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INFLUENCE OF AQUATIC PLANT PHOTOSYNTHESIS ON THE RESERVOIR EFFECT OF GENGGAHAI LAKE, NORTHEASTERN QINGHAI-TIBETAN PLATEAU

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ABSTRACT. Terrestrial plant remains in the sediments of lakes from semi-arid and arid regions are rare and therefore the establishment of a sediment chronology depends on accurate assessment of the reservoir effect of the lake water. In a study of Genggahai Lake in the Gonghe Basin, northeastern Qinghai-Tibetan Plateau, we used accelerator mass spectrometry radiocarbon (AMS ^{14}C) dating to determine the age of (1) dissolved inorganic carbon in the water (DIC_{LW}), (2) macrophyte remains in the uppermost samples of core sediments, (3) living *P. pectinatus* in the lake, and (4) dissolved inorganic carbon of spring water in the catchment. The results show that the ages of the DIC_{LW} (910 ^{14}C yr BP on average) were much younger than the ages of the groundwater (6330 ^{14}C yr BP on average), which may result mainly from CO_2 exchange between the lake water and the atmosphere. In addition, the ^{14}C ages of DIC_{LW} and macrophyte remains in the uppermost core sediments varied from site to site within the lake, which we ascribe to the different photosynthesis rates of *Chara* spp. and vascular plants. The higher photosynthesis rate of *Chara* spp. decreases lake-water pCO_2, which leads to more atmospheric CO_2 being absorbed by the lake water, and thereby greatly reducing the age of carbon species in areas dominated by *Chara* spp. Although Genggahai Lake is well mixed, the differences between the apparent ages of the lake water are significantly modulated by the photosynthesis intensity of submerged plants.

KEYWORDS: charophyte, China, dissolved inorganic carbon, radiocarbon dating, reservoir effect.

INTRODUCTION

Lake sediments from arid and semi-arid areas provide high-resolution records of climatic and environmental changes. Radiocarbon (^{14}C) dating has been widely used to develop chronologies of lake sediments as old as ~50,000 yr (Martin 1999). Terrestrial plant remains in lacustrine sediments are ideal materials for ^{14}C dating, because their carbon is derived directly from atmospheric CO_2 (Bertrand et al. 2012). However, in arid regions the sparse vegetation cover and rapid organic matter decomposition rate often result in the scarcity of terrestrial plant remains in the lake sediments (Zhang et al. 2006). Therefore, in most cases lake sediment chronologies must be based on the dating of bulk organic matter, aquatic plant remains, and/or carbonates (e.g. Shen et al. 2005a, 2005b; Liu et al. 2007; Zhao et al. 2010; An et al. 2012). However, these materials are usually composed of a complex mixture of carbon from various sources, and, depending on the magnitude of the reservoir effect of the lake, they typically yield ^{14}C ages that are older than the true age (Fontes et al. 1996). Therefore, the chronological framework provided by the dating of these materials may be unreliable unless the reservoir effect is properly assessed (Stein et al. 2004; Zhou et al. 2009; Ascough et al. 2010; Hou et al. 2012).

The potential reservoir effect of a lake can be assessed using different methods. Assuming the sedimentation rate was constant during the recent past, the reservoir effect can be estimated from the intercept on the age axis using a linear regression between ^{14}C age and depth (Fontes et al. 1996; Shen et al. 2005a, 2005b). However, this assumption is unlikely for most lakes, and therefore, polynomial regressions are often used when the sedimentation rate in a lake has changed through time (e.g. Li et al. 2012; Zhou et al. 2014; Zhang et al. 2016a, 2016b). In addition, the reservoir effect of lakes can also be determined by a mass balance model that allows for different sources of carbon transported to the lake water if their respective ^{14}C activities can be quantified (Yu et al. 2007). Such a model requires a better understanding of modern carbon cycles in watershed ecosystems. However, the past carbon cycles of a lake are

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difficult to quantify; furthermore, the ^{14}C ages of dissolved inorganic carbon of lake water (DIC_{LW}) and aquatic plant remains from surface sediments usually vary between different areas of a lake (e.g., Geyh et al. 1998; Mischke et al. 2013), indicating that the reservoir effects of sediment cores from different lake areas may be inconsistent; this further compounds the difficulty of assessing the potential reservoir effect. Therefore, thorough investigations of the variability of the reservoir effect and its potential determining factors are essential to provide insights into the assessment of the reservoir effects of sediment cores.

In general, the reservoir effect of aquatic plant remains is controlled by the age of the DIC_{LW}, which depends mainly on the input of exogenous old carbon and on CO_2 exchange between the lake water and the atmosphere (Hatté and Jull 2007; Zhang et al. 2016a). In lakes with a relatively stable hydrological cycle and well-mixed lake water, the photosynthesis of aquatic plants will significantly affect lake-water pCO_2 and CO_2 exchange between the lake water and the atmosphere (Longhurst and Harrison 1989; Coletta et al. 2001), and therefore it is likely to impact the reservoir effect of DIC_{LW}. However, detailed studies of the influence of photosynthesis on reservoir effects are scarce. Here, we present the results of ^{14}C dating of different carbon species from the Genggahai Lake system, a small, shallow lake in the Gonghe Basin on the northeastern Qinghai-Tibetan Plateau; submerged macrophytes currently flourish in the lake. Combined with the results of monitoring of the physical and chemical properties of the lake water from different parts of the lake with different aquatic plant communities, we attempt to investigate the variability of ^{14}C ages of different carbon sources and their potential influencing factors.

STUDY AREA

Genggahai Lake (36°11′N, 100°06′E) is in the central Gonghe Basin (Figure 1a), ~50 km south of Qinghai Lake, at an altitude of 2860 m above sea level (asl). From the meteorological data from Gonghe Station from 1981 to 2010 AD, the mean annual temperature was ~4.6°C and the mean annual precipitation was ~325 mm; precipitation was mainly from May to September (Figure 1a). The basin was filled by fiuviolacustrine sediments (the Gonghe Formation), during the early- to mid-Pleistocene, and was subsequently tectonically up lifted after the mid-Pleistocene (Perrineau et al. 2011). Aeolian activity is prevalent in the basin at the present (Qiang et al. 2014).

The lake contains two separate basins, Upper Genggahai and Lower Genggahai Lake (Figure 1b). The latter is currently almost dry, and in this study Genggahai Lake refers to Upper Genggahai Lake. It is a small shallow lake with an area of ~2 km^2 and a maximum water depth of ~1.8 m. The lake is currently occupied by the dense growth of submerged macrophytes (e.g., *Potamogeton pectinatus*, *Myriophyllum spicatum*, and *Chara* spp.) and is surrounded by grassland. Currently, there are no large glaciers on the summits of the surrounding mountains and thus excess meltwater has little effect on the modern hydrology. The lake has no natural discharge outlets or direct surface inflows and is fed mainly by groundwater. Within the lake basin, springs emerge as artesian water. Small spring-water streams emanate from sediment outcrops in the northwest part of the catchment and feed Genggahai Lake and sustain the grassland (Figure 1b). The modern spatial distribution of aquatic plants in the lake depends on water depth (Figure 1b). *Chara* spp. occupy the depth range of 20–100 cm, while *P. pectinatus* and *M.* spicatum grow within the depth range of 50–180 cm (Qiang et al. 2013). Desert steppe mainly dominates the vegetation community in the terrestrial part of the catchment (Qiang et al. 2014). Human activity is of low intensity around the lake, consisting of grazing by the animals of Tibetan herdsmen.

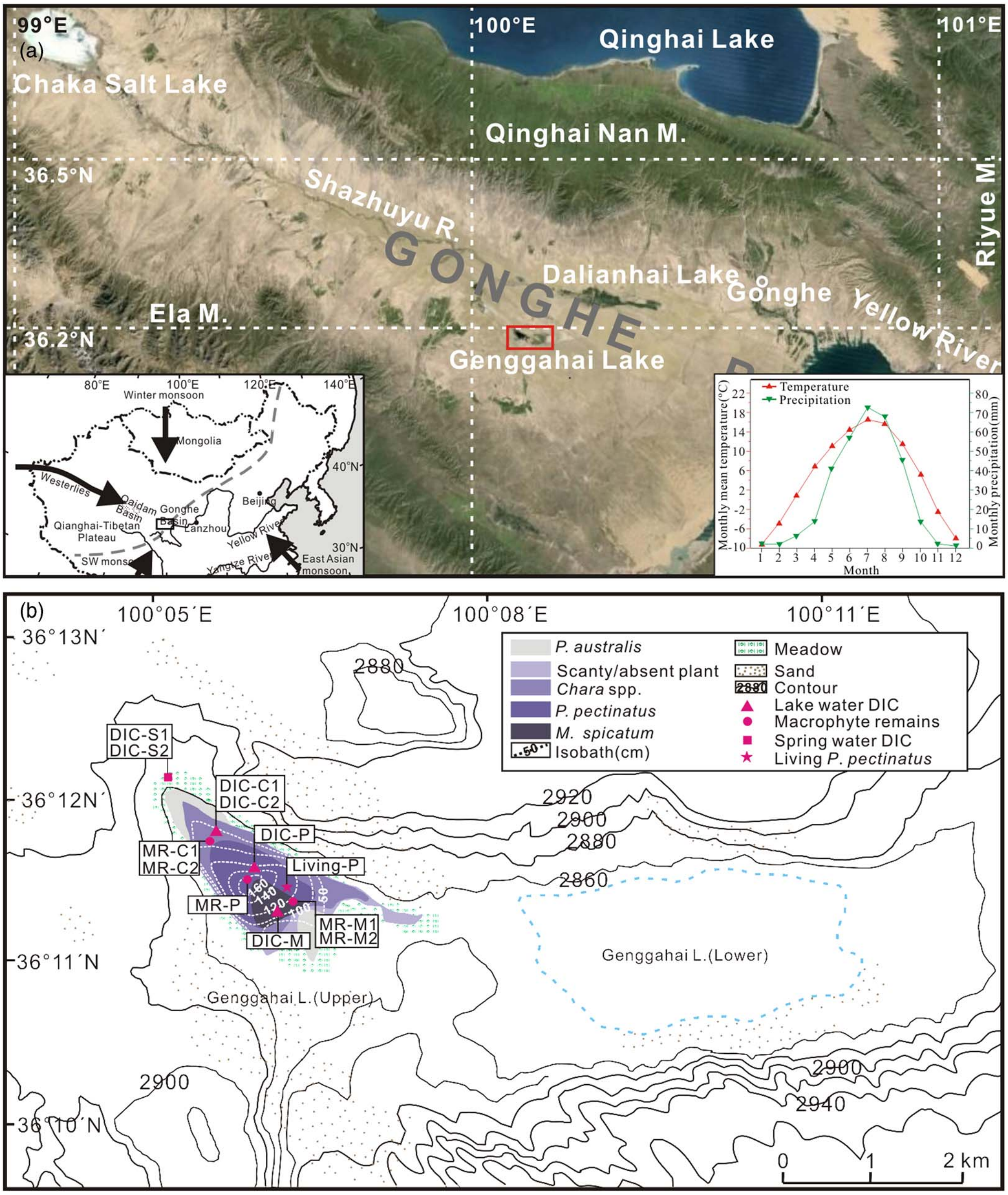

Figure 1 Settings and location. (a) Physical environments of the Gonghe Basin. Insets: Major atmospheric circulation systems influencing the study area (the modern extent of the Asian summer monsoon is indicated by the grey dashed line; after Gao et al. 1962); and the monthly mean precipitation and mean temperature at Gonghe Meteorological Station from 1981 to 2010 AD (source: Chinese Meteorological Administration). (b) Topography of the area surrounding Genggahai Lake, lake bathymetry, and location of sampling sites. The filled triangles, filled circles, filled squares, and filled pentagrams represent the locations of the lake-water DIC samples, macrophyte-remain samples, the spring-water DIC samples, and the living *P. pectinatus* sample, respectively.

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MATERIALS AND METHODS

In the summer seasons (May to September) from 2012 to 2013 we conducted a monitoring program of the physical and chemical properties of the lake, in areas with different aquatic plant communities (Figure 1b). Temperature, dissolved oxygen (DO) concentration, pH, and conductivity of lake water were measured using a portable water quality analyzer (Aquaread AP-1000). Macrophytes (*Chara* spp., *P. pectinatus*, and *M. spicatum*), lake water at the 20-cm depth of the water body from the monitoring sites, and spring water in the northwestern part of the catchment, were collected. Three sediment cores were recovered from different areas of the lake using a modified Livingstone piston corer. Large pieces of macrophyte remains (MR) from the uppermost 1-cm interval of the sediment cores were picked for AMS ^{14}C dating. Samples MR-C1 and MR-C2 are the remains of *Chara* spp. Samples MR-P, MR-M1 and MR-M2 are the remains of vascular plants (*P. pectinatus* and *M. spicatum*) (Figure 1b).

Water samples were stabilized using 20 μL saturated mercuric chloride ($HgCl_2$) solution and sealed in the field. Dissolved inorganic carbon (DIC) was precipitated as $BaCO_3$ by adding 10 mL of saturated $BaCl_2$ solution to 500 mL water before filtering with cellulose nitrate filter papers, followed by drying at 40°C. DIC concentration was measured by acid and alkali titration. Stable carbon isotopes of aquatic plants ($\delta^{13}C_{org}$) were measured using an on-line Conflo III-Delta Plus isotope ratio mass spectrometry, combined with a Flash EA1112 elemental analyzer. The results are reported in ‰ relative to VPDB. The precision was better than 0.1‰ from replicated measurements of standards. All the above experiments were carried out in the Key Laboratory of Western China's Environmental Systems, Lanzhou University. Six DIC samples, five samples of macrophyte remains and one sample of living *P. pectinatus* (Figure 1b), were radiocarbon dated using accelerator mass spectrometry (AMS) by Beta Analytic Inc. (Miami, FL, USA). The fraction of modern carbon (pMC) of the sample is defined as (Donahue et al. 1990)

$$pMC = D^{14}C_S / D^{14}C_{1950}$$

where $D^{14}C_S$ is the measured ratio for the sample, blank-corrected and adjusted to $\delta^{13}C$ values; and $D^{14}C_{1950}$ is the measured ratio of the standard, blank-corrected, adjusted to $\delta^{13}C$ values, and recalculated to AD 1950. The AMS ^{14}C dates are standardized using a consensus value for the National Institute of Standards and Technology (NIST) modern reference standard (SRM 4990C). The ^{14}C age of a sample is defined as

$$^{14}C_{age} = -8033 \times \ln(pMC)$$

RESULTS

^{14}C Ages

The sampling locations are shown in Figure 1b and sample details and the ^{14}C ages of DIC and macrophyte remains are listed in Table 1. Two spring water DIC samples (DIC_{Spring}; i.e., DIC-S1 and DIC-S2) have significantly different ^{14}C ages (7030 ± 30 ^{14}C yr BP and 5630 ± 30 ^{14}C yr BP) (Table 1). Compared to spring water, the ^{14}C ages of lake-water DIC (DIC_{LW}) and macrophyte remains (MR) from the uppermost 1-cm interval of the sediments are much younger, ranging from 490 ± 30 to 1440 ± 30 ^{14}C yr BP (Table 1). It is noteworthy that the ^{14}C ages of DIC_{LW} and MR from areas dominated by *Chara* spp. (DIC_{Chara} and MR_{Chara}; i.e., DIC-C1, DIC-C2, MR-C1 and MR-C2) are younger than those from areas dominated by vascular plants ($DIC_{Vascular}$ and $MR_{Vascular}$; i.e., DIC-P, DIC-M, MR-P, MR-M1 and MR-M2) (Table 1). In addition, a living individual of *P. pectinatus* (Living-P) was dated to 1500 ± 30 ^{14}C yr BP.

Table 1 ^{14}C ages of spring water, lake water and plant macrophytes from core top samples.

Sample nr	Material	$\delta^{13}C$ (‰.)	pMC (%)	^{14}C age (yr BP)	Sampling date
DIC-S1	Spring DIC	–13.1	41.7	7030 ± 30	September 8, 2012
DIC-S2	Spring DIC	–11.8	49.6	5630 ± 30	July 9, 2016
DIC-C1	Water DIC	–17.3	91.4	720 ± 30	September 8, 2012
DIC-C2	Water DIC	–15	91.5	710 ± 30	July 9, 2016
DIC-P	Water DIC	–6.8	87.2	1100 ± 30	September 8, 2012
DIC-M	Water DIC	–13.4	87.3	1090 ± 30	September 8, 2012
MR-C1	*Chara* spp.remains	–12.8	94.1	490 ± 30	January 22, 2013
MR-C2	*Chara* spp. remains	–14	92.3	640 ± 30	January 22, 2013
MR-P	*P. pectinatus* remains	–15.2	85.5	1010 ± 30	January 20, 2008
MR-M1	*M. spicatum* remains	–12.2	83.7	1430 ± 30	January 22, 2013
MR-M2	*M. spicatum* remains	–11.5	83.6	1440 ± 30	January 22, 2013
Living-P	Living *P. pectinatus*	–9.2	83.0	1500 ± 30	July 9, 2016

Physical and Chemical Properties of the Lake Water and $\delta^{13}C_{org}$ Values of Aquatic Plants

The pH values and conductivity of the lake water range from 8.1 to 9.5 and from 1.5 to 2.1 ms cm^{-1}, respectively. The temperature of the lake water is high in June and July. In addition, the lake water from areas dominated by *Chara* spp. has a higher DO concentration (DO_{Chara}) and lower DIC concentration (DIC_{Chara}) than those from areas dominated by vascular plants ($DO_{Vascular}$ and $DIC_{Vascular}$) (Figure 2d–e). The concentrations of DO_{Chara} and $DO_{Vascular}$ range from 100–248% (mean of 188%) and 85–220% (mean of 157%), respectively. The ranges of DIC_{Chara} and $DIC_{Vascular}$ concentrations are 8–14 mmol L^{-1} (mean of 10 mmol L^{-1}) and 10–15 mmol L^{-1} (mean of 12 mmol L^{-1}), respectively. In addition, *Chara* spp. has more negative $\delta^{13}C_{org}$ values, with the range of –18.6 to –14‰ (mean of –16.1‰), than those of vascular plants, which have the range of –15.2 to –9.3‰ (mean of –12.5‰) (Figure 2f).

DISCUSSION

The two DIC_{Spring} samples, collected in 2012 and 2016, have significantly different ^{14}C ages: 7030 ± 30 ^{14}C yr BP and 5630 ± 30 ^{14}C yr BP (Table 1). The catchment substrate of Genggahai Lake consists mainly of surface fluvial-fan sediments and loose fluvio-lacustrine sediments of the Gonghe Formation (Xu et al. 1984; Perrineau et al. 2011), which contain abundant ancient carbonates. Dissolution of carbonates in topsoil or sediments within the catchment produces old DIC which infiltrates into the groundwater (Arslan et al. 2006; Olaaon 2009). However, the infiltrating water also carries atmospheric CO_2 and the CO_2 generated by plant root respiration, which results in relatively younger ^{14}C ages of the groundwater. Nevertheless, the distinctly different ^{14}C ages of the two DIC_{Spring} samples may suggest that the ^{14}C age of groundwater within the lake basin is quite sensitive to the meteorological conditions, which is probably related to the regional geological and geomorphic features. The porous nature of the sediments and the steep hydraulic gradient make the catchment of Genggahai Lake highly permeable (Qiang et al. 2017), which is conducive to the input of old DIC into the groundwater and may largely account for the significant difference in the ^{14}C ages of the two DIC_{Spring} samples. In addition, variations in the regional meteorological conditions may also play an important role in determining the ^{14}C ages of the groundwater, which need to be further investigated by long term, continuous monitoring of the ^{14}C ages of spring water.

The DIC_{LW} and MR have much younger ^{14}C ages compared to those of the groundwater, varying from 490 ± 30 to 1440 ± 30 ^{14}C yr BP. Further, the ^{14}C ages of DIC_{chara} and MR_{chara}

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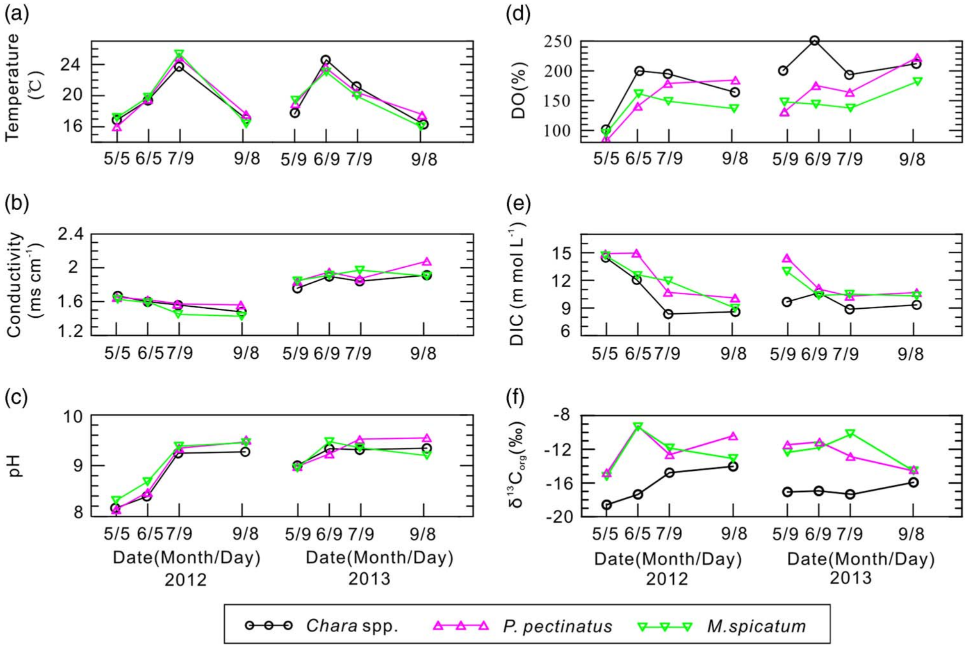

Figure 2 Physical and chemical properties of lake water in areas dominated by different submerged aquatic plants, and stable carbon isotope values of aquatic plants. (a–e) Temperature, conductivity, pH, DO, and DIC contents of the lake water, respectively. (f) $\delta^{13}C_{org}$ of various aquatic plants.

are younger than those of $DIC_{Vascular}$,$MR_{Vascular}$ and Living-P (Table 1). The water in Genggahai Lake has a high alkalinity which could inhibit carbonate dissolution; therefore, the old carbon in the lake is mainly derived from dissolved lithogenic and biogenic sources due to inflowing groundwater (Abbott and Stafford 1996; Geyh et al. 1998; Billett et al. 2007). Consequently, it would be expected that the input of groundwater (spring water) into lakes may affect the ^{14}C ages of DIC_{LW} and MR. Based on the dating of DIC_{LW} from Gahai Lake in the Qaidam Basin, Zhang et al. (2016a) pointed out that the input of groundwater into the lake leads to site-specific ^{14}C ages of the DIC_{LW}, which decreased rapidly with increasing distance from the springs that feed the lake. In the Genggahai Lake basin, the ^{14}C ages of samples DIC-S1 and DIC-S2, collected at different times, differ by 1400 yr, while samples DIC-C1 and DIC-C2 have similar ^{14}C ages, i.e., 720 ± 30 ^{14}C yr BP and 710 ± 30 ^{14}C yr BP. This reflects the fact that the input of exogenous old DIC dissolved in the groundwater has not significantly changed the ^{14}C ages of DIC_{LW}. The springs flowing into Genggahai Lake emerge as artesian water, reflecting the lower position of the lake relative to the catchment water table (Qiang et al. 2017). Therefore, it is plausible that artesian water flowing into Genggahai Lake might also be found in other parts of the catchment and even in the lakebed. Nevertheless, the sub-surface artesian springs feeding lakes probably lead to efficient mixing of the lake water (Anderson et al. 2005), and thus it would be expected that the ages of DIC_{LW} would be similar, even in different areas of the lake. However, the apparent difference between the ages of DIC_{LW} and MR from the areas dominated by different aquatic plants suggests that the input of exogenous old DIC transported by the spring-water streams cannot fully explain the differences in the dating results.

Besides the input of old carbon, CO_2 exchange between the lake water and the atmosphere also has a large impact on the reservoir ages of lakes (Hatte and Jull 2007). A significant exchange of CO_2 between them would impart a younger bias to the DIC_{LW} ages (Fontes et al. 1996). At Genggahai Lake, the much younger ^{14}C ages of DIC_{LW}, compared to the ages of groundwater, suggest that the lake water is proceeding towards equilibrium with the atmosphere. In general, the CO_2 exchange between lake water and the atmosphere is controlled by lake water stratification (i.e., water depth), wind regime, and ice-cover duration (Zhang et al. 2016a). There is no thermal stratification in such a shallow water body as Genggahai Lake and in addition wind regimes in the study area are generally strong; thus, these conditions favor a high rate of CO_2 exchange between the lake water and the atmosphere. In addition, the photosynthesis of aquatic plants exerts a large influence on the rate of CO_2 exchange between lake water and the atmosphere (Longhurst and Harrison 1989). Coletta et al. (2001) have demonstrated that that the intense photosynthesis of aquatic plants in the summer season consumes a large amount of DIC and decreases the lake-water pCO_2, which effectively enhances the rate of CO_2 exchange between lake water and the atmosphere, and results in the increased absorption of atmospheric CO_2 by the lake water. Therefore, the overall young ^{14}C ages of DIC_{LW} and MR in Genggahai Lake can be ascribed to the photosynthesis of aquatic plants.

The temperature, pH and conductivity of the lake water are consistent across the different lake areas (Figure 2a–c), which reflects the fact that the shallow water body and the strong wind regimes at Genggahai Lake promote thorough mixing. Nevertheless, the ^{14}C ages of DIC_{LW} from areas of the lake with different aquatic plant communities are still variable. The lake-water samples were collected at 20-cm water depth, which excludes the influence of water depth on the variations in the ^{14}C ages of $DIC_{LW.}$ In fact, the photosynthesis rates of *Chara* spp. and vascular plants are distinctly different (Van den Berg et al. 2002), which is also revealed by the different DO and DIC concentrations in areas of the lake with different aquatic plant communities (Figure 2d–e). Aquatic plants absorb DIC and release oxygen through photosynthesis, resulting in high concentrations of DO and low concentrations of DIC in lake water. Therefore, the high concentrations of DO_{Chara} and the low concentrations of DIC_{Chara} reflect the higher photosynthesis rate of *Chara* spp. compared to vascular plants (Figure 2d–e). Moreover, *P. pectinatus*, *M. spicatum*, and *Chara* spp. preferentially utilize ^{12}C for photosynthesis, giving rise to depleted ^{13}C values in plant tissues (Hammarlund et al. 1997; Sand-Jensen 1983; Ray et al. 2003). The more negative $\delta^{13}C_{Chara}$ is further evidence of the high photosynthesis rate of *Chara* spp. (Figure 2f). The photosynthesis of aquatic plants not only fixes carbon into plant tissues, but it also promotes carbonate precipitation (Apolinarska et al. 2011). The high photosynthesis rate of *Chara* spp. can lead to heavy carbonate precipitation directly onto charophyte plant surfaces as mineral encrustations (Apolinarska et al. 2011). Blindow (1992) noted that encrustations account for up to 70% of the dry mass of *Chara tomentosa*. In fact, abundant encrustations are also found on *Chara* spp. from Genggahai Lake (Qiang et al. 2013). During the growing season, the rapid and high consumption of DIC in the lake due to the intense photosynthesis of *Chara* spp. significantly promotes CO_2 exchange between the lake water and the atmosphere, thereby inducing a large bias in the ages of carbon species towards younger values in areas dominated by *Chara* spp. The ^{14}C age of DIC-C1 is almost identical to that of DIC-C2, although the former was affected by the input of much older exogenous carbon by the inflowing groundwater (Table 1). The lake water in areas dominated by *Chara* spp. at the time of sampling of DIC-C1 has a higher concentration of DO_{Chara} (165%) and a lower concentration of DIC_{Chara} (9 mmol L^{-1}), compared to DIC-C2 (135% and 13 mmol L^{-1}, respectively), reflecting a higher photosynthesis rate. The higher photosynthesis rate of *Chara* spp. may have largely compensated for the influence of the input of exogenous old carbon and maintained the overall young age of DIC-C1. The difference in the ages of lake water and macrophyte remains in Genggahai Lake suggests that photosynthesis of aquatic plants plays an important role in determining changes in the reservoir effect of lake water.

CONCLUSIONS

In Genggahai Lake, the ^{14}C ages of living plants, DIC_{LW} and MR in the uppermost sediments are much younger than those of groundwater. This can be ascribed to the exchange CO_2 between the lake water and the atmosphere, in addition to the absence of stratification and the presence of a strong wind regime. The ^{14}C ages of the lake-water DIC and macrophyte remains in the uppermost core sediments vary from site to site within the lake, which may be the result of differences between the photosynthesis rates of *Chara* spp. and vascular plants. Our results suggest that the photosynthesis intensity of aquatic plants, or the occurrence of succession within the aquatic community, should be considered when assessing the reservoir effects of a lake system, especially for lakes with a dense growth of aquatic plants.

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