ELEMENTA Science of the Anthropocene

Ota, K, et al. 2021. Lake water dissolved inorganic carbon dynamics revealed from monthly measurements of radiocarbon in the Fuji Five Lakes, Japan. *Elem Sci Anth*, 9: 1. DOI: https://doi.org/10.1525/elementa.2020.00149

RESEARCH ARTICLE

# Lake water dissolved inorganic carbon dynamics revealed from monthly measurements of radiocarbon in the Fuji Five Lakes, Japan

Kosuke Ota[1,2,*], Yusuke Yokoyama[1,2,3,4,5,*], Yosuke Miyairi[1], Shinya Yamamoto[6], and Toshihiro Miyajima[1]

Lakes are sensitive recorders of anthropogenic activities, as human society often develops in their vicinity. Lake sediments thus have been widely used to reconstruct the history of environmental changes in the past, anthropogenic, or otherwise, and radiocarbon dating provides chronological control of the samples. However, specific values of radiocarbon in different carbon reservoirs due to the different pathways of radiocarbon from the upper atmosphere to the lake, called the radiocarbon reservoir age, is always difficult to evaluate because of dynamic processes in and around lakes. There are few systematic studies on radiocarbon reservoir ages for lakes owing to the complex radiocarbon transfer processes for lakes. Here, we investigate lake waters of the Fuji Five Lakes with monthly monitoring of the radiocarbon reservoir effects. Radiocarbon from dissolved inorganic carbon (DIC) for groundwater and river water is also measured, with resulting concentrations ($\Delta^{14}C$) at their lowest at Lake Kawaguchi in August 2018 (–122.4 $\pm$ 3.2‰), and at their highest at Lake Motosu in January 2019 (–22.4 $\pm$ 2.5‰), despite a distance of 25 km. However, winter values in both lakes show similar trends of rising $\Delta^{14}C$ (about 20‰). Our lake water DIC $\Delta^{14}C$ results are compared to previously published records obtained from sediments in Lake Motosu and Lake Kawaguchi. These suggest that total organic carbon and compound-specific radiocarbon found in sediments are heavily influenced by summer blooms of aquatic organisms that fix DIC in water. Thus, future studies to conduct similar analyses at the various lakes would be able to provide further insights into the carbon cycle around inland water, namely understanding the nature of radiocarbon reservoir ages.

**Keywords:** Radiocarbon reservoir effect, Radiocarbon, Lake water, Groundwater, Lake sediments

## Introduction

Reconstructing past terrestrial environments is vital for a comprehensive understanding of the Anthropocene. Various techniques have been employed to this end, including the utilization of speleothems and tree-ring archives (e.g., Sakashita et al., 2017; Cheng et al., 2020), but lake sediments are unique as they are distributed widely in many parts of the world. In some lakes, annual varve counting techniques can be used to establish sediment chronology and quantify the timing of past environmental changes (e.g., Bronk Ramsey et al., 2012), but the majority of lake sediment studies rely on radiocarbon dating (e.g., Nakamura et al., 2016; Yamamoto et al., 2018; Ghazoui et al., 2019; Safaierad et al., 2020). Radiocarbon ($^{14}C$) measurements require careful consideration of the local radiocarbon reservoir effects (e.g., Jull et al., 2013; Yokoyama et al., 2019a). The radiocarbon reservoir effect is a phenomenon in which the $^{14}C$ ages of water and sediments have an older $^{14}C$ age than the ambient atmospheric radiocarbon ages due to the exchange of $^{14}C$-depleted carbon stored in soil or host rock (Ascough et al., 2010). Although freshwater ecosystems fix carbon from the atmosphere, dissolved carbon can also enter the lake water via groundwater. If the dissolved inorganic carbon (DIC) is derived from eroded carbonaceous bedrock, it may have very low amounts of $^{14}C$ and lead to a reservoir age in the catchment or basin area (Broecker and Walton, 1959).

Since radiocarbon reservoir ages reflect hydrosphere dynamics, there are many studies that consider changes in seawater radiocarbon in the ocean with time (e.g., Hirabayashi et al., 2017, 2019; Ota et al., 2019; Servettaz et al.,

[1] Atmosphere and Ocean Research Institute, The University of Tokyo, Chiba, Japan

[2] Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan

[3] Graduate Program on Environmental Sciences, Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, Japan

[4] Biogeochemistry Program, Japan Agency for Marine-Earth Science and Technology, Kanagawa, Japan

[5] Research School of Physics, The Australian National University, Canberra, Australia

[6] Mount Fuji Research Institute, Yamanashi Prefectural Government, Yamanashi, Japan

* Corresponding authors:
Emails: k.ota@aori.u-tokyo.ac.jp; yokoyama@aori.u-tokyo.ac.jp

2019). However, few systematic lake water reservoir age studies have been reported. The radiocarbon reservoir effect of lakes has been reported in many areas, with some areas having a sediment radiocarbon reservoir age of more than 1,500 years (e.g., Nakamura et al., 2016, Schneider et al., 2019). One source of atmospheric $^{14}C$ to consider is bomb-derived $^{14}C$ produced in the atmosphere during the nuclear weapons tests in the 1950s. "Bomb-$^{14}C$" increased rapidly during the decade of weapons testing (Broecker and Walton, 1959), then decreased due to exchange between the atmosphere and other carbon reservoir such as the oceans and biosphere (Sweeney et al., 2007). Subsequently, usage of fossil fuels has been increasingly important to reduce atmospheric $^{14}C$ level (Suess effect; Suess, 1955). In addition to atmospheric $^{14}C$, groundwater and/or river water may be the source of lake $^{14}C$ (Brady et al., 2009). Yu et al. (2007) constructed a mass balance model considering variations in $^{14}C$ due to changes in atmospheric, groundwater, and river water inflow or outflow. It has been suggested that the contribution of $^{14}C$ from these sources may vary due to environmental changes including anthropogenic forcing, such as the use of fossil fuels (Graven, 2015; Blattmann et al., 2018). However, few studies mention the time scale of the variation of radiocarbon reservoirs in lake water. Therefore, systematic sampling and analysis are needed to estimate reliable radiocarbon reservoir ages of lake water, including measurements on groundwater and river water.

The Fuji Five Lakes were selected for this study in order to monitor DIC radiocarbon fluctuations in lake water. Their proximity to each other allows us to collect water monthly from each of the lakes. The lakes are situated within 40 km from the flank of Mount Fuji. It is a unique research setting to understand lake dynamics because the size and depths of each lake are different (**Table 1**). Water stored in the Fuji Five Lakes is sourced from precipitation, groundwater, and surface water. Geological and hydrological surveys were conducted in the mid-1940s and 1960s for groundwater resource development (Hamano, 1976), and the regional hydrology was studied by Hayashi and Tsuboi (2005), reporting the source distribution of groundwater by utilizing hydrogen and oxygen isotope ratios. In recent years, chlorofluorocarbons (CFCs) and tritium measurements have been used to estimate groundwater ages (Asai and Tsujimura, 2010). However, the degree of groundwater contribution has not been determined due to limitations in the earlier studies (e.g., Ochiai, 1995).

In this study, DIC radiocarbon was measured monthly for the Fuji Five Lakes. The results are discussed in regard to local hydrological dynamics. Previously measured sediment total organic carbon (TOC) and compound-specific radiocarbon data were compared to DIC radiocarbon data for Lake Motosu and Lake Kawaguchi in order to examine local reservoir ages in the context of paleo environmental studies using lake sediment.

## Materials and methods

The Fuji Five Lakes are dammed lakes formed by the volcanic activity of Mt. Fuji. They are surrounded to the north by the Misaka and Tanzawa Mountains and to the south by Mt. Fuji (Takeuchi et al., 1995). The groundwater stream boundary 50 m underground was found by a survey conducted previously at altitudes of 900 m to 1,000 m at the foot of Mt. Fuji (Hamano, 1976). Most of the lake water in the Fuji Five Lakes is considered to be derived from the Mikasa or Tanzawa Mountains, and groundwater from Mt. Fuji is thought to rarely flow into the lake (Hamano, 1976). The section below 50 m is an impermeable layer, and groundwater has been shown to move along the buried fossil valley through the permeable upper layer (Ogata et al., 2014; Yamamoto et al., 2017a).

The map, water level, elevation, and water depth of the Fuji Five Lakes are shown in **Figure 1** and **Table 1**. Lakes Motosu, Shoji, and Sai are situated at around 900 m above sea level, whereas Lake Kawaguchi, on the east side of Lake Sai, is 831 m above sea level. Lake Yamanaka is the most eastern lake in the five lakes area and has an altitude of 981 m. There are no rivers that constantly discharge to or from the lakes, other than for Lakes Kawaguchi and Yamanaka. However, lake water is artificially released from Lake Motosu to the Fuji River, from Lake Sai to Lake Kawaguchi, and from Lake Kawaguchi to the Katsura River.

Lakes Motosu, Sai, and Shoji are located to the northwest of Mount Fuji (**Figure 1**). Lava flows cover the southern side of the Lakes Sai and Shoji from the surface to 135 m in depth (Chiba et al., 2010), and at the eastern side of Lake Motosu, a lava flow of 167 m thick was reported (Koshimizu et al., 2007). This characterizes the high underwater flow velocity (Ochiai, 1995). The other 3 sides are surrounded by the steep Misaka mountains of 1,000 m to 1,800 m, and there is no constant river inflow or outflow. Hamada et al. (2012) conducted a yearlong vertical survey of water temperature and water quality, noting that precipitation dominated the water balance.

Lake Kawaguchi is the lowest of the Fuji Five Lakes at an altitude of 831 m, with the southern shore of Lake Kawaguchi covered by lava from Mount Fuji (Takada et al., 2016). The other 3 sides are surrounded by Misaka Mountains with an altitude of 1,400 m to 1,700 m. The inflowing water from Rivers Tera and Oku from the Misaka Mountains is considered to be mainly underground water (Yoshizawa and Mochizuki, 2005; Yamamoto et al., 2017a). Groundwater resources have been investigated by Hamano (1976), and the outflow from the lake is suggested to be due to the underground valley structure in the southeastern part of Lake Kawaguchi (Yoshimura and Kawada, 1942; Kanno et al., 1986; Hayashi and Tsuboi, 2005; Ogata and Kobayashi, 2015; Yamamoto et al., 2017b). Mt. Fuji lava does not contain rocks such as limestone that reduce $\Delta^{14}C$, but calcareous rock layers have been reported in the Misaka Mountains to the northern side of the Fuji Five Lakes (Matsuda, 2007).

To the southwest of Lake Yamanaka, sediments of gently sloping volcanic foot fans from Mt. Fuji overlap, and from the north to the east, the Tanzawa mountains with an altitude of 1,200 m to 1,400 m of mountains. The Tanzawa Mountains around Lake Yamanaka are classified as impervious layers. The groundwater level of the Ichinosuna and Ohori rivers that inflow into the lake is higher

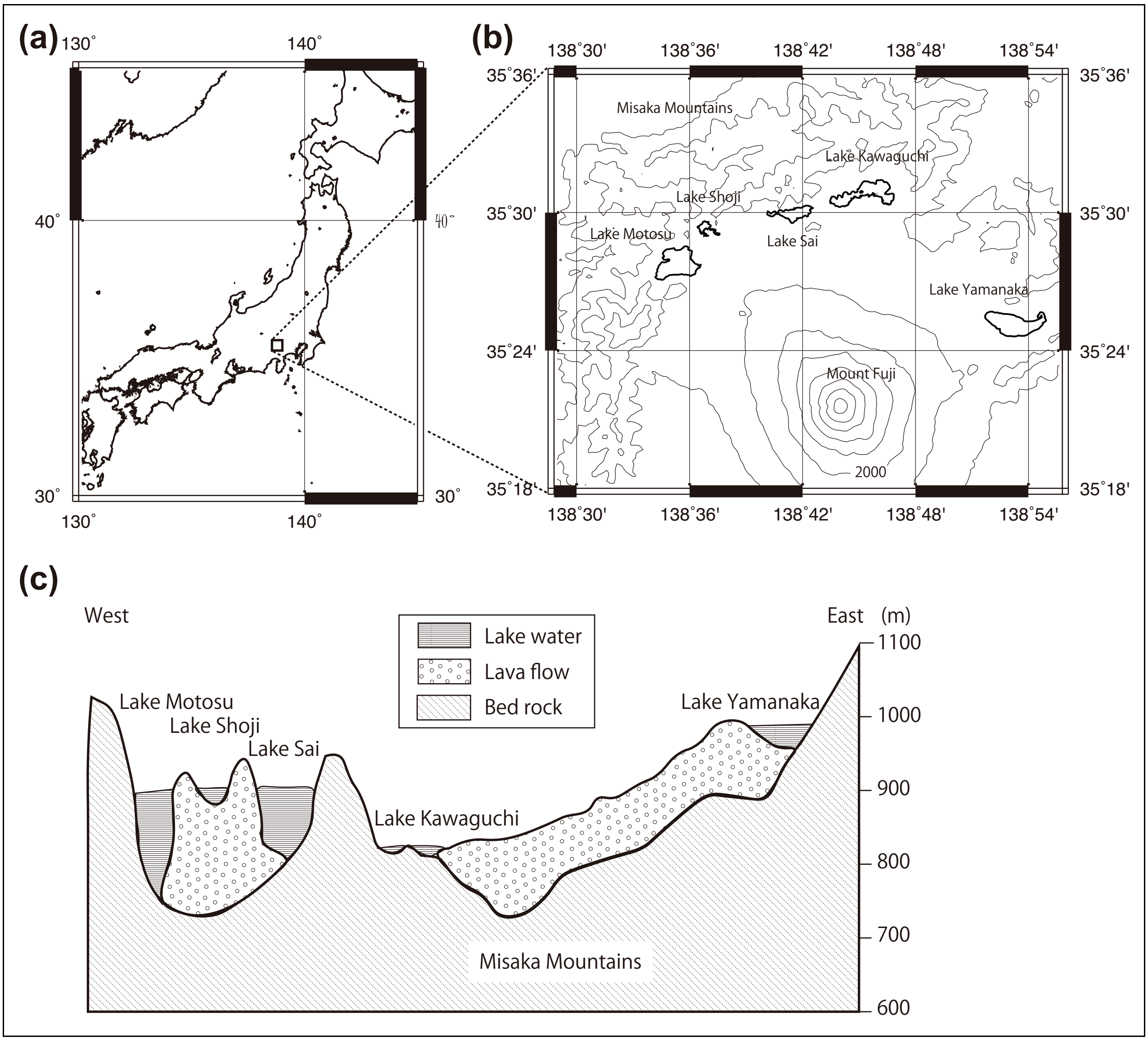


**Figure 1. Figures showing (a) map of Japan, (b) locations of Mount Fuji and the Fuji Five Lakes, and (c) west to east schematic cross section of Fuji Five Lakes (modified from Yamamoto, 1971).** DOI: https://doi.org/10.1525/elementa.2020.00149.f1

**Table 1.** Summary of sizes, depth, altitude, and retention time of Fuji Five Lakes (Geospatial Information Authority of Japan and Yamanashi Prefecture, 1993). DOI: https://doi.org/10.1525/elementa.2020.00149.t1

| Lake | Motosu | Shoji | Sai | Kawaguchi | Yamanaka |
|---|---|---|---|---|---|
| Area (km$^2$) | 4.7 | 0.5 | 2.1 | 5.7 | 6.8 |
| Altitude (m) | 900 | 900 | 900 | 831 | 981 |
| Maximum depth (m) | 121.6 | 15.2 | 71.7 | 14.0 | 13.3 |
| Average depth (m) | 67.9 | 3.7 | 34.8 | 9.8 | 9.2 |
| Retention time (year) | 7.9 | 0.11 | 2.3 | 0.37 | 0.52 |

than that of the western parts of the lake (Susuki and Taba, 1994).

### *Sampling*

Lake water was collected each month from June 2018 to April 2019 at the surface (0.5 m) of each lake for $\Delta^{14}C$ measurements (**Figure 2b**). A 250-ml glass bottle shaded with aluminum was used for water sampling, and 56 lake water samples were collected. Various other water samples were also analyzed to compare $\Delta^{14}C$ values, including groundwater (wells: $n = 11$) and river water ($n = 6$). For Lake Shoji, we were unable to collect lake water samples

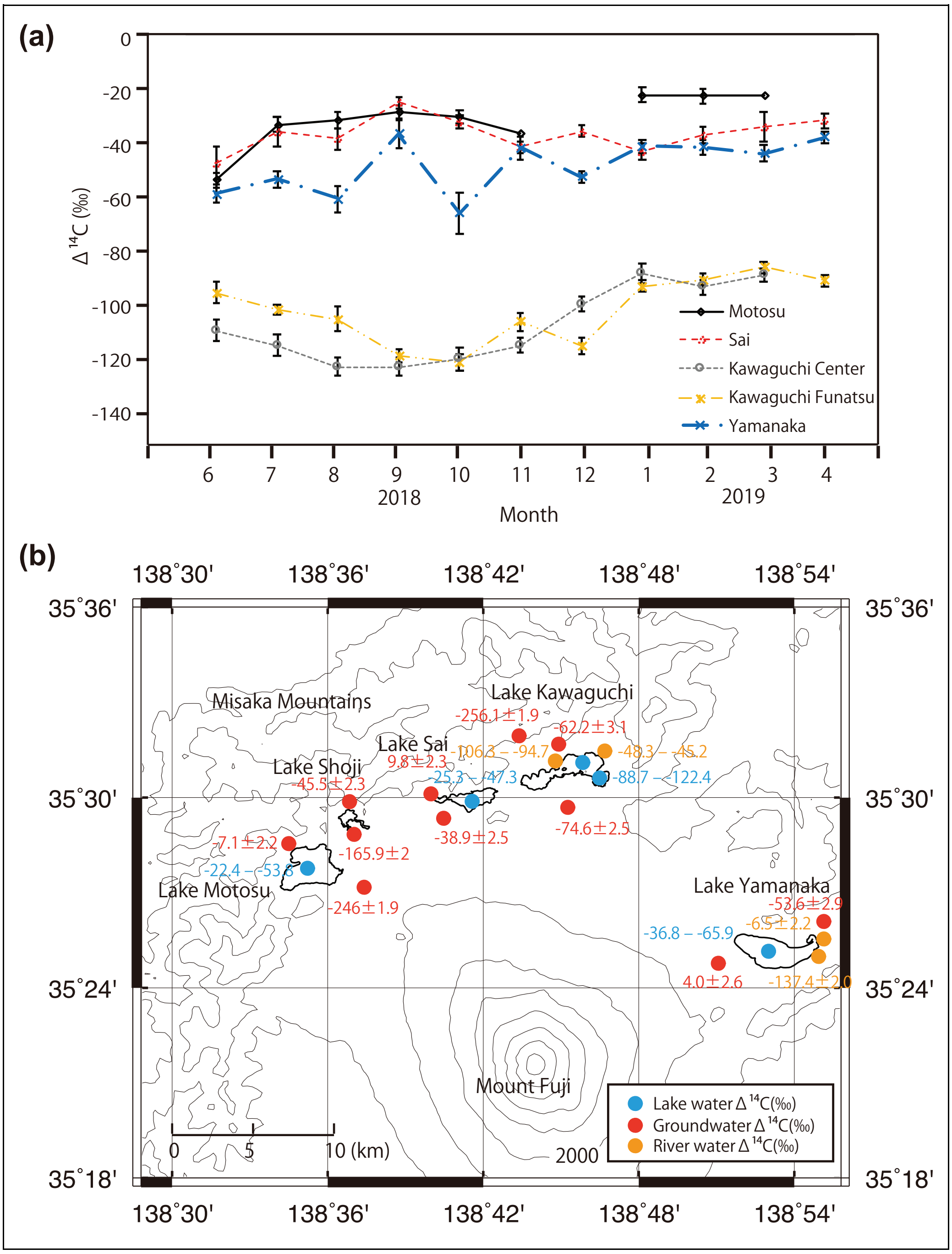


**Figure 2. Figures showing (a) time-series analytical results of lake water radiocarbon and (b) sampling sites of water and spatial distributions of radiocarbon results.** Lake water was sampled monthly from Lakes Motosu, Sai, and Yamanaka, from Lake Kawaguchi Central, and Lake Kawaguchi eastern side (Funatsu) from June 2018 to April 2019. Groundwater was collected to assess water sources on either the Mt. Fuji side of the watershed and on the Misaka mountains side. River water was sampled during October 2019 and November 2019. DOI: https://doi.org/10.1525/elementa.2020.00149.f2



because we did not receive sampling approval in time, but we hope to measure lake water from Lake Shoji in the future. Groundwater was collected from drinking water wells in Fujikawaguchiko town and Narusawa and Yamanakako village. We chose sampling sites for each lake from at least 2 locations to identify the sources of lake water, namely, one for the Mt. Fuji side and the other close to the Misaka Mountains. River water was collected in the autumn when the average flow rate was at a high. Water samples from the Tera and Oku Rivers in the Misaka Mountains around Lake Kawaguchi were collected in October and November 2019. For Lake Yamanaka, river water from the Ohori River and Ichinosuna River were collected in November and December 2019.

### *Method*

A few drops of mercurous chloride ($HgCl_2$) were added to each sample to suppress biological activity after water collection. The samples were processed using the bubbling method (McNichol et al., 1994); 4 ml of phosphoric acid were added to 250 ml of lake water, and bubbling was carried out for 15 min in a glass tube filled with 60 mPa of helium gas to strip $CO_2$ liberated from DIC. During this process, water vapor is released along with the $CO_2$ gas, so 2 cryogenic traps containing ethanol cooled to –120°C were used to remove the water vapor. The $CO_2$ was captured in a liquid nitrogen trap (Servettaz et al., 2019). The $CO_2$ collected was processed under the protocol described in Yokoyama et al. (2007): $CO_2$ was injected into a quartz tube together with 4 mg of iron powder pre-reduced at 450°C and graphitized by heating at 630°C for 6 h. The samples were measured using a single-stage accelerator mass spectrometer at the University of Tokyo Atmosphere and Ocean Research Institute (Yokoyama et al., 2019b).

Throughout this study, we report $\Delta^{14}$C using Equation 1, where *x* is the year of the sample measurement, and *F* is the fraction modern carbon as was defined in a previous study (Stuiver and Polach 1977).

$$\Delta^{14}C = \left(\mathrm{Fe}^{((1950-x)/8267)} - 1\right) \times 1000 ‰, \quad (1)$$

where radiocarbon age and *F* can be written as follows (Donahue et al., 1990):

$$^{14}C \text{ age} = -8033 \ln F. \quad (2)$$

The radiocarbon reservoir age (*R*) expresses the difference in the age of the lake DIC and the contemporary atmosphere, in radiocarbon years. *R* can be written as follows:

$$R = [\text{radiocarbon age}]\text{lake DIC} - [\text{radiocarbon age}] \text{ atmosphere}. \quad (3)$$

Substituting Equations 1 and 3, the following relationship between *R* and *F* can be obtained:

$$R = -8033 \cdot \ln F_{\text{lake}} - (-8033 \cdot \ln F_{\text{atm}}) = -8033[\ln F_{\text{lake}} - \ln F_{\text{atm}}] \quad (4)$$

$$R = -8033 \cdot \ln\left[\frac{F_{\text{lake}}}{F_{\text{atm}}}\right] = 8033 \cdot \ln\left[\frac{F_{\text{atm}}}{F_{\text{lake}}}\right].$$

Solving Equation 1 for *F*, and substituting into Equation 4, we get a relationship between *R* and $\Delta^{14}$C:

$$R = 8033 \cdot \ln\left[\frac{(\Delta^{14}C_{\text{atm}}/1000) + 1}{(\Delta^{14}C_{\text{lake}}/1000) + 1}\right]. \quad (5)$$

Thus, the $^{14}$C offset between the lake water and the ambient atmosphere is presented in the current study, and the younger (smaller) the $\Delta^{14}$C provides the older (larger) the radiocarbon reservoir ages (e.g., Yokoyama et al., 2000; Hirabayashi et al., 2019; Fukuyo et al., 2020).

## Results

### *Radiocarbon measurement in lake water*

The results of radiocarbon measurements are listed in **Table 2** and **Figure 2**. The $\Delta^{14}$C in Lake Motosu was at its highest value in January (–22.4 ± 2.5‰), and the lowest was recorded in June (–53.8 ± 4.3‰). Winter average values were calculated to be around –20‰, but the values from summer to autumn, that is, between July and November, showed average values of around –30‰. It was not possible to measure the radiocarbon content of the lake water sample obtained in December from Lake Motosu due to the extremely small concentration of $CO_2$ gas in the sample.

The results of Lake Sai show the lowest $\Delta^{14}$C values in June (–47.3 ± 5.9‰), with peak values in September (–25.3 ± 2.3‰). The values fall between –30‰ and –45‰ after October. When comparing the values between the Lake Sai and the Lake Motosu, similar $\Delta^{14}$C values in both lakes are observed from June to November, but the Lake Sai values drop after December by as much as 10‰.

The $\Delta^{14}$C trend at Lake Kawaguchi follows a similar trajectory as that of Lake Motosu, namely lower values in summer and higher values in winter. However, actual values are distinctly lower than the other lakes, where $\Delta^{14}$C observed at a site in the center of the lake is –122.4 ± 3.2‰ in August and –87.8 ± 3.6‰ in January.

The $\Delta^{14}$C values in Lake Yamanaka were below –60‰ in August and October, which is about 20‰ less than the value in September (–36.8 ± 5.3‰). The $\Delta^{14}$C fluctuated more than 20‰ per month from August to October.

### *Radiocarbon values of groundwater (wells) and river water*

**Table 2** shows the radiocarbon results for 11 groundwater (wells) and 6 river water samples. Groundwater sampling was conducted from October to November 2019, whereas 2 separate sampling campaigns (October and November 2019) were made for the Tera River and the Oku River. At least 2 ground water sampling sites were designed to collect waters for each lake, considering the incoming water routes from either the northern mountain ranges (e.g., Misaka Mountains) or southern mountain (i.e., Mt. Fuji). In the case of Lake Motosu, the groundwater from the Mt. Fuji side (YAUT-05815) had extremely low $\Delta^{14}$C (–246.0 ± 1.9‰). The groundwater $\Delta^{14}$C values from Koan (on the Misaka Mountains side: YAUT-050826) were measured at –7.1 ± 2.2‰, which was higher than that of surface lake water (**Figure 2**). For Lake Shoji, groundwater $\Delta^{14}$C was as low as –165.9 ± 2.0‰ from Shojiaoki, on the Mt. Fuji side (YAUT-050813), with higher values measured from Shojikyoson (–45.5 ± 2.3‰: YAUT-050812), on the Misaka Mountains side. At Lake Sai, $\Delta^{14}$C values of –38.9 ± 2.5‰ were obtained from Aoki (on the Mt. Fuji side: YAUT-050809), while $\Delta^{14}$C values in Shinhonsawa were 9.8 ± 2.3‰ (on the Misaka Mountains side: YAUT-050811), which is equivalent to, or higher, than the corresponding lake water $\Delta^{14}$C value.

Results from 2 other lakes, Lake Kawaguchi and Lake Yamanaka, show different features than the other 3 lakes described above. At Okune, located on the southern (Mt. Fuji) side of Lake Kawaguchi, $\Delta^{14}$C values of –74.6 ± 2.5‰ were obtained, whereas values of –62.2 ± 3.1‰ were measured from the sample collected from Goto (YAUT-050805). The values from Wakahiko, located further

**Table 2.** Radiocarbon results of lake water, groundwater, and river water dissolved inorganic carbon radiocarbon. DOI: https://doi.org/10.1525/elementa.2020.00149.t2

| Lab. No. | Location | Date | $\Delta^{14}C$ (‰) | Error (±) | $^{14}C$ Age (yBP) | Error (±) |
|---|---|---|---|---|---|---|
| Lake Water | | | | | | |
| YAUT-051526 | Motosu | 06/06/2018 | −53.8 | 4.3 | 377 | 37 |
| YAUT-047429 | Motosu | 11/07/2018 | −33.2 | 2.6 | 204 | 22 |
| YAUT-047431 | Motosu | 01/08/2018 | −31.7 | 3.0 | 192 | 25 |
| YAUT-047432 | Motosu | 10/09/2018 | −28.9 | 2.8 | 168 | 23 |
| YAUT-047433 | Motosu | 03/10/2018 | −30.4 | 2.4 | 181 | 20 |
| YAUT-047436 | Motosu | 07/11/2018 | −36.6 | 2.5 | 233 | 21 |
| N/A | Motosu | 05/12/2018 | N/A | N/A | N/A | N/A |
| YAUT-047437 | Motosu | 09/01/2019 | −22.4 | 2.5 | 115 | 21 |
| YAUT-047438 | Motosu | 06/02/2019 | −22.7 | 3.0 | 118 | 24 |
| YAUT-047439 | Motosu | 06/03/2019 | −22.6 | 2.6 | 117 | 22 |
| YAUT-046617 | Sai | 05/06/2018 | −47.3 | 5.9 | 322 | 50 |
| YAUT-046618 | Sai | 03/07/2018 | −35.9 | 5.3 | 226 | 44 |
| YAUT-046619 | Sai | 06/08/2018 | −38.7 | 4.1 | 250 | 34 |
| YAUT-046623 | Sai | 11/09/2018 | −25.3 | 2.3 | 139 | 19 |
| YAUT-046817 | Sai | 02/10/2018 | −32.5 | 2.4 | 198 | 20 |
| YAUT-046818 | Sai | 06/11/2018 | −41.6 | 2.0 | 275 | 17 |
| YAUT-046819 | Sai | 04/12/2018 | −35.7 | 2.3 | 225 | 19 |
| YAUT-046936 | Sai | 08/01/2019 | −43.4 | 2.9 | 289 | 24 |
| YAUT-046937 | Sai | 05/02/2019 | −37.3 | 3.1 | 238 | 26 |
| YAUT-046938 | Sai | 05/03/2019 | −34.3 | 5.5 | 213 | 46 |
| YAUT-046939 | Sai | 16/04/2019 | −32.0 | 2.7 | 194 | 22 |
| YAUT-046219 | Kawaguchi Funatsu | 05/06/2018 | −95.1 | 4.0 | 735 | 35 |
| YAUT-046223 | Kawaguchi Funatsu | 03/07/2018 | −101.4 | 2.0 | 792 | 18 |
| YAUT-046224 | Kawaguchi Funatsu | 06/08/2018 | −104.8 | 4.8 | 822 | 43 |
| YAUT-046225 | Kawaguchi Funatsu | 11/09/2018 | −118.3 | 2.4 | 944 | 22 |
| YAUT-046226 | Kawaguchi Funatsu | 02/10/2018 | −120.7 | 3.1 | 966 | 29 |
| YAUT-046119 | Kawaguchi Funatsu | 06/11/2018 | −105.9 | 3.2 | 833 | 29 |
| YAUT-046828 | Kawaguchi Funatsu | 04/12/2018 | −114.8 | 2.8 | 913 | 26 |
| YAUT-046829 | Kawaguchi Funatsu | 08/01/2019 | −92.8 | 2.0 | 715 | 18 |
| YAUT-046831 | Kawaguchi Funatsu | 05/02/2019 | −90.3 | 2.0 | 693 | 18 |
| YAUT-046832 | Kawaguchi Funatsu | 05/03/2019 | −85.8 | 2.0 | 654 | 18 |
| YAUT-046833 | Kawaguchi Funatsu | 16/04/2019 | −90.8 | 2.0 | 697 | 18 |
| YAUT-046402 | Kawaguchi Center | 05/06/2018 | −109.1 | 4.1 | 861 | 37 |
| YAUT-046403 | Kawaguchi Center | 03/07/2018 | −114.7 | 4.0 | 912 | 36 |
| YAUT-046404 | Kawaguchi Center | 06/08/2018 | −122.4 | 3.2 | 982 | 29 |
| YAUT-046405 | Kawaguchi Center | 11/09/2018 | −122.4 | 3.3 | 981 | 30 |
| YAUT-046406 | Kawaguchi Center | 02/10/2018 | −119.6 | 4.1 | 956 | 38 |
| YAUT-046409 | Kawaguchi Center | 06/11/2018 | −114.6 | 2.9 | 910 | 26 |
| YAUT-046823 | Kawaguchi Center | 04/12/2018 | −99.4 | 2.8 | 774 | 25 |
| YAUT-046824 | Kawaguchi Center | 08/01/2019 | −87.8 | 3.6 | 671 | 32 |
| YAUT-046825 | Kawaguchi Center | 05/02/2019 | −93.1 | 2.8 | 718 | 25 |
| YAUT-046826 | Kawaguchi Center | 05/03/2019 | −88.7 | 2.4 | 679 | 21 |
| YAUT-046411 | Yamanaka | 06/06/2018 | −58.7 | 3.5 | 419 | 30 |
| YAUT-046412 | Yamanaka | 04/07/2018 | −53.4 | 2.9 | 373 | 25 |
| YAUT-046413 | Yamanaka | 01/08/2018 | −60.6 | 4.9 | 435 | 42 |

*(continued)*

**Table 2.** *(continued)*

| Lab. No. | Sample | Location | Date | $\Delta^{14}C$ (‰) | Error (±) | $^{14}C$ Age (yBP) | Error (±) |
|---|---|---|---|---|---|---|---|
| YAUT-046415 | | Yamanaka | 05/09/2018 | −36.8 | 5.3 | 234 | 44 |
| YAUT-046416 | | Yamanaka | 03/10/2018 | −65.9 | 7.5 | 481 | 64 |
| YAUT-046417 | | Yamanaka | 07/11/2018 | −41.8 | 4.2 | 276 | 35 |
| YAUT-046836 | | Yamanaka | 05/12/2018 | −52.5 | 2.3 | 366 | 19 |
| YAUT-046837 | | Yamanaka | 15/01/2019 | −41.2 | 2.4 | 271 | 20 |
| YAUT-046838 | | Yamanaka | 06/02/2019 | −41.7 | 2.9 | 275 | 24 |
| YAUT-046839 | | Yamanaka | 06/03/2019 | −43.9 | 3.1 | 294 | 26 |
| YAUT-046816 | | Yamanaka | 17/04/2019 | −37.9 | 2.1 | 244 | 18 |
| Lab. No. | Sample | Location | Date | $\Delta^{14}C$ (‰) | Error (±) | $^{14}C$ Age (yBP) | Error (±) |
| Groundwater | | | | | | | |
| YAUT-050826 | Koan | Northwest of Motosu | 21/10/2019 | −7.1 | 2.2 | −10 | 18 |
| YAUT-050815 | Motosu | Southeast of Motosu | 11/11/2019 | −246.0 | 1.9 | 2201 | 20 |
| YAUT-050812 | Shojikyoson | North of Shoji | 11/11/2019 | −45.5 | 2.3 | 307 | 20 |
| YAUT-050813 | Shojiaokigahara | South of Shoji | 11/11/2019 | −165.9 | 2.0 | 1390 | 20 |
| YAUT-050811 | Shinhonsawa | North of Sai | 11/11/2019 | 9.8 | 2.3 | −145 | 18 |
| YAUT-050809 | Aoki | South of Sai | 28/10/2019 | −38.9 | 2.5 | 251 | 21 |
| YAUT-050805 | Goto | North of Kawaguchi | 11/11/2019 | −62.2 | 3.1 | 449 | 26 |
| YAUT-050806 | Wakahiko | Northwest of Kawaguchi | 11/11/2019 | −256.1 | 1.9 | 2310 | 20 |
| YAUT-050804 | Okune | South of Kawaguchi | 11/11/2019 | −74.6 | 2.5 | 556 | 21 |
| YAUT-050803 | Yamanaka | South of Yamanaka | 21/10/2019 | 4.0 | 2.6 | −99 | 21 |
| YAUT-050802 | Hirano | North of Yamanaka | 21/10/2019 | −53.6 | 2.9 | 376 | 25 |
| Lab. No. | Sample | Location | Date | $\Delta^{14}C$ (‰) | Error (±) | $^{14}C$ Age | Error (±) |
| River Water | | | | | | | |
| YAUT-050816 | Ichinosuna | Yamanaka | 21/10/2019 | −6.5 | 2.2 | −15 | 18 |
| YAUT-050817 | Ohori | Yamanaka | 21/10/2019 | −137.4 | 2.0 | 1120 | 19 |
| YAUT-050818 | Tera | Kawaguchi | 01/10/2019 | −48.3 | 2.2 | 331 | 19 |
| YAUT-050819 | Tera | Kawaguchi | 05/11/2019 | −45.2 | 2.2 | 304 | 19 |
| YAUT-050823 | Oku | Kawaguchi | 01/10/2019 | −106.3 | 2.3 | 836 | 21 |
| YAUT-050824 | Oku | Kawaguchi | 05/11/2019 | −94.7 | 2.5 | 732 | 22 |

north on the Misaka mountains side are considerably higher, with $\Delta^{14}C$ values of –256.1 ± 1.9‰ (YAUT-050806). The 2 rivers flowing into Lake Kawaguchi, namely the Tera and Oku Rivers, had water $\Delta^{14}C$ values of –106.3 ± 2.3‰ to –94.7 ± 2.5‰ and –48.3 ± 2.2‰ to –45.2 ± 2.2‰, respectively.

At Lake Yamanaka, $\Delta^{14}C$ values of 4.0 ± 2.6‰ were obtained (on the Mt. Fuji side: YAUT-050803), whereas the value obtained from Hirano was –53.6 ± 2.9‰ (northern side: YAUT-050802). They are similar to the $\Delta^{14}C$ values of 2 river waters flowing into the lake: Ichinosuna and Ohori of –6.5 ± 2.2‰ and –137.4 ± 2.0‰, respectively.

## Discussion

### *Factors controlling the radiocarbon reservoir ages of lake waters*

Systematic $\Delta^{14}C$ analyses and reservoir ages for Fuji Five Lakes show seasonal variations depend on their setting. As all the lakes are located within 40 km of the northern flank of Mt. Fuji, climate conditions including precipitations and evaporations are similar for the Fuji Five Lakes. Monthly precipitation is preeminent in the summer months, with the maximum in September 2018. However, the value of lake water $\Delta^{14}C$ did not show a significant change in September, except for Lake Yamanaka. Thus, the specific hydrological dynamics of each lake are likely responsible for the fluctuations in $\Delta^{14}C$.

The results can be categorized into 2 groups: The first includes lakes that show seasonal variations in $\Delta^{14}C$, such as Lake Motosu and Lake Kawaguchi. Their $\Delta^{14}C$ values are relatively low (i.e., older reservoir ages) in summer but high (i.e., younger reservoir age) in winter. The second group, such as Lake Sai and Lake Yamanaka, does not show clear seasonality.

Two possible causes can explain the $\Delta^{14}C$ fluctuations (i.e., reservoir ages) for these lakes. The first is that the decrease in $\Delta^{14}C$ is due to the changes in retention time of each lake. However, since a previous study revealed that

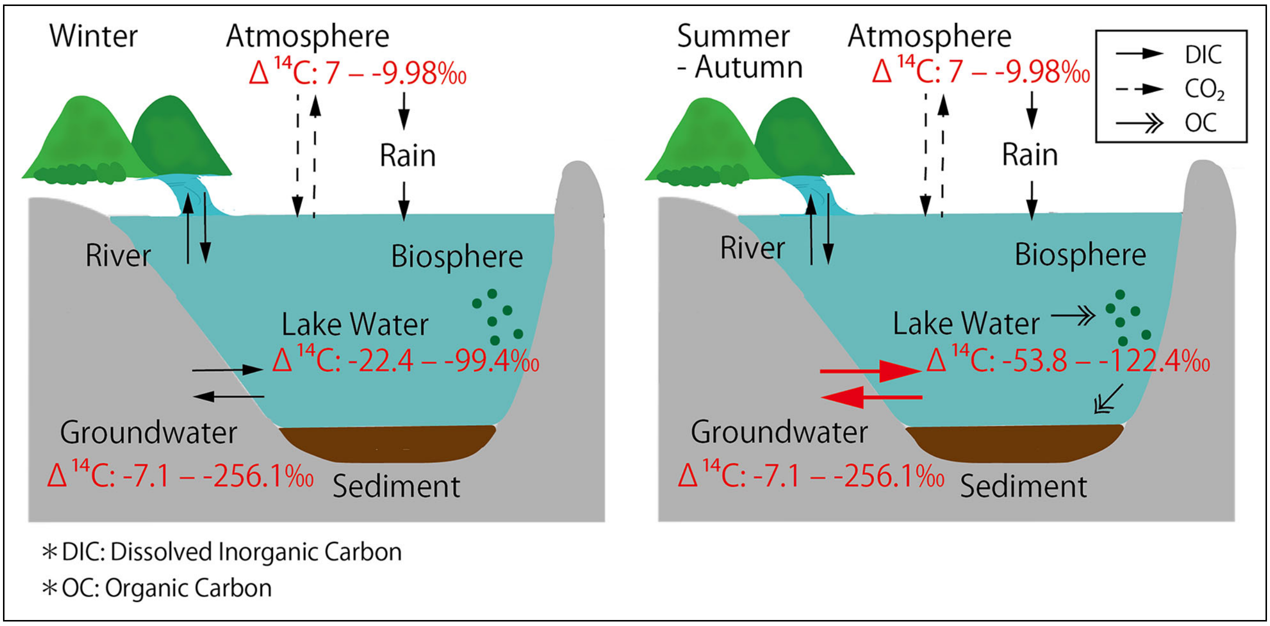


**Figure 3. Schematic figures of lacustrine radiocarbon reservoir system and carbon transport (black arrows, solid line: DIC, dotted line: $CO_2$, double arrow; OC).** The $\Delta^{14}C$ values of Lakes Motosu and Kawaguchi is larger in summer than in winter (red arrow). DOI: https://doi.org/10.1525/elementa.2020.00149.f3

the retention time of lake water in Lake Motosu is typically 7.9 years and the retention of each lake is significantly different (**Table 1**), it is unlikely that seasonal $\Delta^{14}C$ fluctuations are due to retention time. If there is an effect of retention time, the longer the retention time, the lower the $\Delta^{14}C$ value. However, Lake Motosu has the longest retention time of 7.9 years, yet the $\Delta^{14}C$ value in Lake Motosu is the highest of the five lakes.

The second possible cause could be changes in contributions of waters with low $\Delta^{14}C$ flowing into the lake. Since the groundwater $\Delta^{14}C$ values around the Fuji Five Lakes are sufficiently low compared to the ambient atmospheric values, it is likely that groundwater supplies water with lower $\Delta^{14}C$ to the lake waters. In Lakes Motosu and Kawaguchi, $\Delta^{14}C$ tended to increase during winter (**Figure 2**, **Table 2**), while no seasonal $\Delta^{14}C$ variation was observed at Lakes Sai and Yamanaka. In the following section, hydrological dynamics changes are discussed in the view of the mixtures of low $\Delta^{14}C$ water that enter each lake.

At Lake Motosu, the water is heated from the surface, which leads to the development of a thermocline during spring and summer. In contrast, the lake waters do not stratify during winter because of the U-shaped lake basin with a maximum depth of 121.6 m. Hamada et al. (2012) suggested the possibility of meteoric water accumulation at the surface layer of the lake during the stratified period based on seasonal changes from electric conductivity measurements. However, the lake water $\Delta^{14}C$ showed relatively lower values from spring to autumn compared to winter, suggesting contribution from groundwater with low $\Delta^{14}C$. Although the groundwater from the Misaka Mountains side (YAUT-050826) has high $\Delta^{14}C$ in October 2018, the data may not be indicative of average values of the groundwater because the water was sampled just after a typhoon passed through. It could be explained by higher hydrostatic pressure caused by precipitation during summer to autumn and snowmelt in spring (**Figure 3**).

The $\Delta^{14}C$ value during the summer at the eastern site (Funatsu) is around –122‰, which is lower than the site where water is collected at the center of Lake Kawaguchi (Central site: $\Delta^{14}C$ is around –100‰). Groundwater samples collected from Wakahiko, located further north and situated on the Misaka mountains side, have $\Delta^{14}C$ of –256.1 ± 1.9‰ (YAUT-050806). The water temperature of Funatsu is higher than that of the lake center in summer (Horiuchi et al., 1992), suggesting that the subsurface water or groundwater influx is more significant during summer (July–October).

Unlike the above lakes, no seasonal variation was observed at Lakes Sai and Yamanaka. The $\Delta^{14}C$ increase of around 20‰ in September in Lake Yamanaka is attributed to the increase in precipitation due to a typhoon (Typhoon #21), which directly hit the region on September 4 and 5, 2018. The typhoon resulted in 200 mm of precipitation, causing the surface lake water $\Delta^{14}C$ to rise. This typhoon also caused lake level to rise by up to +24 cm. An increased amount of low $\Delta^{14}C$ groundwater flowed into the lake due to an increase in groundwater pressure during October 2018, or lake water was diluted by precipitation around September 2018.

The DIC $\Delta^{14}C$ value in lake waters is considered to be a function of groundwater, precipitation, and carbon retained in the lake water. A combination of these factors causes $\Delta^{14}C$ fluctuations in the lake waters. In this paragraph, we conducted a 2-box model simulation to estimate relative contributions of groundwater and precipitation for the Fuji Five Lakes surface waters (**Figure 4**). Previous studies have suggested that the main sources of water for the lakes are either groundwater or

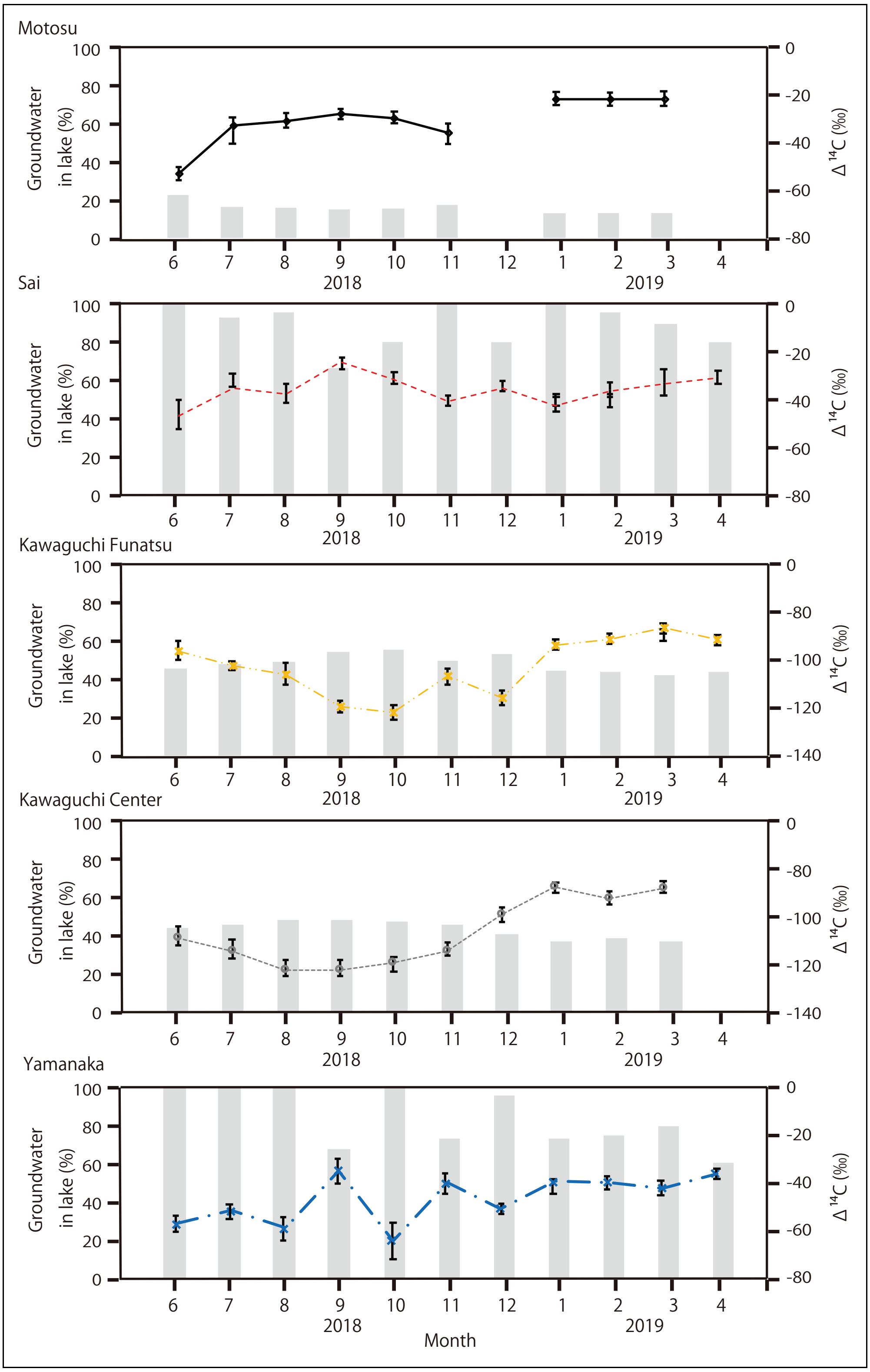


**Figure 4. Results of groundwater $^{14}C$ contribution (%) in the Fuji Five Lakes compared to actual $\Delta^{14}C$ values.** Percentage of ground water $^{14}C$ in lake water $^{14}C$ (gray bar), lake water DIC $^{14}C$ (black: Motosu, red: Sai, yellow: Kawaguchi Funatsu, gray: Kawaguchi Center, and blue: Yamanaka). DOI: https://doi.org/10.1525/elementa.2020.00149.f4

precipitation; however, groundwater is abundant in Lake Yamanaka (see Hamada and Kitagawa, 2010; Hamada et al., 2012). In fact, 3 lakes: Lake Motosu, Lake Shoji, and Lake Sai, have no rivers that constantly discharge to or from the lakes. Although Tera and Oku Rivers are flowing into Lake Kawaguchi, and Ichinosuna and Ohori Rivers flow into Lake Yamanaka, we cannot confirm the effects of river water due to the lack of flow rate data. Although the case mentioned above exists only under limited conditions, semiquantitative analysis of the hydrology of the lakes is useful in evaluating the mechanisms for understanding $\Delta^{14}C$ changes in the lake surface water. Newly obtained groundwater $\Delta^{14}$C values by this study are employed, and an atmospheric $\Delta^{14}$C value of each month ranged from 7.0 ± 1.9‰ to –9.98 ± 1.5‰ (ICOS RI, 2019) at station Saclay was used in the following equation. The calculation formula is described below.

$$\Delta^{14}C_{\text{lake}} = (1-f) \times \Delta^{14}C_{\text{atm}} + (f) \times \Delta^{14}C_{\text{groundwater}}. \quad (6)$$

Here, $f$ is the proportion (%) of groundwater $\Delta^{14}$C in the lake, whereas $\Delta^{14}C_{\text{lake}}$ DIC is the lake water $\Delta^{14}$ C, and $\Delta^{14}C_{\text{atm}}$ is the atmospheric $\Delta^{14}$C value observed in 2018. Groundwater also originates from precipitation, but $\Delta^{14}$C in groundwater decreases before reaching the lake because it is isolated from the atmosphere (e.g., Bente, 2013). Although the lake water in the Fuji Five Lakes is considered to be mainly derived from the Mikasa and Tanzawa Mountains (Hayashi, 2020), $\Delta^{14}C_{\text{groundwater}}$ DIC values obtained from wells around the Fuji Five Lakes are employed for Lakes Motosu and Sai where the $\Delta^{14}C_{\text{groundwater}}$ DIC values of the Misaka Mountain are higher than the lake DIC $\Delta^{14}$ C values. The values obtained from the Misaka Mountains side (i.e., Northern Sites) are used to calculate the proportion of groundwater $^{14}$C for Lakes Kawaguchi and Yamanaka. The proportion of groundwater contribution to DIC$^{14}$C for the surface lake water in Lake Motosu is about 20%. This is consistent with the chemical measurements of waters reported in Hamada et al. (2012). Water in Lake Kawaguchi is largely influenced by groundwater, as the proportion is approximately 50%. For the Lakes Sai and Yamanaka, more than 80% of the lake water is derived from groundwater DI$^{14}$C, including months when lake water $\Delta^{14}$ C values are smaller than groundwater DI$^{14}$C value of each lake. Since the groundwater collected in this study is very limited in this area, further investigation is needed to clarify the origin of the lake water.

### *Implications for reservoir ages of Lake Motosu and Lake Kawaguchi*

Previous studies collected sediment cores from Lake Motosu to study past environmental changes in the region (Lamair et al., 2018, 2019; Obrochta et al., 2018). Obrochta et al (2018) measured radiocarbon in TOC from sediments, and they reported a $\Delta^{14}$C surface value of $\Delta^{14}$C of –41 ± 2.5‰. Our observed lake water $\Delta^{14}$C in Lake Motosu from this study between July and November is similar with values around –30‰. This suggests that the carbon produced in the lake due to carbon fixation during spring to summer by phytoplankton living in the lake surface water is the dominant source of carbon for the sediments in the lake. As a result, it is considered that the DIC in the lake water from spring to summer is comparable to the TOC $\Delta^{14}$C of the sediments. Thus, the $\Delta^{14}$C of lake water DIC in spring to summer can be utilized to estimate the reservoir age of the sediments.

We also compared lake water DIC $\Delta^{14}$C with compound-specific $\Delta^{14}$C reported for Lake Kawaguchi sediments (Yamamoto et al., 2020). Compound-specific $\Delta^{14}$C extracted from fatty acids from Lake Kawaguchi sediments were reported for each fraction. The results show that $C_{16}$ fatty acid $\Delta^{14}$C (–124 ± 6‰), chlorophyll a $\Delta^{14}$C (–133 ± 6‰), and lake water DIC $\Delta^{14}$C (–117 ± 2‰) are consistent with each other for the samples collected in June 2017. Our study revealed that the seasonal magnitude of $\Delta^{14}$C changes was around 35‰ from August 2018 (–122.4 ± 3.2‰) to March 2019 (–88.7 ± 2.4‰); thus, an increase in $\Delta^{14}$C could have occurred between the summer and winter in 2017 when Yamamoto et al. (2020) collected samples. If so, the value of DIC $\Delta^{14}$C observed from the current study is close to the values of $C_{24}$ fatty acid ($\Delta^{14}$C = –77 ± 6‰) or $C_{28}$ fatty acid ($\Delta^{14}$C = –75 ± 7‰). Both $C_{24}$ and $C_{28}$ fatty acids are considered to be derived from higher plants, soil-derived compounds (Gagosian et al., 1981; Simoneit 1977), and/or aquatic macrophytes (Ficken et al., 2000). Hence, the $\Delta^{14}$C of these fatty acids could be partly affected by additional aquatic sources in addition to terrestrial plant materials.

Further systematic studies are needed to clarify the relationship between lake water and organic matter produced by living organisms. To elucidate the origin of organic matter, $\delta^{13}$C measurements would be able to provide clear pathways of carbon transported from lake water to organic matter.

## Conclusions

Monthly $\Delta^{14}$C measurements on the Fuji Five Lakes surface water DIC revealed the following:

1. $\Delta^{14}$C values of Lake Motosu and Lake Kawaguchi decreased in summer, as compared to winter, whereas relatively low $\Delta^{14}$C values were observed in Lake Sai. $\Delta^{14}$C values decrease in June–August and October at Lake Yamanaka.
2. Reservoir ages of sediment may reflect lake water DIC in spring to summer. Lake water DIC is likely to be fixed as organic matter and supplied to sediments due to the expansion of aquatic organisms that are active from spring to summer.
3. Seasonal variations of lake water $\Delta^{14}$C are mainly driven by groundwater amount and also suggest that $\Delta^{14}$C of lake seasonality was shown to be useful for improving the accuracy of lake hydrology and radiocarbon dating.

## Data accessibility statement

The following datasets were generated:

- Sizes, depth, altitude, and retention time of Fuji Five Lakes: Geospatial Information Authority of Japan (https://www.gsi.go.jp/), and Yamanashi

Prefecture (1993) [The water quality of the Fuji Five Lakes over 21 years (1971–1991)] *Yamanashi Prefectural Environment Bureau.*

- Radiocarbon data: uploaded as **Table 2**.
- Atmospheric $\Delta^{14}C$ value data: ICOS RI (2019) [ICOS Atmospheric Greenhouse Gas Mole Fractions of $CO_2$, $CH_4$, CO, $^{14}CO^2$, and Meteorological Observations September 2015–April 2019 for 19 stations (49 vertical levels), final quality controlled Level 2 data], dataset. DOI: doi.org/10.18160/CE2R-CC91.


## Acknowledgments

We would like to express our gratitude to the Fuji Healing Forest Laboratory of the University of Tokyo, Yamanakako Village, Narusawa Village, Fujikawaguchiko Town, Motosu Kohan Koan, Yamanashi Prefectural Air Quality Protection Division, and the Yamanashi Institute of Public Health and Environment for providing water samples. We would like to thank Dr. T. Aze and Dr. C. Sawada (AORI) for their support on AMS measurements, and W. Wong for a part of sample preparation. Discussions with E. Tam, B. Behrens, and A. D. Sproson were also appreciated. We thank Prof. G. Burr (National Taiwan University) and an anonymous reviewer for constructive comments which improved the manuscript.

## Funding

A part of this research was supported by JSPS KAKENHI Grant Numbers 18K03769 and JP20H00193.


## Competing interests

The authors have no competing interests to declare.

## Author contributions

Contributed to conception and design: YY, KO.

Contributed to acquisition of data: KO, YY, YM, SY.

Contributed to analysis and interpretation of data: KO, YY, YM, SY, TM.

Drafted and/or revised the article: KO, YY, SY, TM.

Approved the submitted version for publication: YY, KO.

## References


**Asai, K., Tsujimura, K**. 2010. Dating method for young groundwater using environmental tracers – Application of CFCs dating method to spring in volcanic areas. *Journal of Japanese Association of Hydrological Sciences* **39**:67–78. DOI: http://dx.doi.org/10.4145/jahs.39.67.

**Ascough, PL, Bird, MI, Meredith, W, Wood, RE, Snape, CE, Brock, F, Higham, TFG, Large, DJ, Apperley, DC**. 2010. Hydropyrolysis: Implications for radiocarbon pretreatmenrt and characterization of black carbon. *Radiocarbon* **52**: 1098–1112. DOI: http://dx.doi.org/10.1017/S0033822200046427.

**Bente, P**. 2013. The freshwater reservoir effect in radiocarbon dating. *Heritage Science* **1**:24. DOI: http://dx.doi.org/10.1186/2050-7445-1-24.

**Blattmann, MT, Wessels, M, McIntyre, PC, Eglinton, IT**. 2018. Projections for future radiocarbon content in dissolved inorganic carbon in Hardwater lakes: A retrospective approach. *Radiocarbon* **60**(3): 791–800. DOI: http://dx.doi.org/10.1017/RDC.2018.12.

**Brady, AL, Slater, G, Lavel, B, Lim, DS**. 2009. Constraining carbon sources and growth rates of freshwater microbialites in Pavilion Lake using $^{14}C$ analysis. *Geobiology* **7**: 544–555. DOI: http://dx.doi.org/10.1111/j.1472-4669.2009.00215.x.

**Broecker, WS, Walton, A**. 1959. The geochemistry of C14 in fresh-water systems. *Geochimica et Cosmochimica Acta* **16**: 15–38. DOI: http://dx.doi.org/10.1016/0016-7037(59)90044-4.

**Bronk Ramsey, C, Staff, RA, Bryant, CL, Brock, F, Kitagawa, H, van der Plicht, J, Schlolaut, G, Marshall, MH, Brauer, A, Lamb, HF, Payne, RL, Tarasov, PV, Haraguchi, T, Gotanda, K, Yonenobu, H, Yokoyama, Y, Tada, R, Nakagawa, T**. 2012. A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr B.P. *Science* **338**(6105): 370–374. DOI: http://dx.doi.org/10.1126/science.1226660.

**Cheng, H, Zhang, H, Spötl, C, Baker, J, Sinha, A, Li, H, Bartolome, M, Moreno, A, Kathayat, G, Xhao, J, Dong, X, Li, Y, Ning, Y, Jia, X, Xong, B, Brahim, YA, Pérez-Mejias, C, Cai, Y, Novello, VF, Cruz, FW, Severinghaus, JP, An, Z, Edwards, RL**. 2020. Timing and structure of the Younger Dryas event and its underlying climate dynamics. *Proceedings of National Academy of Science, USA.* **117**: 23408–23417. DOI: http://dx.doi.org/10.1073/pnas.2007869117.

**Chiba, T, Suzuki, Y, Arai, K, Tomita, Y, Koizumi, S, Nakashima, K, Ogawa, K**. 2010. The measurement of magma discharge volume of the "Jogan" eruption in Aokigahara on Fuji volcano, based on the micro topography by LiDAR and result of the drilling. *Journal of Erosion Control Engineer* **63**(1): 44–48. DOI: http://dx.doi.org/10.11475/sabo.63.1_44.

**Donahue, DJ, Linick, TW, Jull, AJT.**, 1990. Isotope-ratio and background corrections for accelerator mass spectrometry radiocarbon measurements. *Radiocarbon* **32**(2): 135–142. DOI: http://dx.doi.org/10.1017/S0033822200040121.

**Ficken, KJ, Li, B, Swain, DL, Eglinton, G**. 2000. An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. *Organic Geochemistry* **31**(7–8): 745–749. DOI: http://dx.doi.org/10.1016/S0146-6380(00)00081-4.

**Fukuyo, N., Clark, G., Purcell, A, Parton, P, Yokoyama, Y**. 2020. Holocene sea level reconstruction using lagoon specific local marine reservoir effect and geophysical modeling in Tongatapu, Kingdom of Tonga. *Quaternary Science Reviews* **244**: 106464. DOI: http://dx.doi.org/10.1016/j.quascirev.2020.106464.

**Gagosian, RB, Peltzer, ET, Zafiriou, OC**. 1981. Atmospheric transport of continentally derived lipids to the tropical North Pacific. *Nature* **291**: 312–314. DOI: http://dx.doi.org/10.1038/291312a0.

**Ghazoui, Z, Bertrand, S, Vanneste, K, Yokoyama, Y, Nomade, J, Gajurel, AP, van der Beek, P**. 2019. Potentially large post-1505 AD earthquakes in western Nepal revealed by a lake sediment record. *Nature Communications* **10**: 2258. DOI: http://dx.doi.org/10.1038/s41467-019-10093-4.

**Graven, HD**. 2015. Impact of fossil fuel emissions on atmospheric radiocarbon and various applications of radiocarbon over this century. *Proceedings of the National Academy of Sciences of the United States of America* **112**(31): 9542–9545. DOI: http://dx.doi.org/10.1073/pnas.1504467112.

**Hamada, H, Katsumata, D, Oyagi, H**. 2012. Investigation of seasonal change of water temperature and water quality and water balance on Lake Motosu-ko. *Bulletin of Faculty of Education, Chiba University* **60**: 459–468.

**Hamada, H, Kitagawa, Y**. 2010. Investigation of Seasonal change of Water temperature and Water quality and Water balance on Lake Yamanaka-ko. *Bulletin of Faculty of Education, Chiba University* **58**: 371–380.

**Hamano, K**. 1976. Groundwater of north ridge of Mount Fuji. *Yamanashi University Faculty of Liberal Arts Research Report* **27**: 59–66.

**Hayashi, T**. 2020. Understanding the groundwater flow system at the northern part of Mt. Fuji: Current issues and prospects. *Journal of Geography (Chigaku Zasshi)* **129**(5): 677–695.

**Hayashi, T, Tsuboi, T**. 2005. Interchange between mountain groundwater and lake at the foot of Mt. Fuji. *Journal of Ground Water Technology* **47** (11) 3–14.

**Hirabayashi, S, Yokoyama, Y, Suzuki, A, Miyairi, Y**. 2019. Insight into western pacific circulation from South China sea coral skeletal radiocarbon. *Radiocarbon* **61**(6): 1923–1937. DOI: http://dx.doi.org/10.1017/RDC.2019.145.

**Hirabayashi, S, Yokoyama, Y, Suzuki, A, Miyairi, Y, Aze, T**. 2017. Short-term fluctuations in regional radiocarbon reservoir age recorded in coral skeletons from the Ryukyu Islands in the north-western Pacific. *Journal of Quaternary Science* **32**(1): 1–16. DOI: http://dx.doi.org/10.1002/jqs.2923.

**Horiuchi, S, Lee, Y, Watanabe, M, Fujita, E**. 1992. Some limnological characteristics of Mt. Fuji. *Proceedings of the Institute of Natural Sciences, Nihon University* **27**: 45–56.

**ICOS RI**. 2019. ICOS Atmospheric greenhouse gas Mole Fractions of $CO_2$, $CH_4$, CO, $^{14}CO^2$ and meteorological observations September 2015 - April 2019 for 19 stations (49 vertical levels), final quality controlled Level 2 data. *Integrated Carbon Observation System*. DOI: http://dx.doi.org/10.18160/CE2R-CC91.

**Jull, AJT, Burr, GS, Hodgins, GWL**. 2013. Radiocarbon dating, reservoir effects, and calibration. *Quaternary International* **299**: 64–71. DOI: http://dx.doi.org/10.1016/j.quaint.2012.10.028.

**Kanno, T, Ishii, T, Kuroda, K**. 1986. Study on groundwater flow in the northern foot area of Mt. Fuji and water level changes of Lake Kawaguchi, based on the hydrogeological structure. *The journal of the Japanese Association of Groundwater Hydrology* **28**: 25–32. DOI: http://dx.doi.org/10.5917/jagh1959.28.25.

**Koshimizu, S, Uchiyama, T, Yamamoto, G**. 2007. Volcanic history of Mt. Fuji recorded in borehole cores from Fuji Five Lakes surrounding Mt. Fuji, in Aramaki, S, Fujii, T, Nakada, S, Miyaji, N eds., *Fuji volcano* (pp. 365–374). Yamanashi, Japan: Yamanashi Institute of Environmental Sciences.

**Lamair, L, Hubert-Ferrari, A, Ouahabi, ME, Yamamoto, S, Schmidt, S, Auwera, JV, Lepoint, G, Boes, E, Fujiwara, O, Yokoyama, Y, Batist, MD, Heyvaert, V.MA**. 2019. Late holocene changes in erosion patterns in a lacustrine environment: Landscape stabilization by volcanic activity versus human activity. *Geochemistry, Geophysics, Geosystems* **20**(4), 1720–1733. DOI: http://dx.doi.org/10.1029/2018GC008067.

**Lamair, L, Hubert-Ferrari, A, Shinya Yamamoto, S, Ouahabi, M. E, Auwera, JV, Obrochta, S, Boes, E, Nakamura, A, Fujiwara, O, Shishikura, M, Schmidt, S, Siani, G, Miyairi, Y, Yokoyama, Y, Batist, MD, Heyvaert, VMA, QuakeRecNankai Team**, 2018. Volcanic influence of Mt. Fuji on the watershed of Lake Motosu and its impact on the lacustrine sedimentary record. *Sedimentary Geology* **363**: 200–220. DOI: http://dx.doi.org/10.1016/j.sedgeo.2017.11.010.

**Matsuda, T**. 2007. Geology and geohistory of the Tertiary basement of Mt. Fuji, in Aramaki, S, Fujii, T, Nakada, S, Miyaji, N eds., *Fuji volcano*. Yamanashi, Japan: Yamanashi Institute of Environmental Sciences: 45–57.

**McNichol, AP, Jones, GA, Huton, DL, Gagno, AR**. 1994. The rapid preparation of sea water $\Sigma CO_2$ for radiocarbon analysis at the national ocean science facility. *Radiocarbon* **36**: 237–246. DOI: http://dx.doi.org/10.1017/S0033822200040522.

**Nakamura, A, Yokoyama, Y, Maemoku, H, Yagi, H, Okamura, M, Matsuoka, H, Miyake, N, Osada, T, Pani Adhikari, D, Dangol, V, Ikehara, M, Miyairi, Y, Matsuzaki, H**. 2016. Weak monsoon event at 4.2 ka recorded in sediment from Lake Rara, Himalayas. *Quaternary International* **397**(18): 349–359. DOI: http://dx.doi.org/10.1016/j.quaint.2015.05.053.

**Obrochta, SP, Yokoyama, Y, Yoshimoto, M, Yamamoto, S, Miyairi, Y, Nagano, G, Nakamura, A, Tsunematsu, K, Lamair, L, Hubert-Ferrari, A, Lougheed, BC**. 2018. Mt. Fuji Holocene eruption history reconstructed from proximal lake sediments and high-density radiocarbon dating. *Quaternary Science Reviews* **200**: 395–405. DOI: http://dx.doi.org/10.1016/j.quascirev.2018.09.001.

**Ochiai, T**. 1995. *East Mount Fuji groundwater analysis*. Tokyo, Japan: Liebel Publishing.

**Ogata, M, Kobayashi, H**. 2015. Chronological change of water level of Lake Kawaguchi and that of ground water level around south east area of Lake Kawaguchi. *Y-CROST Research Report* **10**: 91–94.

**Ogata, M, Kobayashi, H, Koshimizu, S**. 2014. Concentration of fluorine in groundwater and groundwater table at the northern foot of Mt. Fuji. *The Journal of the Japanese Association of Groundwater Hydrology* **56**(1): 35–51. DOI: http://dx.doi.org/10.5917/jagh.56.35.

**Ota, K, Yokoyama, Y, Miyairi, Y, Hayakawa, J, Satoh, N, Fukuda, H, Tanaka, K**. 2019. Northeast pacific seawater radiocarbon recorded in abalone shells obtained from Otsuchi Bay, Japan. *Radiocarbon*. DOI: http://dx.doi.org/10.1017/RDC.2019.95.

**Safaierad, R, Mohtadi, M, Zolitschka, B, Yokoyama, Y, Vogt, C, Schefuß**. 2020. Elevated dust depositions in West Asia linked to ocean–atmosphere shifts during North Atlantic cold events. *Proceedings of the National Academy of Sciences of the United States of America* **117**(31): 18272–18277.

**Sakashita, W, Miyahara, H, Yokoyama, Y, Aze, T, Nakatsuka, T, Hoshino, Y, Ohyama, M, Yonenobu, H, Takemura, K**. 2017. Hydroclimate reconstruction in central Japan over the past four centuries from tree-ring cellulose $\delta^{18}O$. *Quaternary International* **455**: 1–7. DOI: http://dx.doi.org/10.1016/j.quaint.2017.06.020.

**Schneider, L, Pain, FC, Haberle, S, Blong, R, Alloway, VB, Fallon, JF, Hope, G, Zawadzki, A, Heijnis, H**. 2019. Evaluating the radiocarbon reservoir effect in Lake Kutubu, Papua New Guinea. *Radiocarbon* **61**(1): 287–308. DOI: http://dx.doi.org/10.1017/RDC.2018.49.

**Servettaz, APM, Yokoyama, Y, Hirabayashi, S, Kienast, M, Miyairi, Y, Mohtadi, M**. 2019. Dissolved inorganic radiocarbon content of the Western Coral sea: Implications for intermediate and deep water circulation. *Radiocarbon* **61**(6): 1685–1696. DOI: http://dx.doi.org/10.1017/RDC.2019.122.

**Simoneit, BRT**. 1977. Organic matter in eolian dusts over the Atlantic Ocean. *Marine Chemistry* **5**: 443–464. DOI: http://dx.doi.org/10.1016/0304-4203(77)90034-2.

**Stuiver, M, Polach, HA**. 1977. Discussion Reporting of $^{14}C$ data. *Radiocarbon* **19**(3): 355–363. DOI: http://dx.doi.org/10.1017/S0033822200003672.

**Suess, HE**, 1955. Radiocarbon concentration in modern wood. *Science* **122**: 415–417. DOI: http://dx.doi.org/10.1126/science.122.3166.415-a.

**Susuki, H, Taba, Y**. 1994. A study on the mechanism of exchange between lake waters of FUJI-GOKO (five lakes) and the groundwater around the lakes. *Bulletin of the Institute of Natural Science, Nihon University* **29**: 4–60.

**Sweeney, C, Gloor, E, Jacobson, AR, Key, RM, McKinley, G, Sarmiento, JL, Wanninkhof, R**. 2007. Constraining global air-sea gas exchange for $CO_2$ with recent bomb $^{14}C$ measurements. *Global Biogeochemical Cycles* **21**: GB2015. DOI: http://dx.doi.org/10.1029/2006GB002784.

**Takada, R, Yamamoto, T, Ishizuka, Y, Nakano, R**, 2016. Geological Map of Fuji Volcano. Geological survey of Japan. Available at https://www.gsj.jp/Map/JP/geology5.html#misc_12.

**Takeuchi, K, Kiriishi, F, Imamura, H**. 1995. The water balance analyses of the Five Lakes of Mt. Fuji. *The Journal of Japan Society of Civil Engineers* **39**: 31–36.

**Yamamoto, S**. 1971. Hydronic study of volcano Fuji and its adjacent areas. *Mount Fuji Comprehensive Academic Research Report* **1**: 151–208.

**Yamamoto, S, Miyairi, Y, Yokoyama, Y, Suga, H, Ogawa, ON, Ohkouchi, N**. 2020. Compound-specific radiocarbon analysis of organic compounds from Mount Fuji proximal lake (Lake Kawaguchi) sediment, central Japan. *Radiocarbon* **62**(2): 439–451. DOI: http://dx.doi.org/10.1017/RDC.2019.158.

**Yamamoto, S, Nakamura, T, Uchiyama, T**. 2017a. Newly discovered lake bottom springs from Lake Kawaguchi, the northern foot of Mount Fuji, Japan. *Journal of Japanese Association of Hydrological Sciences* **47**(2): 49–59. DOI: http://dx.doi.org/10.4145/jahs.47.49.

**Yamamoto, S, Uchiyama, T, Miyairi, Y, Yokoyama, Y**. 2018. Volcanic and environmental influences of Mt. Fuji on the $\delta^{13}C$ of terrestrially-derived n-alkanoic acids in sediment from Lake Yamanaka, central Japan. *Organic Geochemistry* **199**: 50–58. DOI: http://dx.doi.org/10.1016/j.orggeochem.2018.02.002.

**Yamanashi Prefecture**. 1993. *The water quality of the Fuji Five Lakes over 21 years (1971–1991)*. Tokyo, Japan: Yamanashi Prefectural Environment Bureau.

**Yokoyama, Y, Esat, TM, Lambeck, K, Fifield, LK**. 2000. Last ice age millennial scale climate changes recorded in Huon Peninsula Corals. *Radiocarbon* **42**: 3838–4401. DOI: http://dx.doi.org/10.1017/S0033822200030320.

**Yokoyama, Y, Hirabayashi, S, Goto, K, Okuno, J, Sproson, AD, Haraguchi, T, Ratnayake, N, Miyairi, Y**. 2019a. Holocene Indian Ocean sea level, Antarctic melting history and past Tsunami deposits inferred using sea level reconstructions from the Sri Lankan, Southeastern Indian and Maldivian coasts. *Quaternary Science Reviews* **206**: 150–161. DOI: http://dx.doi.org/10.1016/j.quascirev.2018.11.024.

**Yokoyama, Y, Miyairi, Y, Aze, T, Yamane, M, Sawada, C, Ando, Y, de Natris, M, Hirabayashi, S, Ishiwa, T, Sato, N, Fukuyo, N**. 2019b. A single stage accelerator mass spectrometry at the atmosphere and ocean research institute, The University of Tokyo. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions With Materials and Atoms* **455**: 311–316. DOI: http://dx.doi.org/10.1016/j.nimb.2019.01.055.

**Yokoyama, Y, Miyairi, Y, Matsuzaki, H, Tsunomori, F**. 2007. Relation between acid dissolution time in the vacuum test tube and time required for graphitization for AMS target preparation. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **259**(1): 330–334. DOI: http://dx.doi.org/10.1016/j.nimb.2007.01.176.

**Yoshimura, S, Kawada, S**. 1942. Research of Fuji five lakes (2), physicochemical properties of Lakes Kawaguchi and Shoji in summer. *Geographical Review of Japan* **22**(11). DOI: http://dx.doi.org/10.4157/grj.18.441.

**Yoshizawa, K, Mochizuki, E**. 2005. Water quality of bottom layer water in Lake Kawaguchi during the summertime. *Yamanashi Prefectural Institute of Public Health Annual Report* **49**: 54–59.

**Yu, S-Y, Shen, J, Colman, SM**. 2007. Modeling the radiocarbon reservoir effect in lacustrine systems. *Radiocarbon* **49**(3): 1241–1254. DOI: http://dx.doi.org/10.1017/S0033822200043150.



**How to cite this article:** Ota, K, Yokoyama, Y, Miyairi, Y, Yamamoto, S, Miyajima, T. 2021. Lake water dissolved inorganic carbon dynamics revealed from monthly measurements of radiocarbon in the Fuji Five Lakes, Japan. *Elementa: Science of the Anthropocene* 9(1). DOI: https://doi.org/10.1525/elementa.2020.00149

**Domain Editor-in-Chief:** Steven Allison, University of California Irvine, Irvine, CA, USA

**Guest Editor:** Chuan-Chou Shen, Department of Geosciences, National Taiwan University, Taipei, Taiwan

**Knowledge Domain:** Ecology and Earth Systems

**Part of an Elementa Special Feature:** Pan-Pacific Anthropocene

**Published:** September 20, 2021 **Accepted:** August 12, 2021 **Submitted:** October 1, 2020



ELEMENTA Science of the Anthropocene

*Elem Sci Anth* is a peer-reviewed open access journal published by University of California Press.

OPEN ACCESS