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Asymmetric response of sedimentary pool to surface water in organics from a shallow hypereutrophic lake: The role of animal consumption and microbial utilization

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ABSTRACT

Despite of the importance for tracking sources and fates of organics in determining carbon cycling and assessing the overall health of lacustrine ecosystems, little is known of organics behaviors in shallow eutrophic lakes. In this study, for relating the benthic organics to pelagic sources, an ecosystem-level investigation was performed in hypereutrophic Lake Taihu, China, by using source-specific fatty acid biomarkers on the molecular level. Results exhibited the unexpected asymmetric phenomena of organics between surface water and sediments. In the abundance, the dominant organics shifted from cyanobacteria in surface water to terrestrial plants in sediments. In the spatial pattern, as opposed to terrestrial plants, cyanobacteria were found not site-to-site symmetrical, although both of their spatial distributions varied strongly. Essentially, these asymmetric phenomena ascribed to a more considerable loss of cyanobacteria compared to terrestrial plants during sinking, caused by aquatic animal consumption and microbial utilization with different degree. Combined dual stable isotopes (δ^{13}C and δ^{15}N) and fatty acid biomarkers revealed that there were only subtle differences in the diets of benthic and pelagic animals and cyanobacteria were their main food source. Concomitantly, results of δ^{13}C of bacteria-specific fatty acids demonstrated that bacteria equally and profoundly affected organics accumulation or preservation in the sediments, because they preferentially utilized labile cyanobacteria as their carbon source instead of terrestrial plants (>95% within these two sources). Consequently, these novel findings clarify that not only in deep lakes, but also shallow eutrophic ones, the extensive losses of autochthonous organic matter can be expected during sedimentation coupling with the dramatical modifications of biogeochemical processes.

1. Introduction

Organic matter in lakes generally derives from autochthonous sources produced by phytoplankton and terrestrial (allochthonous) subsidies delivered by river discharge and runoff (Meyers and Ishiwatari, 1993). Therein, a critical portion provides carbon and energy sources for consumers and forms the base of the diverse food web, the residuals sink through the water column and are ultimately preserved in sediments (Tranvik et al., 2009). The vertical migration of organic matter drives the development of benthic communities; however, continuously increasing of sinking fluxes probably results in hypoxic or anoxic conditions coupling with the release of nutrients and deteriorates of the benthic habitats (Qin et al., 2010). Therefore, a profound knowledge of organic matter dynamics including the fate of organic matter in water column, alternatively, the origin of organic matter in the sediments is crucial for understanding material flow and cycling in lake ecosystems and for decision-making in lake management.

The migration process of organic matter from the water column to the sediments is known to be affected by various biotic and abiotic factors. In deep lakes, vertical mixing above the thermocline induced by winds and waves or thermo convection prolongs the exposures of organic matter to oxidation. As a result, nearly 85% of the organic carbon losses before leaving the epilimnion (Eadie et al., 1984). Aquatic animal utilization by zooplankton or filter-feeder fishes and microbial degradation by

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heterotrophic organisms within the water column play a substantial role in decreasing the sinking flux of organic particles (Meyers and Ishiwatari, 1993; Sarnelle, 1999). On the other hand, the sinking flux may significantly increase through light-mediated as well as microbially-induced flocculation of dissolved organic matter in the water column (von Wachenfeldt et al., 2008, 2009). These observations imply that organic particles sinking from surface water with long residence time in deep lakes are not necessarily proportional to the organic matter contents of underlying sediments. In contrast to the deep lake ecosystems, the information from shallow lakes especially eutrophic lakes is scarcely known.

Sinking organic matter selectively undergoes the aforementioned biotic and abiotic processes during the transit onto bottom sediments, depending on its sources and composition. Recently, approaches that have been used for assessing the sources and composition of sinking and sedimentary organic matter include bulk stable carbon isotopic signatures and molecular level biomarkers of fatty acids. In numerous studies, carbon isotope ratios have been applied to evaluate the relative contributions of terrestrial and marine sources to sedimentary organic pool with their obvious discrepancies of isotope ratios in estuarine, coastal and marine environments (Cook et al., 2004; Dunn et al., 2008; Volkman et al., 2008). When assessing various organic matter sources with similar isotope ratios in freshwater lakes, fatty acids have been proven to be more suitable due to their structural diversity, source specificity and relative stability (Bechtel and Schubert, 2009; Xu et al., 2014, 2015). Fatty acid profiles and stable isotope ratios ($^{13}C/^{12}C$ and $^{15}N/^{14}N$) have also been employed to identify food web relationships and the strength of interactions among dominant taxa in aquatic systems (Alfaro et al., 2006; Budge et al., 2007; Kharlamenko et al., 2001). The biological specificity and unchanged transformations from primary producers to consumers make fatty acids suitable to be biomarkers (Alfaro et al., 2006). Measurement of stable isotope ratios of primary producers and consumer tissues can trace the carbon source on the base of a food web and indicate the trophic level of a consumer population, as these ratios can show predictable changes through a food chain from the respiration and excretion of lighter isotopes by the consumers (Peterson and Fry, 1987). Fatty acids, complemented by stable isotopes thus serve as an ideal technique to evaluate the organics sources and fates in freshwater lakes.

For the purpose of tracking organics behaviors in shallow and eutrophic lakes, the suspended particulate organic matter (SPOM) in the water column and sedimentary organic matter (SOM) were systematically investigated in Lake Taihu, China. The sources and composition of SPOM and SOM were analyzed and their relationships were compared with fatty acid biomarkers. Aquatic animals and benthic bacteria were also performed for the interpretation of their roles in alternation of organics dynamics in the lake. In shallow eutrophic lakes, organic matter would have shorter sinking time and consequently shorter exposures to oxidation in the water column. Especially for photosynthetic organisms, export onto the sediments (as live or dead cells) is probably their fates with intensively and high-frequency sedimentation. Hence, we hypothesized that in large shallow and eutrophic lakes, organics in surface water are proportional to the contents of the sediments with faint influence of animal consumption and microbial utilization.

2. Materials and methods

2.1. Site description

Lake Taihu (119°54′–120°36′ N, 30°56′–31°33′ E), one of the largest freshwater lakes in China, is located in the southeastern part of the Yangtze Delta. It provides significant services including water supply, flood control, shipping and aquaculture, tourism and recreation, agriculture and irrigation. The lake covers a water area of 2338 km^2 and its mean water volume of approximately 44.3×10^8 m^3 (Chen, 2001). The shallow average depth of 1.89 m ensures that it remains polymictic with no seasonal stratification (Qu et al., 2000). The river network is densely distributed surrounding the lake, with more than 30 input sources, ranging from streams to canals and rivers. Water exits the southeastern corner of Lake Taihu via Taipu River, which drains through Shanghai into the East China Sea. The named rivers in Fig. 1 contribute more than 85% of the lake's freshwater inflows (Paerl et al., 2011). Large amounts of exogenous organic matter are delivered via these inflows into the lake coupling with inevitably anthropogenic nutrients. As a result, it has experienced accelerating eutrophication over the past three decades and was transformed into its present hypereutrophic state, with *Microcystis* blooms occurring regularly throughout much of the lake (Otten et al., 2012). The littoral zone of the northern and western part of the lake is distributed by common reed, while 95% of the easterly portion of the lake is covered by aquatic vegetation with more than 60% of total species composed of submerged macrophytes (Qin, 2008; Wu and Kong, 2009).

2.2. Sampling strategy

In the present study, sample collections of flora, fauna, water and sediments were conducted in Lake Taihu between August 20th and 29th, 2013 in considering of algae flourishing season. Among them, sediments and their corresponding overlying water were collected from thirty-three locations encompassing the whole lake. The accurate positions of these sampling locations recorded by global position system (GPS) were shown in Fig. 1. Triplicate sediment samples (0–2 cm) from each site were combined and homogenized before being stored in the dark at <4 °C in the field, using the cylindrical PVC coring tubes coupling with a grab sampler. Based on the ecological characteristic descriptions of the lake as mentioned above, vegetation was obtained including triplicate higher plant samples (*Phragmites communis*) along the western shoreline, triplicate cyanobacteria samples (using a 64 μm mesh-size net) in the northwestern region where cyanobacteria assemblages were in high density on surface water, and macrophytes in the southeastern region (floating-leaf: *Nymphoides indica*, *Nymphoides peltatum* and *Trapa incisa*; submerged: *Elodea nuttalli*, *Hydrilla verticillata*, *Ceratophyllum demersum*, *Potamogeton malaianus* and *Vallisneria natanus*; emergent: *Zizania latifolia* and *Nymphaea nucifera*). A range of animal samples including three species of shrimps, seven species of fishes, snails (*Bellamya aeruginosa*) and bivalves (*Anodonta woodiana*) were randomly gathered where there were, however, it is certain that all of these samples were collected both from regions with and without cyanobacterial blooms. Considering the prevailing species in Lake Taihu, shrimps were sampled with *Macrobrachium nipponensis*, *Exopalaemon modestus* and *Procambius clarkii*, and fishes were sampled with phytoplanktivorous: *Hypophthalmichthys molitrix*, *Aristichthys nobilis* and *Ctenopharyngodon idellus*, and omnivorous: *Cyprinus carpio*, *Carassius auratus*, *Mylopharyngodon piceus* and *Neosalanx tangkahkeii*. The fishes of carnivorous types were excluded, as their food habits were not in relation to vegetation dynamics within the purpose of this study. Both of snail and bivalve samples were collected from eight locations in considering their small active areas. After being transported to laboratory rapidly, the suspended particles were collected by GF/F filters, and vegetation samples were washed with distilled water for removing attached particulate organic matter, and animals were dissected for removing shells or scales if there were. Lastly, all of the suspended particle, sediment, vegetation and