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Analyzing the contribution of climate change to long-term variations in sediment nitrogen sources for reservoirs/lakes

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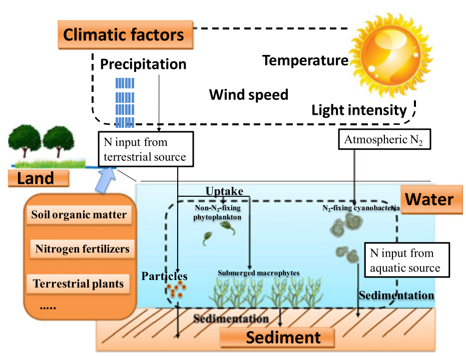
HIGHLIGHTS

- A mixing model was built to analyze sediment N sources of lakes/reservoirs.
- Fertilizer/soil and macrophytes showed decreasing trends during the past two decades.
- Contribution of phytoplankton source to sediment N increased during the past 50 years.
- Impacts of climate change on variations in sediment N sources were quantified.
- N_2-fixing phytoplankton can be used as a response factor to climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

We applied a mixing model based on stable isotopic $\delta^{13}C$, $\delta^{15}N$, and C:N ratios to estimate the contributions of multiple sources to sediment nitrogen. We also developed a conceptual model describing and analyzing the impacts of climate change on nitrogen enrichment. These two models were conducted in Miyun Reservoir to analyze the contribution of climate change to the variations in sediment nitrogen sources based on two ^{210}Pb and ^{137}Cs dated sediment cores. The results showed that during the past 50 years, average contributions of soil and fertilizer, submerged macrophytes, N_2-fixing phytoplankton, and non-N_2-fixing phytoplankton were 40.7%, 40.3%, 11.8%, and 7.2%, respectively. In addition, total nitrogen (TN) contents in sediment showed significant increasing trends from 1960 to 2010, and sediment nitrogen of both submerged macrophytes and phytoplankton sources exhibited significant increasing trends during the past 50 years. In contrast, soil and fertilizer sources showed a significant decreasing trend from 1990 to 2010. According to the changing trend of N_2-fixing phytoplankton, changes of temperature and sunshine duration accounted for at least 43% of the trend in the sediment nitrogen enrichment over the past 50 years. Regression analysis of the climatic factors on nitrogen sources showed that the contributions of precipitation, temperature, and sunshine duration to the variations in sediment nitrogen sources ranged from 18.5% to 60.3%. The study demonstrates that the mixing model provides a robust method for calculating the contribution of multiple nitrogen sources in sediment, and this study also suggests that N_2-fixing phytoplankton could be regarded as an important response factor for assessing the impacts of climate change on nitrogen enrichment.

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1. Introduction

Global climate change includes long-term changes in climatic factors (such as precipitation, temperature, wind speed, and sunshine duration), as well as short-term extreme weather events (Larsen et al., 2011; Xia et al., 2014). There is increasing evidence that climate change is markedly influencing nutrient cycles in lakes or reservoirs (Khalili et al., 2010; Jeppesen et al., 2011; Kortelainen et al., 2013; Wu et al., 2014a). Climate change will alter the inputs, retention, and losses of nutrients in aquatic environment by inducing shifts in the hydrological cycle, biochemical reactions, and growth of algae. Rising temperature can lead to the increase of phytoplankton (Arheimer et al., 2005; Komatsu et al., 2007; Wu et al., 2014a). For instance, the simulation results of Arheimer et al. (2005) showed that global warming could lead to the increase of phytoplankton such as cyanobacteria by 80% in Spirit Lake. Komatsu et al. (2007) also applied a reservoir water quality model and a regional climate model to predict the water quality of the Shimajigawa Reservoir under future climate change. The results indicated that the algae biomass maximum increased from 0.68 mg C L^{-1} in the 1990's to 1.18 mg C L^{-1} in the 2090's as temperature increased by 3.4 °C; this finding demonstrated that global warming would promote algal growth and change aquatic ecosystems. Meanwhile, enhanced intensity and frequency of precipitation will deliver more nutrients from land to the aquatic environment (Bennion et al., 2004; Paerl et al., 2011a). Changes in sunshine duration and wind speed could also affect the migration and transformation of nutrients in the aquatic environment directly or indirectly through influencing certain processes such as photosynthesis and sediment resuspension (Cózar et al., 2005; Montes-Hugo et al., 2009; Fragoso et al., 2011; Paerl et al., 2011b).

The enrichment of nutrients in lakes or reservoirs is affected by multiple influencing factors including climate change and human activities such as the use of agricultural fertilizers and discharge of domestic sewage. The determination of the impacts of climate change on nutrient enrichment is of great significance to water resource management. However, quantitatively distinguishing the effects of climate change on nutrient enrichment from other factors is difficult. Obtaining the long-term monitoring data of lake/reservoir water quality is also difficult due to the spatial and temporal limitations of the monitoring sites.

To solve the data deficiency problem, lake sediment cores containing an archive of past environmental conditions and biogeochemical processes in and around the aquatic environment can be used to track the changes through time (Brenner et al., 1999; Torres et al., 2012). Geochemical fingerprint values ($\delta^{13}C$, $\delta^{15}N$, and C:N ratios) of organic nitrogen from different sources differ from one to another (Elliott and Brush, 2006; Collins et al., 2010; Holtgrieve et al., 2011; Woodward et al., 2012; Barnard et al., 2014), and different sources have their own values. For example, sources of waste water and agriculture runoff could yield sediment cores with low $\delta^{13}C$ and high $\delta^{15}N$ because of the preferential utilization of ^{12}C-riched CO_2 and volatilization of light nitrogen isotopes (Kendall et al., 2007). Sources from aquatic algae have low C:N ratios (3–7), and terrestrial plants have high C:N ratios (>20) due to the high protein contents in aquatic plants and high fiber contents in terrestrial plants (Heyng et al., 2012; Torres et al., 2012). Because N_2-fixing phytoplankton fix nitrogen from the atmosphere, they have similar $\delta^{15}N$ values with nitrogen in the atmosphere (−3–2‰). Nitrogen in lake sediments mainly exists as organic forms (Ni et al., 2011); therefore, sources of nitrogen can be identified using mixing models based on the geochemical fingerprint values of different sources. Several studies of sediment core analysis used mixing models to estimate the sources of the organic matter with only one or two parameters (i.e., $\delta^{13}C$, $\delta^{15}N$ or C:N ratios). However, these studies did not consider the variations with respect to an individual source (Waterson and Canuel, 2008; Yu et al., 2010; Ni et al., 2011). Up to now, there has been little research published using a model coupled with $\delta^{13}C$, $\delta^{15}N$, and C:N ratios in sediment cores to determine the temporal variations in multiple sources of nitrogen. Only Mayr et al. (2009) used a mixing model in a sediment core to analyze the change in the sources of organic matter. Because climate change can influence various sources through affecting the transformation and migration of nitrogen compounds (Xia et al., 2014; Wu et al., 2014a,b), the impacts of climate change on variations in sediment nitrogen enrichment should be quantitatively estimated.

Therefore, in this study we applied a mixing model using $\delta^{13}C$, $\delta^{15}N$, and C:N ratios, combined with a paleolimnological approach to quantitatively examine the sources of nitrogen in sediment. Then, a conceptual model describing and analyzing the impacts of climate change on nitrogen enrichment was proposed. Miyun Reservoir was chosen as an example to study the effects of climate change on nutrient enrichment because the water quality there is less affected by point source pollution compared with other plain lakes/reservoirs. Geochemical analysis ($\delta^{13}C$, $\delta^{15}N$, C:N ratios, and total phosphorus (TP)) and $^{210}Pb/^{137}Cs$ age models in two sediment cores were used to calculate the temporal variations in different nitrogen sources using the mixing model. In particular, the impacts of climate change, including temperature, precipitation, sunshine duration, and wind, on multiple nitrogen sources were analyzed.

2. Materials and methods

2.1. Study site

Miyun Reservoir, built in 1958, is a large and deep artificial lake in Miyun County of northern Beijing (Fig. S1); detailed characteristics of the reservoir are shown in Table S1. The Chaohe and Baihe Rivers are the two main rivers flowing into the reservoir, dividing the Miyun Reservoir into the Chaohe and Baihe Reservoirs (Fig. S1). Hills and low mountains characterize the topography around the Miyun Reservoir. The main soil types around the reservoir are brown soil and leached cinnamon soil.

As a drinking water source, Miyun Reservoir is less affected by industrial pollution due to few industries in the catchment. In addition, there are very few residential and tourist activities in the Chaohe Watershed, resulting in little domestic sewage discharge. The major land use in the Miyun Reservoir watershed is agricultural land, and approximately 74.14% of the fertilizer use is nitrogen fertilizer (Huang et al., 2007). Miyun Reservoir is an algal reservoir with 7 phyla and 71 genera of phytoplankton such as Cyanophyta, Chlorophyta, and Cryptophyta (Li, 2013). The eutrophic state of Miyun Reservoir has transitioned from oli-mesotrophic to light eutrophic over the past 50 years (Wang et al., 2006). The biomass of phytoplankton, one of the main sources of sediment nitrogen, has increased significantly since 1980, and cyanobacteria became the dominant species (Du et al., 2005; Liu et al., 2004; Li, 2013). Among the phytoplankton, the growth of N_2-fixing cyanobacteria will be influenced by climate change. Submerged macrophytes of the Miyun Reservoir are mainly distributed around the lake basin and are dominated by *Potamogeton crispus* L., *Myriophyllum spicatum*, *Hydrilla verticillata*, *Potamogeton malaianus*, and *Najas marina* (Liu et al., 2004). According to the above information, the changes in sediment nitrogen will be mainly affected by climate change, especially for the Chaohe watershed.

The climate in Miyun belongs to the semi-arid and semi-humid warm temperate zone, with distinct four seasons. Data of monthly air temperature, precipitation, wind speed as well as sunshine duration of the Miyun Reservoir watershed from 1960 to 2011 were collected from the China Meteorological Data Sharing Service System.

2.2. Sediment core sampling and analysis

Two sediment cores named M1 and M2 were retrieved from two locations (Fig. S1) in the Chaohe Reservoir using a gravity corer (Core 69, Uwitec, Austria) on the 26th of October, 2012; detailed characteristics of the sampling sites are shown in Table S2. Sediments were immediately subsampled in 1 cm intervals and were frozen within 24 h and freeze-