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Feedback of threshold via estimating sources and composition of sedimentary organic matter across trophic gradients in freshwater lakes

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HIGHLIGHTS

- SOM composition in different trophic state lakes were systematically compared.
- Multiple sources of SOM were identified using fatty acid biomarkers.
- Terrestrial plant derived organic carbon was a useful predictor for sediment TOC.
- Increasing trophic state led to rising aquatic source contribution to SOM pool.
- The threshold of terrestrial to aquatic ratio along trophic gradients was 0.683.

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ABSTRACT

The quantity and quality of sedimentary organic matter (SOM) in relation to material and energy flows are crucial for understanding the current state and future development of lake systems, yet, characterization of organic matter sources and assessment of their relative contributions in different trophic-state lakes caused by anthropogenic impacts are scarcely known. In this study, for obtaining information concerning the source of SOM and its compositional diversity along different trophic gradients, a total of thirty-one sampling sites from four freshwater lakes located in China and Japan were performed by the molecular level analysis using source-specific fatty acid biomarkers. Results indicated that SOM in these lakes was composed of microalgae-, aquatic plant-, terrestrial plant- and bacteria-derived organic matters based on their fatty acid profiles. The scatter plot matrix exhibited correlations between these sources, however, only terrestrial plant-derived organic carbon was a well predictor for sediment TOC with strong, spatiotemporal dynamics. The source and composition of SOM were evidently influenced by lake trophic state with redundancy analysis. Moreover, increase of lake trophic state led to the relatively higher contribution of aquatic organic matter sources to SOM pool compared with terrigenous sources, as evidenced by significant correlations between the trophic state index [TSI (TP)] and the ratio of terrigenous to aquatic fatty acids (TAR_{FA} ratio). Yet, this changing trend became more gradual with higher trophic state and prevented the occurrence of regime shift from allochthonous to autochthonous dominant state by a threshold (0.683) of TAR_{FA} ratio. Together, a conceptual diagram was proposed, which highlighted the prevailing state of allochthonous source and implicated sedimentary organics in biogeochemistry cycle within freshwater lakes.

1. Introduction

Sedimentary organic matter (SOM) plays an important role in carbon and energy cycle of freshwater lakes. It provides a carbon source for microbial metabolism, enhances bacterial biomass and further transfers energy upwards through high trophic levels, and eventually forms a diverse food web (Carpenter et al., 2005). These processes, inherently linked with organic matter turnover as well as consumer performance, depend on SOM source and composition. Lake sediments receive organic matter from autochthonous sources produced by phytoplankton and terrestrial (allochthonous) organic matter delivered by river discharge and runoff (Meyers and Ishiwatari, 1993). Generally, importing large amounts of terrestrial organic matter could be a subsidy to benthic food chains and a drive force of the energy flow in the sediments of lakes, especially within the negative net-production ecosystems (Hieber and Gessner, 2002; Attermeyer et al., 2013). However, the

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transfers of material and energy might be altered to inhibition during the initial process, i.e. microbial metabolism, if the contribution of terrestrial inputs is continuously increasing (Gudasz et al., 2012). The increasing allochthonous contribution coupled with declining autochthonous contribution to SOM pool, or in turn, exhibits a significant influence on these ecological and biogeochemical processes in freshwater lakes. Therefore, the knowledge of the source and composition of SOM is very important.

With nutrient enrichment and greater phytoplankton production in lakes, the shift in the relative contribution to SOM across the trophic gradients might be away from allochthonous sources and towards phytoplankton. For example, Woszczyk et al. (2011) documented that SOM in a highly eutrophic and shallow coastal lake was comprised of large amounts of well-preserved phytoplankton in agreement with the water column characteristics. Similarly, microalgae and bacteria were pointed to be important sources of SOM within an Australian eutrophic inlet (Volkman et al., 2008). However, these studies about the origin of sediments have mainly focused on the estuarine and coastal ecosystems, and information from freshwater lakes is scarce. Additionally, little is known about whether this shift in relation to the composition of SOM crosses the threshold and towards the phytoplankton-dominant state or only triggers a slight increase and keeps in the initial state (allochthonous-dominant state).

Quantification of the relative contribution of allochthonous vs. autochthonous organic matter to SOM pool is challenging, as inputs of diverse organic matter sources result in complex mixtures accumulating heterogeneously on lake bottoms (Rossi et al., 2010). Fatty acid profiles allow the unequivocal identification of potential sources of SOM due to their structural diversity, source specificity and relative stability (Zimmerman and Canuel, 2001). In numerous studies, fatty acids have been used as biomarkers in discriminating multiple SOM sources such as cyanobacteria (Hayakawa et al., 2002), diatoms (Alfaro et al., 2006), dinoflagellates (Alfaro et al., 2006), terrestrial plants (Dunn et al., 2008) and bacteria (Rajendran et al., 1993).

Most studies of SOM source and composition have focused on a single water body and their results are probably site-specific (Dunn et al., 2008; Volkman et al., 2008; Woszczyk et al., 2011), whereas there has been little examination of systematic comparisons in different trophic-state lakes. Hence, in this study, several lakes were selected in different geographical areas from alpine oligotrophic to shallow hypereutrophic lakes, encompassing a broad gradient of trophic states, in China and Japan, for the purpose of revealing potential source contributions to SOM pool and further inferring the patterns of discrepancy and consistency between these freshwater lakes. We hypothesized that nutrient enrichment would strongly impact on autochthonous production in lakes, and to some extent, the predominant source of SOM pool would also shift from terrestrial into autochthonous source along a gradient of trophic-state.

2. Materials and methods

2.1. Site description

Lake Taihu (31°10′N, 120°09′E), located in the southeastern part of the Yangtze Delta, is the third largest freshwater lake in China (Fig. 1). The lake has a surface area of 2338 km^2 and an average depth of 1.9 m with more than 200 input rivers discharging about 7.6 billion m^3 water into the lake every year (Zhu, 1994; Sun and Mao, 2008). Heavy cyanobacterial blooms occur annually in the western and northern areas (especially in Meiliang Bay and Zhushan Bay with the hypereutrophic state, Paerl et al., 2011; Otten et al., 2012) due to discharge of pollutants from surrounding basins. Aquatic macrophytes with more than 60% of total species composed of submerged macrophytes are mainly distributed in easterly portion of the lake (Wu and Kong, 2009).

Lake Izunuma (38°43′N, 141°06′E) is a temperate and eutrophic shallow lake, located in a cropland in northern Miyagi, Japan (Fig. 1). It has a maximum and average depth of 1.6 m and 0.76 m, respectively, with a total area of 3.69 km^2 (Yasuno et al., 2012). Owing to decades of nutrient discharge, the lake has been transformed into its present eutrophic state. Approximately 80% of phytoplankton is green algae, however, emergent and floating-leaf plants are dominant among aquatic

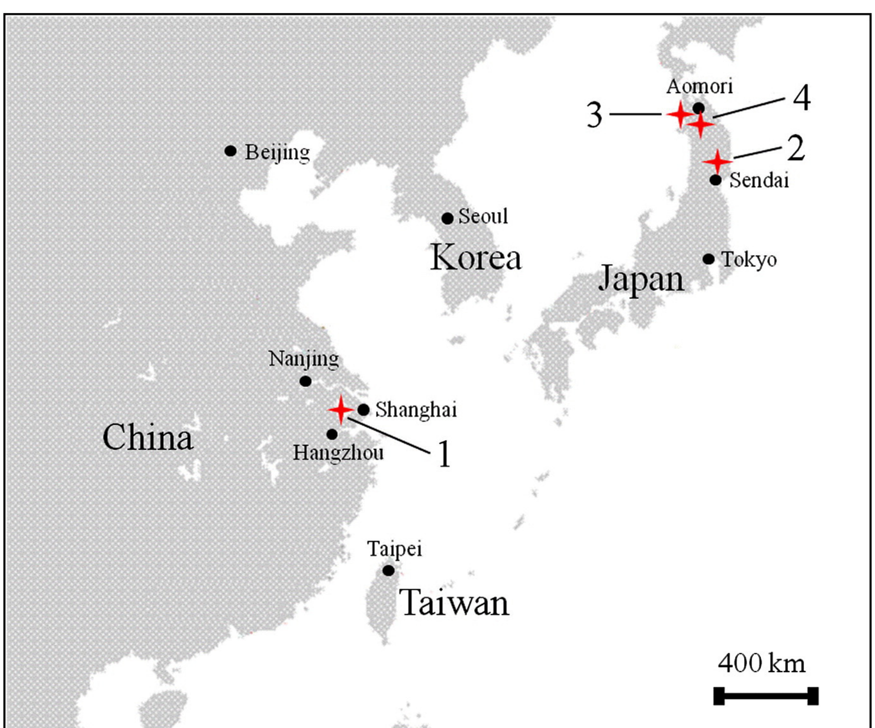

Fig. 1. East Asia map showing the location of four lakes considered in this study: 1. Lake Taihu; 2. Lake Izunuma; 3. Lake Juni; and 4. Lake Towada.