

$\delta^{18}\text{O}$ of tree-ring cellulose in two species (spruce and oak) as proxies of precipitation amount and relative humidity in northern Japan

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Abstract

Relationships between climatic factors and $\delta^{18}\text{O}$ values of tree rings in two species with different root systems were investigated in the northern area in Hokkaido Island, northern Japan. This region has a heavy snow cover in winter and has a humid climate throughout the year. In the case of spruce (*Picea jezoensis*), which has shallow roots, the $\delta^{18}\text{O}$ values are negatively correlated with precipitation in July and August, probably due to higher relative humidity in summer and lower $\delta^{18}\text{O}$ of summer precipitation in a year of higher summer precipitation, which is governed by the precipitation amount effect. Thus, the $\delta^{18}\text{O}$ value of tree-ring cellulose in spruce must be valuable as a proxy of summer precipitation in this area. On the other hand, the $\delta^{18}\text{O}$ value in oak (*Quercus crispula*), which has deeper roots than spruce, is not very sensitive to summer precipitation, but is negatively correlated mainly with relative humidity in July and August; this can be attributed to the smaller ^{18}O enrichment in leaf water in the summer of higher relative humidity. Our results indicate that $\delta^{18}\text{O}$ values of tree rings in two species with different root systems from the same forest have the potential to reconstruct the two different climate factors.

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1. Introduction

Stable isotope records of tree rings possess the potential to show annual to decadal scales of past climatic changes. In precipitation, $\delta^{18}\text{O}$ and δD are correlated with temperature and/or amount of precipitation (Dansgaard, 1964). Consequently, $\delta^{18}\text{O}$ and δD trapped in tree rings essentially exhibit the relationships mentioned above in addition to relative humidity through ^{18}O enrichment of leaf water. The relationships among $\delta^{18}\text{O}$ in tree rings,

each climatic factor, and $\delta^{18}\text{O}$ in precipitation have been primarily researched for the reconstruction of information on paleoclimate in Europe and North America (e.g., Gray and Thompson, 1976; Buhay and Edwards, 1995; Robertson et al., 2001). Particularly, relationships between the $\delta^{18}\text{O}$ value of cellulose in tree rings and $\delta^{18}\text{O}$ in precipitation were examined in England and Switzerland (Saurer et al., 1997; Anderson et al., 1998, 2002). Recently, a few studies have been conducted in China (Liu et al., 2004 for oxygen isotopes and Aucour et al., 2002 for hydrogen isotopes). These studies were confined to relatively dry areas. Only a few studies on tree-ring isotopic ratios have been conducted in cold and damp areas, where precipitation can be observed constantly

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throughout the year, e.g., eastern North America and the northwestern coast of Japan (Lawrence and White, 1984; Buhay and Edwards, 1995; Nakatsuka et al., 2004) are available. It is unclear how thick snow covers during winter and occasional heavy rainfalls during summer are related to the oxygen isotope in tree rings.

In addition, most studies on oxygen and/or hydrogen isotopes of the tree rings have been conducted using only a single tree species. More than two tree species have been examined in a few oxygen and/or hydrogen isotopic studies (e.g., Buhay and Edwards, 1995; Tang et al., 2000). In general, it is expected that a shallow-rooting tree retains a better record of annual variations in the $\delta^{18}\text{O}$ of precipitation, whereas a deep-rooted, groundwater-tapping tree has an advantage in the isolation of the evaporative-enrichment signal of leaf water (MacCarroll and Loader, 2004). However, our knowledge with regard to the isotopic responses of different tree species is limited.

In this study, we present the relationship between climatic factors and annual $\delta^{18}\text{O}$ values in cellulose from the tree rings of two spruce trees (*Picea jezoensis*) and two oak trees (*Quercus crispula*) in the northern area of Hokkaido Island, northern Japan, where the source of precipitation clearly switches in the summer (Pacific Ocean) and winter (Sea of Japan) (Waseda and Nakai, 1983); therefore, there is no dry season. Spruce trees have shallow roots, while oak trees have deep roots (Karizumi, 1998). We have observed that the $\delta^{18}\text{O}$ values of these two species can become different proxies for the reconstruction of paleoclimate in Hokkaido, northern Japan.

2. Theory

The oxygen isotope ratio of tree rings is believed to be controlled by two important factors. One factor is the isotope ratio of the source water, and the other is the isotopic enrichment effect in leaf water (relative humidity). With regard to the former, the isotope ratio of precipitation is generally influenced by certain meteorological conditions such as “temperature effect” and “amount effect”.

2.1. Temperature effect and amount effect

At middle and high latitudes, the stable isotope ratios in monthly precipitation are positively correlated with air temperature (temperature effect: Dansgaard, 1964; Araguas-Araguas et al., 1998). Water vapor in the atmosphere generally originates from surface waters of oceans at low latitudes, and the vapor evaporated from these oceans is

transported toward the poles. During the transport process, some fractions of water vapor successively condense to form precipitations along with a decrease in the air temperature and saturated water vapor pressure, thereby resulting in a decrease in the isotope ratios of the remaining water vapor due to isotopic fractionation during the condensation process. Decrease in the ^{18}O and ^2H content of water vapor is typically described using a Rayleigh distillation model. The Rayleigh equation can be applied to the temperature-isotope evolution during rainout (the condensation of vapor).

Dansgaard (1964) demonstrated a relationship between the amount of precipitation and the stable oxygen isotope ratios of precipitation (amount effect) in the tropical areas and in the mid-latitudes in summer; it suggested that the isotopic ratios decreased in the months that showed higher precipitation amounts. Strong convective systems (thunder clouds, cold fronts, and tropical clouds) are controlled by the amount effect. Maritime tropical air masses crossing the land during summer are destabilized by the heated land surface and rapidly move upwards. This results in convective storms and a substantial amount of rainfall. The deeper the convective storm, the lower the differentiation between various isotopes (fractionation), and the closer the $\delta^{18}\text{O}$ of the precipitation to that of the vapor (depleted in ^{18}O). Inversely, in shallow convective storms, a smaller proportion of vapor condenses and precipitation has relatively high $\delta^{18}\text{O}$ values due to the large isotopic fractionation between water vapor and precipitation.

2.2. Isotope enrichment effect in leaf water (relative humidity effect)

The Craig–Gordon equation for isotopic fractionation was derived for a simple system of evaporation at open water surfaces (Craig and Gordon, 1965). It has been adapted and expanded to modeling of the relationship between $\delta^{18}\text{O}$ of the leaf water and that of soil water ($\delta^{18}\text{O}_s$). Eq. (1) is as follows:

$$\delta^{18}\text{O}_l = \delta^{18}\text{O}_s + \varepsilon^* + \varepsilon_k + (\delta^{18}\text{O}_v - \delta^{18}\text{O}_s - \varepsilon_k)h \quad (1)$$

where ε_k (26.5‰) is the kinetic isotope fractionation factor due to the diffusion of vapor into unsaturated air (Farquhar et al., 1989), h is the relative humidity (%), and ε^* is the equilibrium isotope fractionation factor that is sensitive to air temperature (Majoube, 1971). This equation shows that the higher the relative humidity, the lower the $\delta^{18}\text{O}$ of the leaf water. $\delta^{18}\text{O}_v$ is the isotope ratio of water vapor; this was obtained by assuming that precipitation water and water vapor are in isotopic

equilibrium with each other ($\delta^{18}\text{O}_p$), $\delta^{18}\text{O}_v$ can be represented as $\delta^{18}\text{O}_p - \epsilon^*$. $\delta^{18}\text{O}_l$ indicates the $\delta^{18}\text{O}$ of water at the evaporation site of the leaf—the site of carbohydrate synthesis in the chloroplasts—and not the $\delta^{18}\text{O}$ of bulk leaf water. Roden et al. (2000) showed that $\delta^{18}\text{O}$ of the α -cellulose component of wood primarily depends on the $\delta^{18}\text{O}$ values of soil water and the evaporatively enriched water of the leaf, where photosynthates are produced. Xylem water does not undergo fractionation and is equal to the $\delta^{18}\text{O}$ of soil water and/or precipitation water, which are taken up via the root without any isotopic fractionation (White et al., 1985). Thus, $\delta^{18}\text{O}$ values of tree rings are controlled by relative humidity, temperature, and/or precipitation through the $\delta^{18}\text{O}$ values of soil water.

3. Materials and methods

3.1. Meteorological conditions of the sample site

Hokkaido Island is located in northern Japan and is surrounded by the Sea of Okhotsk, the Pacific Ocean, and the Sea of Japan (Fig. 1). The source of precipitated water in this island changes seasonally according to the main wind directions, and this change can be clearly demonstrated by monitoring seasonal changes in the deuterium excess values ($d = \delta D - 8 \times \delta^{18}\text{O}$) of precipitation. In winter, the prevailing wind direction is northwestern (i.e., from the Asian continent). The dry continental winds capture a large amount of moisture from the Sea of Japan by a nonequilibrium evaporation process. Most

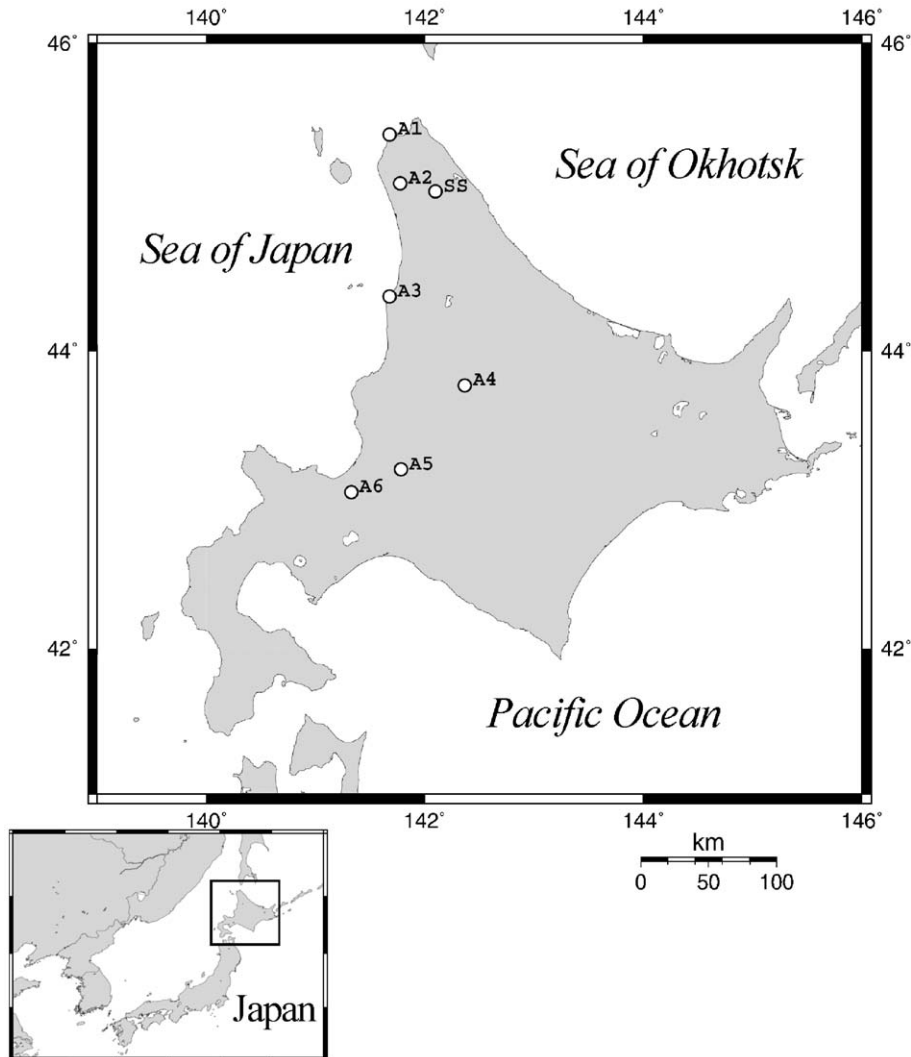


Fig. 1. Sampling site (SS) and meteorological station locations (A1: Wakkanai, A2: Toyotomi, A3: Haboro, A4: Asahikawa, A5: Iwamizawa, A6: Sapporo) in which the climatic data are applied for the statistical analyses in this study.

of this moisture precipitates in the form of heavy snowfall, which has a high d value and low $\delta^{18}\text{O}$, on the northwestern side of the Japanese islands. On the other hand, in summer, the source of precipitation is to the Pacific Ocean, and it shows low d values and high $\delta^{18}\text{O}$ (Dansgaard, 1964; Waseda and Nakai, 1983).

The precipitation on Hokkaido Island mainly comprises snowfall during the winter monsoon period, cyclonic activity (extratropical cyclones and typhoon), and the polar front from spring to fall. The precipitation in the northwestern Hokkaido region, including the sampling site, is minimum from March to June and maximum from August to November.

The sampling site, namely, the “CC-LaG site” (45°03'N, 142°06'E, asl 66 m) is located in a conifer–hardwood mixed forest in the Teshio Experimental Forest of Hokkaido University (Fig. 1). Meteorological data (precipitation and temperature) obtained at the nearest meteorological station (Toyotomi meteorological station; 45°06.1'N, 141°46.7'E, asl 12 m) around the sampling site includes only the period from 1980 to 2002. During this period, the maximum and minimum monthly mean temperatures that were recorded was approximately 19.3 °C in August and –6.8 °C in February, respectively (Fig. 2); the mean annual precipitation was 1092 mm. Relative humidity was maximum in summer and minimum in spring. This area is covered with a blanket of snow with a thickness of approximately 1.5 m for half the year. Since the data recorded by the Toyotomi meteorological station is limited, we used averaged data sets of relative humidity, temperature, and precipitation from 1961 to 2002 that were obtained at several meteorolog-

ical stations in Hokkaido Island; these were as follows: Wakkanai (45°24.9'N, 141°40.7'E, asl 3 m), Haboro (44°21.7'N, 141°21.7'E, asl 8 m), Asahikawa (43°46.3'N, 142°22.1'E, asl 120 m), Iwamizawa (43°12.7'N, 141°47.1'E, asl 42 m), and Sapporo (43°03.5'N, 141°19.7'E, asl 17 m) in order to understand historical changes in large-scale averaged climatic conditions in the northwestern Hokkaido Island around the sample site (Fig. 1). Averaging of two or more time series of meteorological station records avoids many problems associated with record heterogeneities and differences in station microclimates for potentially increasing the reliability of the data in order to calibrate the tree-ring chronologies (Blasing et al., 1981; Jacoby et al., 2000; Singh and Yadav, 2005). This must also be true for the calibration study of tree-ring isotope chronology.

3.2. Sampling procedure and isotope analysis of the tree rings

In June 2003, many several tree disks of oak (*Q. crispula*) and spruce (*P. jezoensis*), both of which were prevalent in the forest for sampling purposes, were cut from the remaining stumps in the CC-LaG site, where all the trees in an area of 14 ha had been logged off in the previous winter in order to investigate the effects of logging and planting on the carbon cycle in forest environments. These tree disks were stored and dried under room temperature.

All trees, namely, Y3, Y4 (spruce), O1, and O3 (oak), for which we investigated stable isotope ratios of the tree-ring disks, were growing at sites within a distance of approximately a few hundred meters. Y3 and Y4 were more than ~117 and ~138 years of age, respectively, and O1 and O3 were ~200 and ~230 years of age, respectively. The individual growth rings were cut every year from 1953 to 2002 by using a razor blade. Each ring was sliced into 20- μm -thick sections along the fibrous direction by using a rotary microtome. Cellulose was extracted from these sections by a modification of the method of Loader et al. (2003).

Extracted α -cellulose from each sample was analyzed for $\delta^{18}\text{O}$ by using a continuous flow system of a pyrolysis-type elemental analyzer (ThermoQuestTCEA) and an isotope ratio mass spectrometer (ThermoQuest Delta plus XL) (Sharp et al., 2001). In the pyrolysis furnace packed with glassy carbon, oxygen in the cellulose is quickly converted to CO gas at 1375 °C. Thus the isotopic ratios of CO can be determined as $\delta^{18}\text{O}$ of the cellulose. The standard deviation for repeated analysis of standard material was 0.3‰. The isotope ratio is expressed in the delta notation, i.e., $\delta^{18}\text{O} = ((^{18}\text{O}/^{16}\text{O})_{\text{sample}} / (^{18}\text{O}/^{16}\text{O})_{\text{standard}} - 1) \times 1000$.

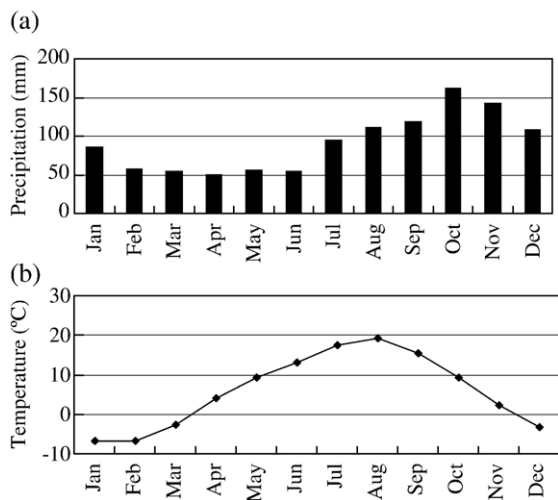


Fig. 2. The averages of monthly precipitation (a) and monthly temperature (b) from 1980 to 2002 in Toyotomi.

standard -1×1000 (‰), relative to the international standard (VSMOW) for oxygen.

4. Results and discussion

4.1. Oxygen isotope ratios of two individuals in spruce and oak

The measured $\delta^{18}\text{O}$ values of two spruce (Y3 and Y4) and oak (O1 and O3) trees are shown in Fig. 3a and b, respectively. The correlation coefficients (r) between the two spruce trees and oak trees are 0.58 ($p < 0.001$, $n = 50$) and 0.52 ($p < 0.001$, $n = 50$) for $\delta^{18}\text{O}$ during 1953 to 2002, respectively. Two $\delta^{18}\text{O}$ time series of spruce trees are likely to have the almost same tendency. The $\delta^{18}\text{O}$ values of one oak tree (O3) were on average 1.2‰ higher than those of the other (O1) during 1953–2002. Although there are considerable differences between the $\delta^{18}\text{O}$ of two individuals from the same species, the statistically significant correlation coefficients (more than 0.5, $p < 0.001$, $n = 50$ in spruce and oak) between the two $\delta^{18}\text{O}$ time series for both spruce and oak suggest that $\delta^{18}\text{O}$ in the tree-ring cellulose of each species is

controlled by specific common external factors. In contrast, the inter-species correlation between spruce and oak is much lower, where the correlation coefficient (r) between $\delta^{18}\text{O}$ of the two averaged spruce and oak trees is 0.32 ($p < 0.05$, $n = 50$) during 1953–2002 (Fig. 3c). This lower inter-species correlation implies that different external factors control the $\delta^{18}\text{O}$ values in each of the two tree species.

4.2. Oxygen isotope ratios in spruce and climatic factors

Single correlation analysis was carried out with respect to the climatic factors; average monthly temperature, monthly precipitation, and average monthly relative humidity observed at a suit of the above-mentioned meteorological stations. The extent of correlation of the monthly data sets with the $\delta^{18}\text{O}$ values of the two individuals and their averages in each tree during 1961 to 2002 was checked. The correlation coefficients (r) for temperature, precipitation, and relative humidity for the current and previous years are shown (Fig. 4). The highest correlations with

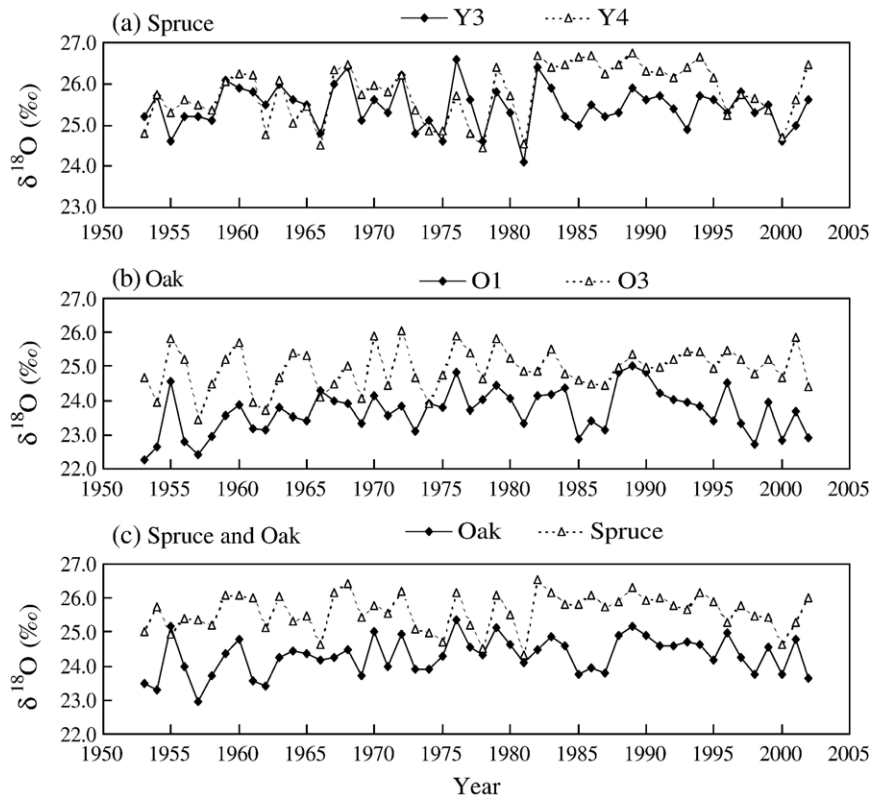


Fig. 3. Inter-annual variation in $\delta^{18}\text{O}$ of (a) both the spruce trees (Y3, Y4) and (b) that of both the oak trees (O1, O3) and (c) the average $\delta^{18}\text{O}$ of two oak trees and that of two spruce trees during 1953–2002.

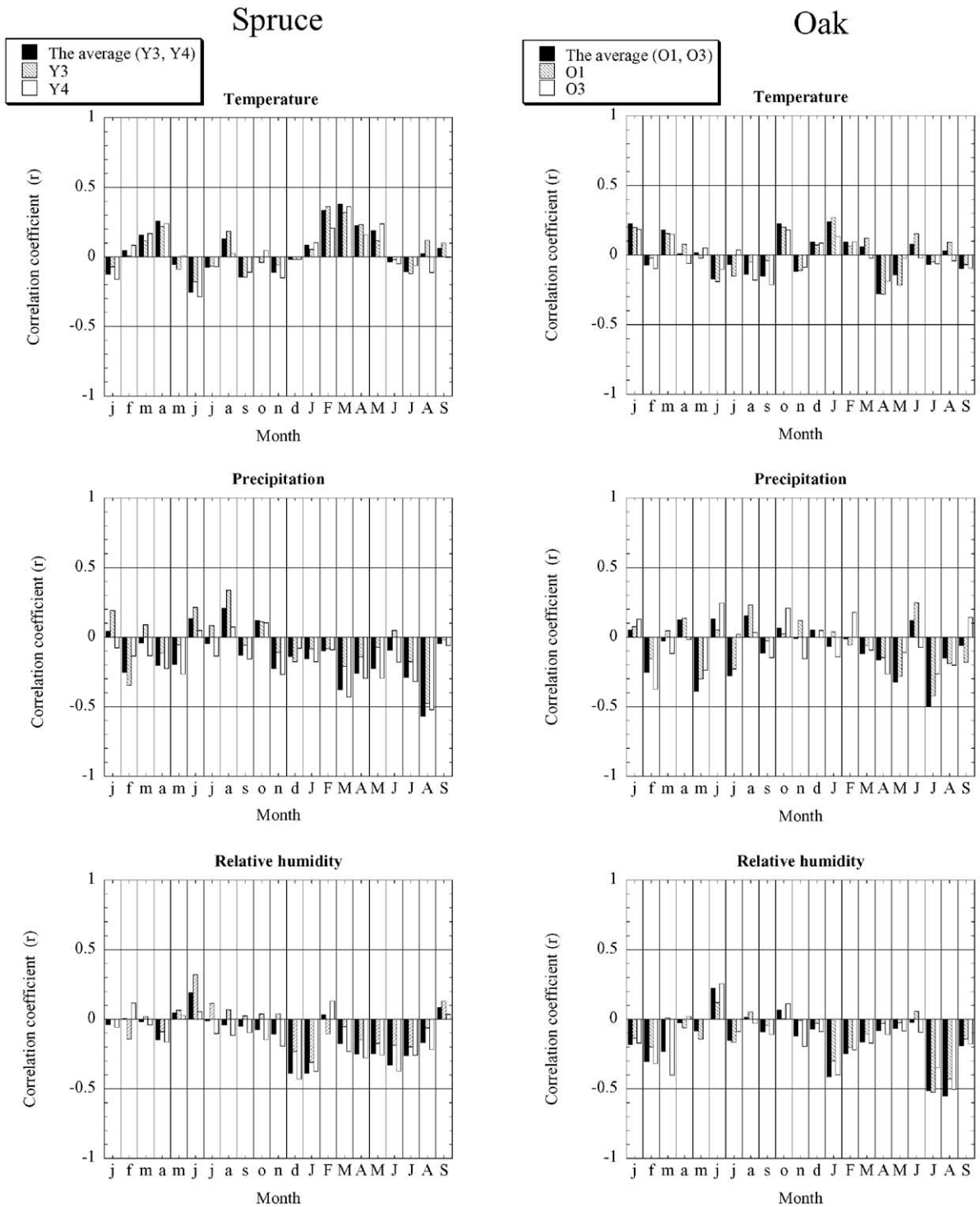


Fig. 4. Correlation coefficients of monthly precipitation, monthly mean temperature, and relative humidity with the $\delta^{18}\text{O}$ values of spruce and oak, respectively. Correlation coefficients were calculated for each tree (Y3 and Y4 for spruce and O1 and O3 for oak) and their averages in the same tree species against monthly average of the climate data obtained in the current year (capital letters) and the previous year (small letters).

Table 1

$\delta^{18}\text{O}$ values of annual tree rings in each spruce and oak versus the best correlation coefficients for the monthly mean temperature (temp.), monthly precipitation (prep.), and monthly mean relative humidity (RH) among the 5 average stations (Wakkanai, Haboro, Asahikawa, Iwamizawa, and Sapporo) during previous January to current September

Spruce	$\delta^{18}\text{O}$		
	February–April temp.	July–August prep.	March–August RH
Y3	0.41**	-0.49***	-0.23
Y4	0.31*	-0.62***	-0.43**
Y3, Y4 avg.	0.41**	-0.63***	-0.39*
Oak	April temp.	July prep.	July–August RH
O1	-0.27	-0.42**	-0.55***
O3	-0.19	-0.26	-0.49***
O1, O3 avg.	-0.27	-0.50***	-0.62***

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

precipitation (negative values) were found in March and July–August, and the correlation coefficients with temperature show peaks in the period from February to April. On the other hand, the correlation coefficients

with relative humidity demonstrated two negative peaks, which is one peak in the winter and one peak which lasts from spring and summer. The strongest correlation between the $\delta^{18}\text{O}$ and precipitation was found in July to August for one spruce and that with temperature was found in February to April for average $\delta^{18}\text{O}$ of spruce. The correlation coefficients are listed in Table 1. In general, $\delta^{18}\text{O}$ of spruce is expected to be controlled by the $\delta^{18}\text{O}$ of the shallow soil water in the season of growth, which is sensitive to the $\delta^{18}\text{O}$ of precipitation during spring and summer because spruce has a shallow-root system (Waterhouse et al., 2002). Thus, the relationship between the $\delta^{18}\text{O}$ of spruce, temperature, and precipitation may be strongly influenced by the $\delta^{18}\text{O}$ of precipitation in the current year.

When precipitation in summer is higher, the $\delta^{18}\text{O}$ value of spruce decreases. This relationship can be explained by the two mechanisms: (1) lower ^{18}O enrichment in leaf water due to higher relative humidity and (2) the negative correlation between the $\delta^{18}\text{O}$ of precipitation and precipitation amount (i.e., amount effect). The former mechanism may not be important because the correlation between the $\delta^{18}\text{O}$ of spruce and

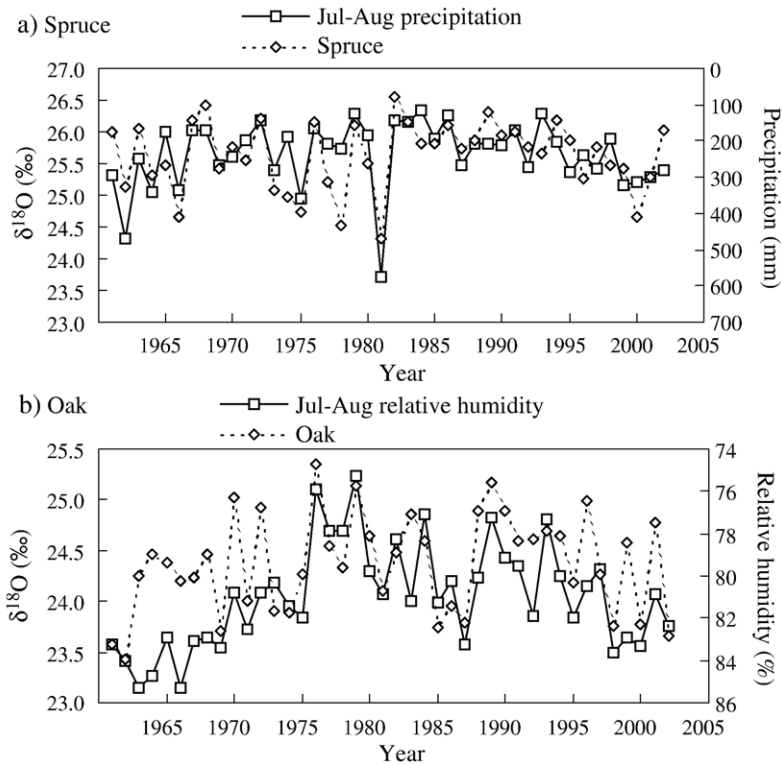


Fig. 5. Comparison of inter-annual variations in (a) $\delta^{18}\text{O}$ for spruce tree rings (the average of Y3 and Y4) and July and August precipitation and (b) $\delta^{18}\text{O}$ for oak tree rings (the average of O1 and O3) and average relative humidity during July and August. (a) Precipitation axis and (b) relative humidity axis are reversed.

relative humidity in summer is low (Fig. 4). Thus, the latter mechanism is assumed to mainly contribute to the relationship between precipitation in summer and the $\delta^{18}\text{O}$ values of spruce. Dansgaard (1964) indicates that in Tokyo (35°N), which is located approximately 1000 km to the south of the sampling site (45°N), the temperature effect exists in winter and the amount effect exists in summer. If heavy rainfall events in summer bring a lower $\delta^{18}\text{O}$ precipitation, thereby causing the amount effect, amount effect can also be expected in Hokkaido Island because heavy rainfall events are occasionally experienced due to the extratropical low and typhoons in Hokkaido Island as well as in the southern part of Japan. In general, it is shown that the $\delta^{18}\text{O}$ of precipitation from tropical cyclones is very low when compared with that of normal summer precipitation (Lawrence and Gedzelman, 1996). For example, the remarkable low values of the average of the two spruces in 1981 and 1966 correspond to the years when devastating typhoons and extratropical lows influenced the Hokkaido Islands in summer (Fig. 5a, the axis of precipitation is reversal). These facts indicate that the high negative correlation between precipitation in July and August and the $\delta^{18}\text{O}$ of spruce results from substantial rainfall events during the season of growth of spruce. The slope of $\delta^{18}\text{O}$ against precipitation in July and August is $-0.37\text{‰}/100\text{ mm}$ (Fig. 6a). On the other hand, the high positive correlation between temperature from February to April and $\delta^{18}\text{O}$ of spruce can be elucidated by a combination of the two factors: (1) influence of snow water with a low $\delta^{18}\text{O}$ value of soil that is retained even in summer and (2) positive correlation between temperature and $\delta^{18}\text{O}$ of precipitation in winter (i.e., temperature effect). High d excess value and low $\delta^{18}\text{O}$ value of the stream water near the sampling site during the period of March to April gradually exchanged with water of low d excess and high $\delta^{18}\text{O}$ values until August in 2002 (Nakatsuka et al., unpublished data). This indicates that snow water (high d excess and low $\delta^{18}\text{O}$ values) is retained in the soil even in summer. The positive correlations between temperature and the $\delta^{18}\text{O}$ of precipitation have been widely observed at mid-latitudes (Dansgaard, 1964; Araguas-Araguas et al., 1998). The evidence suggests that the positive correlation between temperature from February to April and the $\delta^{18}\text{O}$ of spruce is governed by the temperature effect.

4.3. Oxygen isotope in oak and climatic factors

The $\delta^{18}\text{O}$ values of oak are strongly correlated with relative humidity in July and August and with

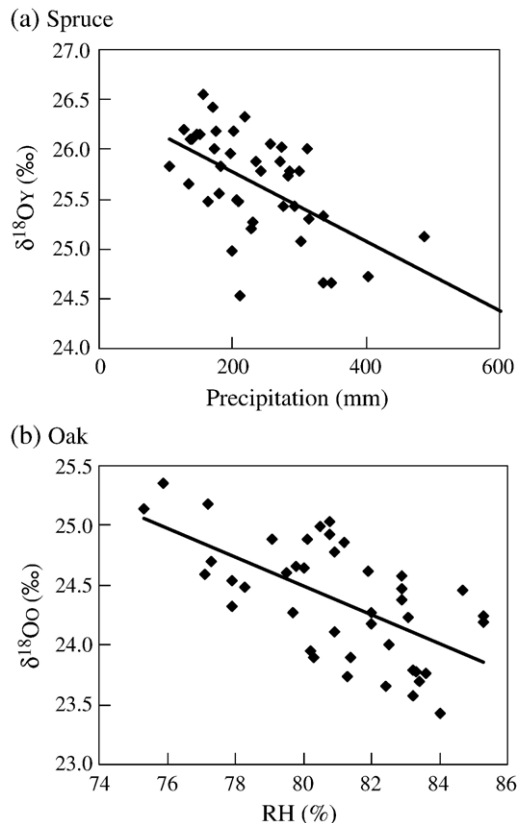


Fig. 6. Relationships between (a) average $\delta^{18}\text{O}$ values for spruce tree rings ($\delta^{18}\text{O}_Y$) and July and August precipitation (prep.) and (b) averaged $\delta^{18}\text{O}$ values for oak tree rings ($\delta^{18}\text{O}_O$) and July and August relative humidity (RH). Relationships can be expressed as follows: (a) $\delta^{18}\text{O}_Y = (-0.00371 \pm 0.00072) \times \text{prep.} + (26.5 \pm 0.3)$, $r = -0.63$, $p = 7.67 \times 10^{-6}$, $n = 42$; (b) $\delta^{18}\text{O}_O = (-0.124 \pm 0.025) \times \text{RH} + (34.2 \pm 1.9)$, $r = -0.62$, $p = 1.38 \times 10^{-5}$, $n = 42$.

precipitation in July (Table 1, Fig. 4). Very weak correlations with temperature—in contrast to the strong correlation with relative humidity—in summer suggest that the oak trees absorb deep soil water with a long retention period; consequently, the $\delta^{18}\text{O}$ values of oak are not governed by the $\delta^{18}\text{O}$ values of precipitation, but by the ^{18}O enrichment effect in leaf water due to transpiration, namely relative humidity. In general, the deep-root system of oak trees probably weakens the correlation between the $\delta^{18}\text{O}$ values of precipitation and that of oak. However, the $\delta^{18}\text{O}$ values of oak were in fact found to be correlated with the $\delta^{18}\text{O}$ of summer precipitation in dry areas (Waterhouse et al., 2002) and that of previous winter precipitation in damp areas (Robertson et al., 2001) in Europe. Nakatsuka et al. (2004) also showed that the negative correlations between the $\delta^{18}\text{O}$ values of oak and winter precipitation were probably due to the lower $\delta^{18}\text{O}$ of

precipitation in winter in the northern Hokkaido Island. In this study, the reason behind the insensitivity of the $\delta^{18}\text{O}$ of oak to the $\delta^{18}\text{O}$ of precipitation cannot be attributed to the physiology of oak trees but to the soil characteristics in the study area, which contained a high proportion of clay and prevented easy penetration of the precipitation into a deep soil layer. The largest correlation coefficients (r) between $\delta^{18}\text{O}$ of the oak trees and climatic factors are found for relative humidity in July and August, which are -0.55 ($p < 0.001$, $n = 42$) and -0.49 ($p < 0.001$, $n = 42$) for O1 and O3, respectively (Fig. 4). The average of O1 and O3 shows a better correlation coefficient for the relative humidity in July and August ($r = -0.62$, $p < 0.001$, $n = 42$) because the averaging process must reduce the noise against the climatic signal (Fig. 5b, the axis of relative humidity is reversal). The $\delta^{18}\text{O}$ values of oak are plotted against relative humidity in Fig. 6b. The slope of single regression is -0.12‰/‰ (Fig. 6b). This slope is almost consistent with those reported by the previous studies in Europe (Robertson et al., 2001; Raffalli-Delercé et al., 2004).

5. Conclusions

Previously, very few studies were conducted on the tree-ring isotope ratios in damp and cold areas. In this study, we demonstrated that the oxygen isotope ratios of tree rings in spruce and oak can become proxies of precipitation and relative humidity in summer in the northern area in Hokkaido Island, Japan, where precipitation can be observed constantly over a year. In general, oxygen isotope ratios of tree rings in two types of tree—one with deep roots and the other with shallow roots—have the potential to record the relative humidity in summer and the $\delta^{18}\text{O}$ of summer precipitation separately, when growing in the same forest with a soil layer that prevents the downward infiltration of precipitation, such as the clay layer in this study area, at the subsurface level.

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