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Combined use of radiocarbon and stable carbon isotope to constrain the sources and cycling of particulate organic carbon in a large freshwater lake, China

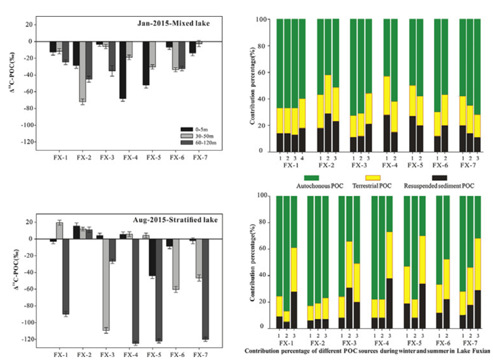
Jingan Chen *, Haiquan Yang, Yan Zeng, Jianyang Guo, Yilong Song, Wei Ding

State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, PR China

HIGHLIGHTS

- Radiocarbon and stable isotope compositions of POC were measured in Lake Fuxian.
- Contributions of autochthonous, terrestrial, and sediment POC to the bulk POC were 61%, 22%, and 17%, respectively.
- Autochthonous POC plays a dominant role in sustaining large lake ecosystem.
- Algal POC has more persistent impacts on lake ecosystem than terrestrial POC.
- Sediment might have significant influence on aquatic environment and ecosystem.

GRAPHICAL ABSTRACT



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ABSTRACT

The concentrations and isotopic compositions of dissolved inorganic carbon (DIC) and particulate organic carbon (POC) were measured in order to better constrain the sources and cycling of POC in Lake Fuxian, the largest deep freshwater lake in China. Model results based on the combined $\delta^{13}C$ and $\Delta^{14}C$, showed that the average lake-wide contributions of autochthonous POC, terrestrial POC, and resuspended sediment POC to the bulk POC in Lake Fuxian were 61%, 22%, and 17%, respectively. This indicated autochthonous POC might play a dominant role in sustaining large oligotrophic lake ecosystem. A mean 17% contribution of resuspended sediment POC to the bulk POC implied that sediment might have more significant influence on aquatic environment and ecosystem than previously recognized in large deep lakes. The contributions of different sources POC to the water-column POC were a function of the initial composition of the source materials, photosynthesis, physical regime of the lake, sediment resuspension, respiration and degradation of organic matter, and were affected indirectly by environmental factors such as light, temperature, DO, wind speed, turbidity, and nutrient concentration.

This study is not only the first systematic investigation on the radiocarbon and stable isotope compositions of POC in large deep freshwater lake in China, but also one of the most extensive radiocarbon studies on the ecosystem of any great lakes in the world. The unique data constrain relative influences of autochthonous POC, terrestrial POC, and resuspended sediment POC, and deepen the understanding of the POC cycling in large freshwater lakes. This study is far from comprehensive, but it serves to highlight the potential of combined radiocarbon and stable carbon isotope for constraining the sources and cycling of POC in large lake system. More radiocarbon investigations on the water-column POC and the aquatic food webs are necessary to illuminate further the fate of autochthonous POC, terrestrial POC, and resuspended sediment POC, and their eco-environmental effects.

* Corresponding author.
E-mail address: chenjingan@vip.skleg.cn (J. Chen).

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1. Introduction

Lake carbon cycle is one of the focuses of current lacustrine research, and its significance lies mainly in two aspects. Firstly, lake carbon cycle is one of the key components of global carbon cycle and has important influence on global source and sink of carbon. On the one hand, as important carbon sinks, lakes bury up to 58% of the carbon that oceans do per year even though the combined surface area of lakes is <2% that of the ocean (Dean and Gorham, 1998; Cole et al., 2007; Zigah et al., 2012a). On the other hand, lakes are nonnegligible carbon sources, with an estimated potential global CO_2 emission of 140 Tg C per year, roughly half the annual carbon transport from rivers to the ocean (Cole et al., 1994). Secondly, lake carbon (C) cycle plays important roles in regulating nutrient cycling and within-lake ecosystem. It is well known that nitrogen (N) and phosphorus (P) are the primary nutrients governing the trophic status of lakes. Excessive N and P may cause lake eutrophication, and further result in algae bloom and drinking water crisis (Qin et al., 2010; Paerl et al., 2011; Ho and Michalak, 2015; Hanifzadeh et al., 2017). The migration and transformation of N and P usually take organic matter as the main carrier. The biogeochemical cycles of C, N and P are tightly coupled by lake primary production and organic matter degradation. The growth process of phytoplankton is certainly accompanied by photosynthetic uptake of C, N and P, while the degradation of organic matter releases synchronously C, N and P back to the water body through a more or less complicated network of microbially mediated biochemical reactions (Bratkič et al., 2012). Therefore, a comprehensive understanding on lake carbon cycle not only enriches our knowledge of global carbon cycle, but also helps to clarify the coupling mechanisms of C-N-P biogeochemical cycles and associated eco-environmental effects, thus providing scientific guidance for the prevention and control of lake eutrophication.

Carbon exists in lake water mainly in four species, including dissolved inorganic carbon (DIC), particulate inorganic carbon (PIC), dissolved organic carbon (DOC) and particulate organic carbon (POC). In comparison to DIC and PIC, knowledge of the sources and transformation of DOC and POC in lake water is very limited due to the complexity of the composition of DOC and POC (millions of monomer compounds) and the difficulty in sampling and analysis (Wu and Tanoue, 2001; Kim et al., 2003; Urban et al., 2005; Bianchi, 2007; Li et al., 2008; Wu and Xing, 2010; Zigah et al., 2012a, 2017). POC is normally defined as organic matter that does not pass a filter with sub-micron pore size (normally 0.7 μm, GF/F glass fiber filter), consisting mainly of terrestrial inputs, autochthonous phytoplankton and macrophyte debris in lake water (Zigah et al., 2011; Adams et al., 2015). POC plays a significant role in carbon and energy flow within lacustrine system, and governs to a large extent the transport of the macronutrients N and P, even metals and organic contaminants (Tipping et al., 1997; Foster et al., 2000; Adams et al., 2015). It is very important to constrain the sources and cycling of POC for fully understanding lake C-N-P cycle, functioning of aquatic ecosystems, and migration of contaminants. However, the sources and cycling of POC in large freshwater lakes has not been well delineated until now.

The combined and complementary use of radiocarbon (^{14}C) and stable carbon isotope (^{13}C) is a promising approach to constrain the sources and cycling of OC in surface earth environment (Raymond and Bauer, 2001a, 2001b; Zigah et al., 2012a, 2017). $\Delta^{14}C$ has the following advantages in tracing OC sources and migration- transformation processes: (1) the dynamic range of $\Delta^{14}C$ (−1000 to +200‰) is much greater than that of $\delta^{13}C$ in organic carbon (−32 to −12‰) (Petsch et al., 2001; Bauer et al., 2002; McCallister et al., 2004; Wakeham et al., 2006; Zigah et al., 2012a), thus providing a more sensitive means for differentiating the sources of OC; (2) as a result of the lower susceptibility of $\Delta^{14}C$ to degradation or diagenesis of OC, the $\Delta^{14}C$ value of given organic matter changes only with time, thus providing unique and reliable information on age and residence time of OC in surface earth environment (Raymond and Bauer, 2001a, 2001b; Zigah et al., 2011); (3) both $\delta^{13}C$ and $\Delta^{14}C$ are linear quantities that can be used directly for isotopic mixing models, which is in favor of distinguishing quantitatively the sources of organic carbon (McNichol and Aluwihare, 2007; Zigah et al., 2012b); and (4) $\Delta^{14}C$ has the advantage of being the same for consumers and their food source in a modern ecosystem (as the $\Delta^{14}C$ calculation corrects for biochemical fractionations), thereby eliminating the need for fractionation correction along trophic levels as is the case for $\delta^{13}C$ and $\delta^{15}N$ (McNichol and Aluwihare, 2007; Bauer and Bianchi, 2011; Zigah et al., 2012a).

Because of the increasing accessibility of accelerator mass spectrometry (AMS) facilities and the decreasing sample size requirement for accurate ^{14}C measurement, numerous studies using radiocarbon measurements have been conducted in aquatic ecosystems in the past few decades (Raymond and Bauer, 2001a, 2001b; McNichol and Aluwihare, 2007; McCallister and del Giorgio, 2008; Bauer and Bianchi, 2011; Zigah et al., 2011, 2012a, 2017; Marwick et al., 2015; Walker et al., 2016; Xue et al., 2017). However, radiocarbon studies on lacustrine POC are very limited, especially in large freshwater lake. Only few studies used limited $\Delta^{14}C$ data to infer lacustrine POC sources (McCallister and del Giorgio, 2008; Zigah et al., 2011, 2012a, 2012b; Kruger et al., 2015; Keaveney et al., 2015; Stimson et al., 2017). More radiocarbon measurements of POC from various lacustrine systems will not only improve our understanding of the global carbon cycle, but also help illuminate the roles of different carbon sources in modern lacustrine ecosystem. To the best of our knowledge, there has not been a radiocarbon study reported to quantitatively identify sources of POC in any large lake of China until now. Therefore, this study attempt to carry out the first systematic investigation on the radiocarbon and stable isotope compositions of POC in Lake Fuxian, the largest deep freshwater lake in China. The objectives of this study are (1) to reveal the spatial-temporal distribution characteristics in radiocarbon and stable isotope compositions of POC; (2) to identify quantitatively the sources of water-column POC; (3) to assess the ages and cycling of lacustrine POC.

Lake Fuxian was selected for this study because (1) as the largest deep freshwater lake in China, Lake Fuxian is the most important freshwater resource in China, accounting for 9.16% of the total volume of China's freshwater lakes (Ai et al., 2010; Dai et al., 2017) and nearly half of the total lake freshwater with average water quality of Class I of the China National Water Quality Standard, thus it is most representative of large freshwater lake in China; (2) plateau lake ecosystem in China is very vulnerable and sensitive to environmental change and human disturbance, due to its strong closeness, species simplification, oligotrophy and simple food chain (Dai et al., 2017). Monitoring data indicated an obvious eutrophication trend as a result of increased N and P concentrations in Lake Fuxian in recent years (Gao et al., 2013; Zhang et al., 2015). In consideration of the correlation between N-P cycle and POC within lacustrine system, a thorough investigation on the sources and cycling of POC will provide scientific basis for the prevention and control of eutrophication in Lake Fuxian.

2. Methods

2.1. Study site

Lake Fuxian (102°49′12″–102°57′26″E, 24°21′28″–24°38′00″N), the largest deep freshwater lake in China, is located in the Yunnan-Guizhou Plateau, Southwest China. Its altitude is 1721 m. The lake is 31.5 km long and 6.7 km wide on average and has a mean depth of 89.7 m, a maximum depth of 155.0 m, and a volume of 190×10^8 m^3. It has a water surface area of 212 km^2, and a long water retention time of 167 years (Wang and Dou, 1998; Liu et al., 2009). The northern basin of the lake is wide and deep, but the south basin is narrow and shallow. It is surrounded on all sides by mountains, receiving water from >20 rivers, of which seven are piedmont rivers flowing through cultivated fields in the northern watershed, with the remainder being intermountain rivers