallow lake ecosystem based on multi-proxy paleolimnological indicators

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ABSTRACT

There have been significant regime shifts in the ecosystem structure and function in a large number of lakes worldwide due to the increasing human disturbance and climate change in recent decades. It has become a critical issue in lake conservation and management to identify the characteristics of regime shifts in lakes and explore potential early-warning signals prior to regime shifts. However, research on identifying and predicting regime shifts in lakes is still a difficult task since recent modelling approaches cannot fully grasp the non-linear processes among multiple ecosystem components and the ecological time series data are too scarce to support the detection in most lakes. In this study, multi-proxy paleolimnological records were used to obtain long time-series ecological data and determine the inflection points of regime shifts in the Baiyangdian Lake, northern China. First, the sediment chronology was established, and macrophyte pollen as well as nutrient conditions in each dated sediment layer were identified. Then the heuristic segmentation algorithm and Pettitt test were used to determine the most significant inflection points of regime shifts. Additionally, multiple early-warning indicators including variance, autocorrelation and skewness were used to test their ability to forecast the major ecosystem regime shift. Results show that the most important abrupt change in the Baiyangdian Lake occurred in the early 1960s. The increasing variance coupled with decreasing autocorrelation and skewness started in 1–16 years before this regime shift, which is consistent with a flickering phenomenon rather than critical slowing down. The detection results of regime shifts and early-warning signals can provide valuable reference information for the lake management and aquatic ecosystem conservation.

1. Introduction

Lakes as the key node of the hydrologic cycle and ecological processes in the watershed have played an important role in providing water resources, controlling floods, and maintaining the regional ecological balance. In recent decades, the water cycle and ecosystem status have altered significantly in a large number of lakes worldwide due to the increasing impacts of human disturbance and climate change (Arthington et al., 2010; Arnell and Gosling, 2013). Although the response of lake ecosystems to external disturbance is usually a gradual changing process, strong enough disturbances which overwhelmed the lakes' recovery ability could accelerate the ecological deterioration and lead to regime shifts of lake ecosystems (Cai et al., 2011; Poff and Zimmerman, 2010). Recent studies have shown that shallow lake ecosystems have generally exhibited alternative stable states (Scheffer et al., 2001). As for the shallow lake ecosystems, there are usually two mutually convertible stable states, i.e., the aquatic macrophyte-dominated clear water state and the phytoplankton-dominated turbid water state (Liu et al., 2013; Scheffer et al., 2001). An abrupt change from a clear water state to a turbid water state occurs when the perturbation (e.g., nutrient loads) passes a critical threshold, leading to sudden changes in the material and energy flows as well as the structure and function of lake ecosystems (Theissen et al., 2012). For example, eutrophication can lead to a severe loss of abundance and diversity of submerged macrophytes (Paillisson and Marion, 2011).

Exploring the characteristics and potential early-warning signals of the abrupt changes or regime shifts in lakes has become a critical issue in the lake conservation and management (Marín et al., 2014). However, it is still a difficult task to identify and predict the inflection points in lake ecosystems due to the incomplete understanding of inherent processes in the real lake ecosystems and the lack of long time series high-resolution data (Eason et al., 2014; Lindegren et al., 2012). On the one hand, it is difficult to fully grasp the complex relationship and non-linear processes among multiple ecosystem components, which often leads to inaccurate forecasting results (Cai et al., 2009; Zhao et al., 2013). On the other hand, various ecosystems differ greatly in the

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structures and functions, and the feature of regime shifts in special ecosystems may be fit for only a few unique ecosystems, which often leads to the poor universality of the existing early warning models (Yue et al., 2016). Additionally, the lack of long time series data with satisfactory resolution greatly hampers the detection in most lakes worldwide. Moreover, before fully understanding the mechanism of regime shifts in ecosystems and establishing reliable predictive models, some common indicators have been proved to be useful for monitoring whether the ecosystem state is close to a mutation threshold (deYoung et al., 2008; Qi et al., 2016). Previous studies show that many ecosystems before the critical transition exhibit similar characteristics or a series of general properties, which can be used as “early warning indicators” to predict whether the ecosystems have a trend of critical transition (Scheffer et al., 2009). For example, the variance of system status variables will increase when the system fluctuates more dramatically near the equilibrium status (Carpenter and Brock, 2006). The slower recovery rate before critical transition may also be signaled by the increasing trend of autocorrelation and skewness (Wang et al., 2012).

Paleolimnological technology has been widely applied to obtain long time-series ecological data for coping with the problems of data deficiencies, which can also provide evidence of influence of climate change and human disturbance on regime shifts of lake ecosystems (Sayer et al., 2012). Paleolimnological techniques, which use various ecological indicators such as pollen, diatoms, chironomids and ostracods, have been widely used to reconstruct historical ecological conditions, detect trends of climate change and evaluate the lake eutrophication (Costa-Böddeker et al., 2012; Garreta et al., 2012; Wischnewski et al., 2011). Among these ecological indicators, macrophyte pollen can effectively represent the growth states of aquatic plants and reflect historical environmental conditions of lakes (Davidson et al., 2010; Salgado et al., 2010). This paper presents a case study on the nature of regime shifts in the Baiyangdian Lake with multi-proxy paleolimnological data. First, the sediment chronology was established, and macrophyte pollen as well as nutrient concentration in each dated sediment layer were identified. Then the heuristic segmentation algorithm and Pettitt test were used to determine the most significnat inflection points of regime shifts. Additionally, multiple early-warning indicators including variance, autocorrelation and skewness were used to test their ability to forecast the major mutation in the lake ecosystem. The detection results of regime shifts and early-warning signals can provide valuable reference information for the lake management and aquatic ecosystem conservation.

2. Materials and methods

2.1. Site description

The Baiyangdian Lake (between 38°43′ − 39°02′N, 115°38′ − 116°07′E) is the largest plant-dominated freshwater lake in the North China Plain, with the largest surface area of about 366 km^2 (Fig. 1). Historically, eight rivers including the Zhulong, Xiaoyi, Tang, Fu, Cao, Pu, Ping, and Baigou River flowed into the Baiyangdian Lake, and the average annual water level ranged from 5.2 m to 11 m during 1919 and 2012 (the average elevation of the lake bottom is 5.2 m). This lake has irreplaceable ecological and social functions such as regulating water cycle, supporting high biological productivity and biodiversity and maintaining ecological balance of its surroundings regions (Yang and Yang, 2013). A large number of submerged and emerged plants are dominant in this lake, and the main species include *Poaceae*, *Typhaceae*, *Polygonaceae*, *Nymphaeceae*, *Ranunculaceae*, *Gentianaceae*, *Cruciferae*, *Potamogetonaceae*, *Cyperaceae*, and *Haloragaceae*.

The annual average water inflow of the Baiyangdian Lake has generally decreased since the late 1950s due to climate change as well as the flow regulation of three large dams (Xidayang Reservoir, Wangkuai Reservoir and Angezhuang Reservoir) in its upper reaches. For example, the inflow of the Baiyangdian Lake in the 1950s, 1960s, 1970s, 1980s, 1990s and 2000s was 1.94, 1.90, 1.03, 0.20, 0.43 and 0.10 billion m^3, respectively. Low or no inflows caused the decreasing water level and increasing concentration of pollutants (Yang et al., 2014). It is an urgent issue in supporting lake management to explore how variation of hydrological conditions and water quality degradation influenced the variation of ecological states of the Baiyangdian Lake.

2.2. Sediment sampling and radiometric dating

Recently, some parts in the Baiyangdian Lake have suffered from considerable human disturbance such as dredging and planting. In order to guarantee the collected sediment core can accurately record historical conditions, a stable region with less human activities was selected as the sampling site. In this study, four sites were firstly identified as candidates with Google Earth and field investigation; then, lithological characteristics (color and grain) in the trial core (40 cm length) collected in each site were compared, the corresponding site of which shows the consistent trend and clear grain is fit for this study. Finally, a 95 cm deep sediment core was collected with a gravity corer in the Shaochedian sampling site in June 2012. The core was cut into 1 cm intervals in the field and saved in plastic bags at 4 °C before returning to the laboratory. In the laboratory, each section was freeze dried into constant weight of about 15–30 g for further treatment.

Dating of the sediment core from the Shaochedian sampling site used ^{210}Pb and ^{137}Cs dating techniques. The ^{210}Pb is a natural radionuclide, which can be used to date sediments from the last 100–150 years. ^{137}Cs is an artificial radionuclide, and ^{137}Cs in the sediment profile was caused by nuclide scattering events including nuclear weapon testing in 1963 and 1974–1975 (Álvarez-Iglesias et al., 2007), the Chernobyl accident in 1986, and the Fukushima Daiichi nuclear disaster in 2011. Therefore, ^{137}Cs can be applied for dating for the last 50 years (Seddon et al., 2012). In this study, all of the sediment intervals were analyzed for ^{210}Pb and ^{137}Cs with direct gamma spectrometry at the Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences. The ^{210}Pb chronology was calculated based on the constant rate supply model (CRS model; Appleby and Oldfield, 1978). Profiles of ^{137}Cs activities in the sediment core were applied to validate the ^{210}Pb chronology. The result of ^{210}Pb dating was further verified with peak ^{137}Cs values across the whole sediment core (Bigelow and Edwards, 2001).

2.3. Analysis of macrophyte pollen and environmental factors

The Baiyangdian Lake is a typical plant-dominated lake, and biomass of macrophytes accounted for the largest portion of the whole lake ecosystem (Yang et al., 2014). Changes of abundance and composition of macrophytes are essential for the material cycle and energy flow among species in upper trophic levels; meanwhile, since macrophytes have a good absorbing ability of nutrients in the water body, it can also influence the water quality of the lake (Zhao et al., 2012). Macrophyte pollen was selected as the ecological indicator in this study because it can reflect the abundance and composition of macrophytes during the historical period in a lake (Davidson et al., 2005). In this study, 5 g subsamples from each 47 samples (taken at 2 cm intervals from 1 to 95 cm) were treated to extract pollen according to the standard procedure (Faegri and Iversen, 1989) in the Pollen Analysis Laboratory at Hebei Normal University. First, the samples were sieved through 200 μm mesh screens to remove small animals and plant fragments, and one tablet containing 27637 ± 563 *Lycopodium* spores was added as a tracer to each sample for estimating pollen concentration and accumulation rates. Then, samples were treated with 10% HCl, 10% NaOH, and 40% HF reagent, washed with distilled water, and sieved through 10 μm mesh screens. Thereafter, the samples were floated with gravity liquid, and the suspensions were centrifuged and acetolysed before being mounted on slides for counting. A BX-51 Olympus light

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