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Differences in $\delta^{13}C$ and $\delta^{15}N$ of Particulate Organic Matter from the Deep Oligotrophic Lake Fuxian Connected with the Shallow Eutrophic Lake Xingyun, People's Republic of China

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Increased anthropogenic activities in watersheds have increased loading of nutrients to lakes, ponds and estuaries. The resulting eutrophication has many adverse effects, i.e., harmful algal bloom, subsequent loss of habitats of grass meadows, and accompanied loss of animal species (Pohle et al., 1991; Duarte, 1995). These adverse effects have prompted search for suitable indicators of eutrophication to assess water quality of aquatic ecosystems. It is now commonplace to assess the trophic state of lakes using data for TP, TN, Secchi depth, and Chlorophyll *a* (Chl. *a*) from water column (Gu et al., 1996). The stable carbon and nitrogen isotope ratios have been used to define food webs, to explain variations in paleoproductivity and to infer carbon and nitrogen cycles, as well as natural tracers of C and N sources (Gu et al., 1996; Peterson, 1999; Post, 2002). Recently, stable carbon and nitrogen isotopes ($\delta^{13}C$ and $\delta^{15}N$) also have been suggested as indicators of trophic state in studies for freshwater and estuarine systems (Cabana and Rasmussen, 1996; Gu et al., 1996; Cole et al., 2004). A number of variables can affect stable carbon isotopes of planktonic organic matter in aquatic systems. These variables include, but are not limited to, dissolved carbon dioxide ($CO_{2(aq)}$) concentration, species composition, algal growth rate, and differential use of $CO_{2(aq)}$ and HCO_3^- (Kendall et al., 2001). Stable nitrogen isotope of primary producers changes with substrate level and growth rate, and with N_2 fixation (Kendall et al., 2001). For example, $\delta^{15}N$ of cyanobacteria decreased with increasing N_2 fixation rate of some N_2-fixation species in freshwater ecosystems (e.g., Yoshioka and Wada, 1994).

In light of these facts, we investigated differences in $\delta^{13}C$ and $\delta^{15}N$ of particulate organic matter (POM) from two connected lakes, Lake Fuxian and Lake Xingyun, which locate in Yunnan Plateau, southwestern China (Fig. 1). Lake Fuxian, the second deepest lake in China, is a typical oligotrophic lake with a surface area of 212 km^2 and a mean depth of 90 m (maximum depth 155 m). The lake is also characterized by inhabitancy of large amount of aquatic organisms including many endemic species (Yang and Chen, 1995). Lake Xingyun, as an upper river

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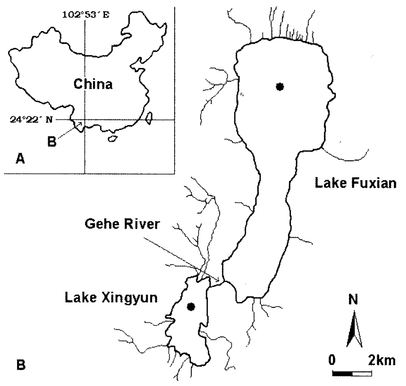

Figure 1. Map of Lake Fuxian and Lake Xingyun, and location of sampling sites. [●: sampling site]

Table 1. Average values of chemical parameters of Lake Fuxian and Lake Xingyun during September 23-26, 2003. [nd = no data]

Parameter ($mg\ l^{-1}$)	Lake Fuxian	Lake Xingyun
TN	0.192	3.22
TDN	nd	1.32
NO_3-N	0.046	0.45
NH_4-N	nd	0.041
TP	0.020	0.44
TDP	nd	0.25

lake of Lake Fuxian, is a shallow eutrophic lake with a surface area of 39 km^2 and a mean depth of 7 m (maximum depth 10 m). The lake develops a heavy cyanobacterial bloom through the year, and the lake water contaminated with abundant algae and nutrients is discharged through Gehe River into Lake Fuxian. The loading of organic carbon from Lake Xingyun to Lake Fuxian through the Gehe River was approximately 5.5% of the total organic carbon inputs to Lake Fuxian (Hayakawa et al., 2002). The purposes of this study were to investigate differences as well as vertical patterns in $\delta^{13}C$ and $\delta^{15}N$ of particulate organic matter (POM) in these two adjacent lakes with different trophic state, and to discuss the possible mechanisms underlying these patterns.

MATERIALS AND METHODS

Lake water for POM was sampled at several water depths at the northern center of Lake Fuxian and the center of Lake Xingyun on 23-26 September 2003, and then filtered onto precombusted glass fibre filters (GF/C Whatman). The filters for isotope analyses were than wrapped in aluminium foil, put into plastic baggies, preserved in an ice box and brought back to laboratory. In the laboratory, the filters were acidified with 1N HCl solution to dissolve possible calcium carbonate ($CaCO_3$), followed by a rinse in distilled water, dried to a constant weight at 50°C in a drying oven, ground and homogenized to a fine powder with a mortar and pestle, and then stored in a desiccator with a silica gel desiccant for subsequent stable isotope analysis. Stable carbon and nitrogen isotope ratios were analyzed with Delta Plus (Finnigan) continuous flow isotope ratio mass spectrometer (CF-IRMS) directly coupled to an EA1110 elemental analyzer (Carlo Erba) for combustion. More than twenty percent of the samples were analyzed two or more times as replicates. Two samples of an internal reference material were analyzed after every five to ten measurements in order to calibrate the system and compensate for drift with time. Isotope ratios were expressed as

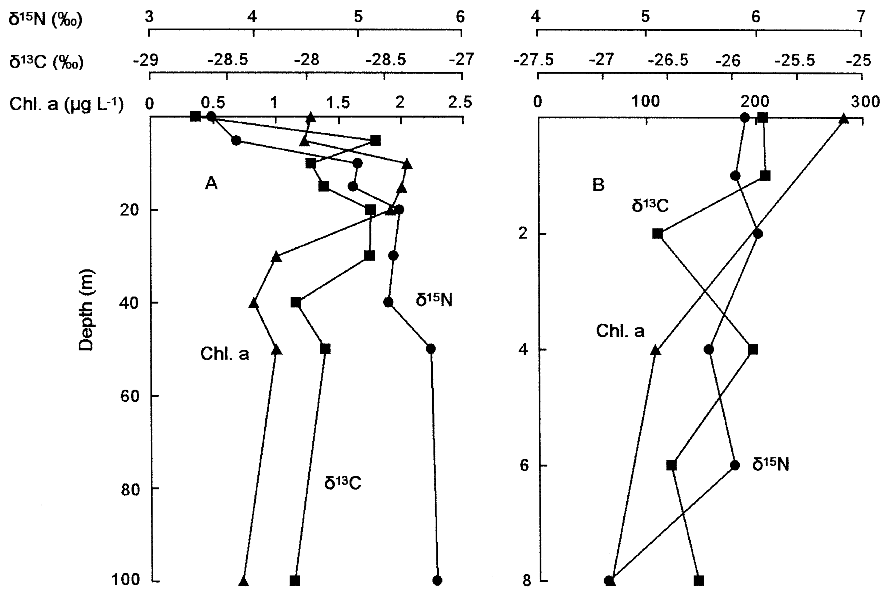

Figure 2. Variations of stable carbon (■) and nitrogen (●) isotope compositions of POM, and Chl. *a* (▲) of Lake Fuxian (A) and Lake Xingyun (B).

parts-per-thousand (‰) differences from a standard reference material using the equation: $\delta X(‰) = (R_{sample}/R_{standard} - 1) \times 1000$, where X is ^{15}N or ^{13}C, R is the corresponding ratio $^{15}N/^{14}N$ or $^{13}C/^{12}C$. The standard reference materials were Vienna Pee Dee Belemnite and atmospheric nitrogen for carbon and nitrogen, respectively. International reference materials were IAEA-NBS18, IAEA-USGS24, IAEA-USGS25 and IAEA-USGS26. The standard deviations of replicate analyses were approximately ± 0.3‰ for both $\delta^{13}C$ and $\delta^{15}N$.

RESULTS AND DISCUSSION

Table 1 gives an overview of the average values of limnological measurements in different layers from the sampling sites of Lake Fuxian and Lake Xingyun, which indicates that Lake Fuxian is a typical oligotrophic lake while Lake Xingyun undergoes a serious eutrophic state. POM in Lake Fuxian exhibited $\delta^{13}C$ from -28.7‰ to -27.6‰ and $\delta^{15}N$ from 3.6‰ to 5.7‰. In the photic layers of the lake, $\delta^{13}C$ and $\delta^{15}N$ of POM, and Chl. *a* showed similar trends, which might be driven mainly by phytoplankton physiology, since it has been suggested that most of the lake organic matter is supplied by autochthonous photosynthetic production in euphotic layer of Lake Fuxian (Hayakawa et al., 2002; Sakamoto et al., 2002), and the active photosynthetic assimilation of inorganic carbon and nitrogen sources in lake water with a small isotopic discrimination could result in relatively enriched ^{13}C and ^{15}N of phytoplankton (Yoshioka and Wada, 1994; Kendall et al., 2001). In the layers of mesolimnion and hypolimnion, $\delta^{13}C$ and Chl. *a* decreased respectively to -28.1‰ and $0.7 \mu g \cdot L^{-1}$, whereas $\delta^{15}N$ increased to 5.7‰ (Fig. 2).

Organic matters both produced by photosynthesis and from watershed were decomposed biologically in the mesolimnion and hypolimnion where the lake undergoes hypolimnetic anoxic condition (Hayakawa et al., 2002; Sakamoto et al., 2002). Yoshioka et al. (1988) and Cole et al. (2004) suggested that, because of denitrification and volatilization of ammonia in anoxic conditions, dissolved inorganic nitrogen usually has a relatively high $\delta^{15}N$ about 10‰ to 22‰. Lehmann (2002) documented that, with the development of anoxia in deep Lake Lugano, sections in the bottom waters shows very negative $\delta^{13}C$ values of up to -60‰, indicating that as much as 80% of the organic matter at deep layers is synthesized in the water column by aerobic and/or anaerobic bacteria utilizing methane as their carbon source. Based on these facts, the relatively negative $\delta^{13}C$ and positive $\delta^{15}N$ values of POM associated with the development of anaerobic conditions in hypolimnion of Lake Fuxian were most likely because that sections in the deep layer water were partially synthesized microbiologically by utilizing ^{13}C-depleted and ^{15}N-enriched sources. In Lake Xingyun, vertical changes of $\delta^{13}C$ and $\delta^{15}N$ of POM were not obvious (ranging from -26.6‰ to -25.8‰ and from 4.6‰ to 6.0‰, respectively), which might be due to the active vertical mixing of lake water by wind in this shallow lake.

When considering all stable isotope data, the average $\delta^{13}C$ and $\delta^{15}N$ values of POM in Lake Xingyun were respectively 1.8‰ and 1.1‰ higher than those in Lake Fuxian. The relatively enriched $\delta^{13}C$ and $\delta^{15}N$ of POM in the eutrophic Lake Xingyun might be partially due to that active utilization of inorganic carbon and nitrogen sources with a small isotopic discrimination by phytoplankton (Kendall et al., 2001), since primary production rate of Lake Xingyun was 4-5 times higher than that of Lake Fuxian (Hayakawa et al., 2002). Lake Xingyun also receives high levels of anthropogenically derived N and C from its surrounding catchment through sewage drainage systems. Previous studies have shown that anthropogenical sewage and animal waste usually have relatively high $\delta^{15}N$ (Mariotti, 1986; Kendall et al., 2001), and nitrogen and carbon metabolism concomitant with eutrophication in lake sediment including biochemical and physicochemical processes could also cause the enrichment of ^{13}C and ^{15}N (Yoshioka et al., 1988; Gu et al., 2004). Thus, the relatively high $\delta^{13}C$ and $\delta^{15}N$ of POM from Lake Xingyun may also indicate active utilization of heavy-isotope-enriched inorganic carbon and nitrogen sources from sewage and animal waste by phytoplankton of the lake. The difference in stable isotope signatures of Lake Fuxian and Lake Xingyun observed in this study demonstrated the dynamic nature in isotopic signatures of different trophic state of lakes. The present study, together with those of previous studies, illustrate that stable carbon and nitrogen isotopes are suitable as indicators of trophic state to assess water quality of aquatic ecosystem (Cabana and Rasmussen, 1996; Gu et al., 1996; Cole et al., 2004).

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