



## Exploring change of internal nutrients cycling in a shallow lake: A dynamic nutrient driven phytoplankton model



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### ABSTRACT

Lake eutrophication is associated with excessive nutrient enrichment and unobserved internal nutrient cycling. In spite of advances in understanding the role of nitrogen (N) and phosphorus (P) cycling in eutrophication, the relative importance of N and P limitation and release from sediment is still an open question. The complicated interaction between N and P cycling and external driving factors leads to dynamics in N or P limitation patterns and internal release that change over time. We developed a nutrient-driven model of phytoplankton dynamics including the critical nutrient cycling processes. It was fitted using Bayesian inference to explore the roles of N and P inputs from external sources, net sediment release, and internal dynamics in Lake Yilong, a shallow eutrophic lake in China. The model provided a good fit to observations, with time-varying parameters required to fit time-dependent variations in the sediment release process. The results demonstrated that, in Lake Yilong, the pattern of nutrient limitation showed a transformation from P limitation to N and P co-limitation after an observed regime shift occurred in 2008. After the shift in 2008, sediment release had an increasing influence on N and P supply, which could make eutrophication remediation more difficult. For Lake Yilong, it would not be possible to reverse eutrophication solely with watershed nutrient load reduction so in-lake manipulation of physical-chemical conditions to inhibit the sediments release should also be considered.

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### 1. Introduction

Eutrophication is a widely studied regime shift in freshwater ecosystems (Carpenter and Lathrop, 2008; Donangelo et al., 2010), usually characterized by unsuspected excessive primary biomass production, low oxygen, decrease of submerged macrophyte, and increased frequency of anoxic events. The dynamics of nutrients, principally nitrogen (N) and phosphorus (P), are the key ecological processes in lakes due to their physiological importance and their influence on rates of primary production (Carpenter, 2005; Ruan et al., 2014). In addition to natural sources, N and P enrichment from watersheds as well as internal release from sediments could also lead to high phytoplankton biomass and turbid water (Imboden, 1974; Carpenter et al., 1985).

The relative importance of N or P limitation and internal release from sediment is still an open question (Smith, 2003; Elser et al.,

2007; Elser et al., 2009; Banaszuk et al., 2011; Søndergaard et al., 2013; Shan et al., 2014). Based on Liebig's Law of the Minimum on algae biomass, N or P limitation is regarded as the key factor for determining algae changes in lakes (Hiddink and Kaiser, 2005; Perini and Bracken, 2014). Such importance of nutrient kinetics in regulating competition and distribution of algae species has stimulated considerable studies on the N or P limitation of lake productivity (Dugdale, 1967; Wyatt et al., 2014). Over the past several decades, the emphasis on controlling eutrophication in freshwater has been focused heavily on decreasing P inputs from external sources (Elser et al., 2007; Schindler et al., 2008). However, the supposed primacy of P limitation of lake productivity has been challenged by some studies showing frequent phytoplankton N limitation in lakes (Elser et al., 2007; Elser et al., 2009). The relative importance of N or P as limiting nutrients will change dynamically due to the coupled interactions between N and P cycling and the food web, dynamically changing forcing (e.g. hydrological conditions.), and relative magnitude of various routes of nutrient supply (Carpenter et al., 1992; Small et al., 2013; Suddick et al., 2013). It is therefore, necessary to conduct temporal analyses of the dynamics of N and P limitation to determine more effective nutrient management strategies.

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Eutrophication remediation efforts, aiming at water quality improvement as well as primary production reduction, generally focus on reducing external sources such as wastewater treatment plant efficiency and non-point agricultural runoff. Some lakes respond rapidly to such reductions (Sas et al., 1989), but a delay in recovery always exists in other cases (Scharf, 1999; Jeppesen et al., 2002). One of the reasons for delay is that N and P may accumulate in lake sediment during heavy loading periods and are released from sediment into the overlying water after external loading reduction. The sediment release may be so great and long lasting that it prevents any improvement of water quality for a considerable period (Jeppesen et al., 2005). The deep lakes, with anoxic hypolimnion during summer, were believed to suffer from internal nutrient loading due to redox-dependent nutrient (Surridge et al., 2007). In contrast, even if well-oxidized conditions throughout the whole water column in shallow lakes could prevent nutrient release, numerous studies showed that sediment also release P even if the overlying water is aerobic (Auer et al., 1993; Lee et al., 1977). Moreover, sediment is in direct contact with overlying water with a higher sediments surface per volume of water as water depth decreases (Søndergaard et al., 2001). All these characteristics increase the importance of sediment–water interactions in shallow lakes. Nutrients from the sediment contribute to a substantial part of the total nutrients loading and sometimes even exceed the external loading (Boers et al., 1998). For shallow lakes, considering the delay effect of sediment release as well as different recovery method to reduce internal release (e.g. dredge), the role of sediment release must be considered (Gächter, 1987; Auer et al., 1993).

Both experimental and modeling approaches are key parts of explorations of lake nutrient dynamics (Scheffer et al., 2009; Liu et al., 2011). Experimental evidence is able to reveal the real status of a system by direct observation, while the internal processes are usually poorly monitored. So observations might not reflect the coupling effects and dynamic change of different process in nutrient cycling in lakes (Fennel et al., 2009). Mathematical modeling based on existing knowledge of relevant biogeochemical mechanisms and their interactions is a valuable tool to explore the dynamic of nutrient cycling. Simple model-based frameworks tested against observations are playing a larger role in understanding lake dynamics and have been proved to be a cost effective way to uncover the N or P dynamics that inform decision making (Carpenter and Lathrop, 2008; Gudimov et al., 2012; Wyatt et al., 2014). Imboden (1974) has developed a two-box input and output model to explore the water column P mass balance and consequently determine the internal loading. A steady-state mass balance based model was developed to evaluate the effect of the N export fraction on external N loading in lakes (Ruan et al., 2014). Choosing appropriate models without system-specific knowledge and parameter estimation as well as uncertainty analysis are challenging, but much can be accomplished by framing the implicit assumptions into equations and using a Bayesian approach. Scavia et al. (2006) used a simple Streeter–Phelps model to simulate dissolved oxygen conditions with Bayesian estimated parameters in Chesapeake Bay. Liu et al. (2010) outlined how a simple hypoxia model could be integrated with Bayesian analysis to explore changes of hypoxia sensitivity to N loading in Gulf of Mexico. These previous studies demonstrated that Bayesian analysis could provide an effective way to incorporate the existing knowledge of parameters and update the joint distribution as new information becomes available. Some of the models mentioned above are configured at steady-state conditions. The steady-state approach delivers realistic results for equilibrated systems but limits the application of these models for dynamic predictions (Wang et al., 2003b). Here, we simulate critical N and P driven phytoplankton biomass in a lake using a dynamic approach, which is

much more flexible and suitable for lake management applications.

Annual or seasonal cycles of temperature, solar irradiance and participation as well as other disturbances will lead to changes in agricultural runoff, mixing in lakes, nutrient supply and plankton growth. These could cause dynamic changes of nutrients cycling in lakes, periodic resuspension, shift of chemical conditions within the sediment and the continuous changing of relative amounts of N and P between overlying water and sediment, which further leads to dynamic sediment release (Folke et al., 2004; Klausmeier and Litchman, 2012; Jochimsen et al., 2013). In turn, internal release dynamics could also contribute to changes in the concentration of N and P in the water-column. It is, therefore, necessary to model sediment release as a dynamic process. For lakes, internal release processes, especially the dynamics, cannot be easily observed or experimentally measured (Wang et al., 2003a). Water quality variables such as total nitrogen (TN), total phosphorus (TP) and Chlorophyll *a* (Chl*a*) directly reflect the system behavior in the lake and can be easily monitored. It is reasonable to believe that variation in TN, TP and Chl*a* could be attributed to the interplay of dynamic changes in internal sediment release (Scheffer and Carpenter, 2003; Carpenter and Lathrop, 2008). We use the statistical approach of change point analysis (CPA) to divide sequences of observed TN, TP and Chl*a* into different periods by detecting distributional changes within time-ordered observations (Szekely and Rizzo, 2005; Matteson and James, 2014). Change point analysis determines whether and when one or more changing points, or regime shifts have occurred. CPA has been used in financial modeling (Bolton and Hand, 2002) and bioinformatics (Muggeo and Adelfo, 2010), but has been less frequently applied within ecology and limnology. In the context of lake dynamics, CPA can be used to help decision makers make targeted policy and recovery decisions corresponding to the changing dynamic process.

We focus our analysis here on Lake Yilong, one of the most eutrophic plateau lakes in Southwestern China. It is semi-enclosed and characterized by low water volume inflow and long residence time which is almost 2.4 years. Previous studies showed that a regime shift might have occurred around 2008 after and water quality deterioration and algae bloom (which can be toxic) have been frequent and serious in the lake (Zhao et al., 2013; Zou et al., 2014). Similar to other eutrophic lakes in China (e.g. Lake Taihu, Dianchi, Chaohu), great efforts have been made to reduce watershed nutrient loading during the past years, yet the observed water quality is far from the expected goals. During the attempts to reverse the Lake Yilong eutrophication, decision makers have confronted two issues: (a) besides external watershed loading, does sediment release play a critical role in impeding the eutrophication recovery? and (b) for N and P, which one is more important to control? To answer the above two questions, a simplified mass balance model was developed; and CPA was conducted to detect different periods in which the sediment release may show different patterns. Bayesian inference was applied to estimate the specific parameters of sediment release in the different periods. The model results can help to reveal the likely temporal change in N and P availability as well as sediment release in different periods and hence determine the importance of sediment release versus external loading.

## 2. Material and methods

### 2.1. Study area

Lake Yilong (Fig. 1) is one of the largest plateau lakes in Yunnan Province, southwestern China with a surface area of 28.37 km<sup>2</sup>, mean depth of 3.9 m, and maximum depth of 5.7 m. It is a warm polymictic system that does not freeze and the water is completely

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