Synchronizations of tree-ring $\delta^{18}\text{O}$ time series within and between tree species and provinces in Korea: a case study using dominant tree species in high elevations

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Abstract

The current study was initiated to test the synchronizations of tree-ring $\delta^{18}\text{O}$ (hereafter $\delta^{18}\text{O}_{\text{TR}}$) time series within and between tree species and provinces, which are about 144 km apart from each other in Korea. For the test, a 50-year $\delta^{18}\text{O}_{\text{TR}}$ time series (1966–2015) was developed using four trees from each tree species which are Pinus densiflora and Quercus mongolica from Songnisan National Park and Taxus cuspidata, Pinus koraiensis, Abies koreana, and Quercus mongolica from Jirisan National Park. Their synchronizations were evaluated using t-value, Gleichläufigkeit (Glk), and Expressed Population Signal (EPS). The mean t-values and Glk scores within the tree species ranged 5.2–11.2 ($p < 0.05$) and 69–83%, and between the tree species ranged 6.1–13.2 ($p < 0.05$) and 73–81%, respectively. The mean t-value and Glk score between the regions were 4.3 ($p < 0.05$) and 72%, respectively. Furthermore, the EPS showed higher than 0.85, which is the generally accepted threshold value in dendrochronology, except for Q. mongolica at Sŏngnisan National Park for which the value is 0.83 calculated by only two $\delta^{18}\text{O}_{\text{TR}}$ time series. Based on the statistical results, we concluded that a $\delta^{18}\text{O}_{\text{TR}}$ chronology established using more than four trees could serve as a promising reference for dating an undated wood without considering the tree species, as well as for research on climate in the past.

Keywords: Oxygen isotope, Cross-dating, Different provinces, Abies koreana, Pinus koraiensis, Taxus cuspidata, Quercus mongolica

Introduction

Tree-ring dating is an accepted scientific method to determine the exact year when a ring was formed [1]. The tree-ring dating not only plays an important role in dating archaeological wooden materials [2–5], but also in investigating the climatic and environmental conditions during the dated years [6–10].

Dendrochronology was introduced in the Republic of Korea in the early 1990s [11, 12], whereas the first paper on dating archaeological woods using the tree-ring dating method was published in the early 2000s [13]. Due to difficulty in obtaining permission to collect tree-ring samples from archaeological woods and lack of long local tree-ring chronologies for dating, it took some time to publish research work related to dendroarchaeological dating. Although a 893-year-long (1126–2018 CE) ring-width chronology was established through many dated archaeological woods of Pinus densiflora (known as the red pine), which has been used to date as the most common archaeological woods in Korea [14–16], long chronologies have not yet been established using other tree species from various regions. Various local master
chronologies comprising different tree species from different regions are required for successful tree-ring dating, because the annual patterns of the ring widths vary depending on the tree species and locations. To this end, archaeological woods containing various tree species need to be found in archaeological relics, buildings, and artifacts, which cover long time range without any interruption. According to past studies [17–20], tree species used for buildings, Buddhist statues, furniture and charcoals were different in some cases with respect to time and region in the Republic of Korea. Due to a lack of long local master chronologies for various tree species, most studies on dating archaeological woods rely on the radiocarbon dating method [21–23].

With the help of developed equipment, measured values of different cell traits, such as cell size, wall thickness and density [9, 24, 25], and stable isotopes such as carbon and oxygen [26–29] were used to establish inter-annual time series for dendrochronological research. Among them, the tree-ring δ18O time series, which has been established using the ratios between 18O and 16O for each year, is considered as a reliable reference chronology, and has been used in dating tree-ring δ18O time series without considering the tree species [30, 31]. For instance, Li et al. [32] published that tree-ring δ18O time series from pine and oak trees under similar growing conditions in Japan showed well synchronization. Furthermore, Jessica et al. [33] reported that tree-ring δ18O time series established within 1000 km in Bolivia also showed good correlations. Apart from such attractive advantage, a tree-ring δ18O chronology, established using a lesser number of trees than the other measurement parameters, can play a role as a reliable proxy representing a potential climate signal at a site [30, 34, 35]. Recently, we verified the synchronizations of tree-ring δ18O time series between different tree species, viz. Pinus densiflora, Abies koreana, Taxus cuspidata, and Quercus mongolica, from Jirisan National Park in Korea, by using four trees per tree species [36]. This study was conducted only at a single site, and therefore, it does not suffice for application of the tree-ring δ18O chronology for cross-dating and/or dating tree-ring δ18O time series for other regions.

In the current study, we aimed to test synchronizations of tree-ring δ18O (hereafter δ18OTR) time series within and between tree species and provinces in the Republic of Korea. The results are expected to offer useful tips to the dendrologists who lack the necessary resources for reliable dating of archaeological woods using ring-width data, and those who are interested in investigating the past climate of Korea.

Materials and methods
Study sites and tree species
Wood samples from living trees were collected at Songnisan (36° 33’ N, 127° 51’ E) and Jirisan (35° 17–20’ N, 127° 32–43’ E) National Parks which are located at the central and southern provinces of the Republic of Korea, respectively (Fig. 1). The highest peaks of Songnisan and Jirisan National Parks are 1029 m a.s.l. and 1915 m a.s.l., respectively. The Songnisan National Park is about 144 km away from the north from Jirisan National Park.

In order to establish tree-ring δ18O (hereafter δ18OTR) time series, 24 tree-ring samples were selected from archived increment cores at Tree-Ring Research Center (www.dendro.kr) at the Chungbuk National University (Table 1). All of them were already cross-dated using ring-width data for publications [36, 37]. At Songnisan National Park, two tree species, viz. Pinus densiflora and Quercus mongolica, and at Jirisan National Park, four tree species, viz. Taxus cuspidata, Pinus koraiensis, Abies koreana, and Quercus mongolica, were chosen as experimental tree species, which are also the dominant species at high altitude of Songnisan [38] and Jirisan National Parks [39, 40]. Based on the previous studies [30, 34, 37], four trees of each tree species were used to establish the δ18OTR time series for living trees.

The δ18OTR time series
Only one core per tree was used to establish the δ18OTR time series. The plate method [29] was conducted to facilitate the processing of several rings simultaneously. First, an increment core was transversely cut into several 1-mm-thick wood plates using a diamond wheel saw, and then the plates were sandwiched between 1-mm-thick Teflon-punch sheets (Fig. 2a, b). A 1.0-mm gap was left between the Teflon-punch sheets to allow flow of the chemical solutions and reach all the surfaces of the wooden plate. Second, α-cellulose was extracted directly from the wood plate using a modified Jayme–Wise method [41, 42], which consists of two principal processes: (1) removal of lignin using an acidified sodium chlorite solution, followed by (2) removal of hemicellulose using sodium hydroxide solution in a water bath heated between 70 and 80 °C (Fig. 2c). Third, each annual ring (120–250 μg) of α-cellulose was partially separated from the cellulose plate under a microscope (Fig. 2d), and then loaded on a silver foil (Fig. 2e). The silver-wrapped sample was finally used to determine oxygen isotope ratio in the α-cellulose of each tree ring using an isotope ratio mass spectrometer (Delta V Advantage, Thermo Fisher Scientific) interfaced with a pyrolysis-type high-temperature conversion elemental analyzer (TC/EA, Thermo Fisher Scientific). The oxygen isotope ratio was expressed in δ notation (%) with
respect to the international oxygen isotope standard (Vienna Standard Mean Ocean Water) as follows:

\[
\delta^{18}O(\text{‰}) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000,
\]

where \(R_{\text{sample}}\) and \(R_{\text{standard}}\) are the \(^{18}\text{O}/^{16}\text{O}\) ratios in the sample and standard, respectively.

Owing to contamination in the process of cellulose extraction, two individual tree cores collected from \(Q.\ mongolica\) were not used for further analysis.

**Synchronization tests**

To verify synchronization within and between the tree species and provinces, the \(t\)-value and Glk

| Site | Location | Altitude (m a.s.l) | Species | DBH (cm) Ave | Min | Max | No. of samples |
|------|----------|-------------------|---------|--------------|-----|-----|----------------|
| SN   | 36° 33´ N 127° 51´ E | 666–823 | \(P.\ densiflora\) | 63.3 | 30 | 86 | 4 |
|   | 36° 33´ N 127° 51´ E | 800–930 | \(Q.\ mongolica\) | 49.4 | 30 | 63 | 4 |
| JR   | 35° 20´ N 127° 43´ E | 1340–1650 | \(T.\ cuspidate\) | 76.8 | 56 | 110 | 4 |
|   | 35° 20´ N 127° 43´ E | 1621–1645 | \(P.\ koraiensis\) | 43.0 | 39 | 45 | 4 |
|   | 35° 17´ N 127° 32´ E | 972–1383 | \(Q.\ mongolica\) | 50.3 | 38 | 68 | 4 |

\(SN\) Songnisan National Park, \(JR\) Jirisan National Park, *: 95.0%, **: 99.0%, DBH: diameter at breast height
(Gleichläufigkeit) scores were used for cross-dating [43]. The \( t \)-value and Glk scores are well-known parameters which represent the matching strength between time series at a certain overlapping position in dendrochronology [44]. The \( t \)-values were calculated using the correlation coefficients between time series and the number of their overlapping years (Eq. 2), whereas the Glk scores were calculated based on the matching ratios of the time series compared in the overlapping years (Eq. 3).

\[
t = \frac{r \times \sqrt{n-2}}{\sqrt{(1-r^2)}},
\]

where \( r \) is the correlation coefficient and \( n \) is the number of overlapped tree rings between time series.

\[
G_{(x,y)} = \frac{1}{n-1} \sum_{i=1}^{n-1} [G_{ix} + G_{iy}]
\]

If \( (x_{i+1} - x_i) > 0 \), \( G_{ix} = +1/2, (x_{i+1} - x_i) = 0 \), \( G_{ix} = 0, (x_{i+1} - x_i) < 0 \), \( G_{ix} = -1/2 \), where \( G_{(x,y)} \) is the Glk value and \( x_i \) is the measurement value at \( i \)-year tree ring.

The TSAPWin program (RINNTECH, Germany) was applied to calculate the \( t \)-values and Glk scores which were further used to test the synchronizations between the \( \delta^{18}O_{TR} \) time series. Fifty-year \( \delta^{18}O_{TR} \) time series (1966–2015) from living trees were used for analyzing the strength of common variations between the different trees.

We also used the expressed population signal (EPS) to evaluate the chronology signal strength [27, 45]. The EPS can be described as shown in Eq. 4:

\[
EPS = n \times R_{bar}/(n \times R_{bar} + (1 - R_{bar})),
\]

where \( n \) is the number of trees at the site and \( R_{bar} \) is the mean correlation coefficient of all the time series. With increase in \( n \) and/or \( R_{bar} \), the EPS was found to increase and reach 1. The suggested threshold value was higher than 0.85 over the entire period.

**Results and discussion**

Oxygen isotope measurement of \( \alpha \)-cellulose from each tree ring was done so that we could establish \( \delta^{18}O_{TR} \) time series for individual sample trees. Due to operating error of the equipment, however, two \( Q. \) mongolica at Songnisan National Park could not be measured. Therefore, only two oak \( \delta^{18}O_{TR} \) time series were used for further analysis (Table 2).

### Synchronization tests within and between tree species

From the synchronization test of \( \delta^{18}O_{TR} \) time series within tree species, the mean \( t \)-values (min.–max.) for \( P. \)
densiflora and Q. mongolica at Songnisan National Park were 5.2 (4.2–6.4) and 6.9 (none), respectively, while their Glk scores were 74% (66–83%) and 79% (none), respectively (Table 2). In addition, the mean t-values (min.– max.) for T. cuspidata, P. koraiensis, A. koreana, and Q. mongolica at Jirisan National Park were 9.5 (5.9–15.6), 11.2 (7.5–14.0), 7.3 (4.9–11.3) and 6.4 (4.0–11.0), respectively, and their Glk scores were 78% (68–87%), 83% (78–86%), 76% (65–84%), and 69% (62–86%), respectively (Table 2). In all the above cases, the conifer tree species at Jirisan National Park showed higher t-values and Glk scores than that at Songnisan National Park; however, Q. mongolica showed lower values in reverse. Although the statistical values showed some differences, the inter-annual δ18OTR time series within the tree species showed similar patterns (Fig. 3).

In the synchronization test of δ18OTR chronologies between tree species, the mean t-value and Glk score between P. densiflora and Q. mongolica at Songnisan National Park were 6.6 and 73%, respectively, while the mean t-values and Glk scores among T. cuspidata, P. koraiensis, A. koreana, and Q. mongolica at Jirisan National Park ranged from 6.1 (P. koraiensis: Q. mongolica) to 13.2 (T. cuspidata: A. koreana) and 73% (P. koraiensis: Q. mongolica) to 81% (T. cuspidata: A. koreana and P. koraiensis: A. koreana), respectively (Table 3, gray background). Except the t-value between P. koraiensis and Q. mongolica in Jirisan National Park, all other statistical values in Jirisan National Park were higher than those in the Songnisan National Park. In these comparisons, we could identify distinct similar patterns among inter-annual δ18OTR chronologies of individual tree species (Fig. 4).

In all the synchronization tests of δ18OTR time series within and between tree species, we verified reliable homogenous patterns as well as meaningful t-values and Glk scores. The oxygen isotope ratios of the tree-ring cellulose were primarily determined by evaporative enrichment of leaf water 18O, which was modulated by relative humidity at the site [26, 27]. Non-climatic factors such as ecological competition did not alter annual variations in δ18OTR values of individual trees significantly. In fact, the δ18OTR time series established from different tree species under the same and/or similar growing conditions were shown to be well correlated with one another [30, 32, 36, 46]. Unlike Q. mongolica, the conifer trees at Jirisan National Park showed higher t-values and Glk scores than the conifer trees (P. densiflora) at Songnisan National Park, and the statistical results between the conifer species tended to be higher than between conifer species and Q. mongolica. According to previous publication [31], such results might occur from differences in the fraction of carbohydrate oxygen that undergoes exchange with oxygen of xylem water, the net fractionation factor between them, differences in root depth and growing seasons of the tree species.

The mean correlation coefficients within trees (Rbar)

and expressed population signal (EPS)

Rbar, and EPS of δ18OTR time series for the Songnisan National Park were higher than 0.61 and 0.83, respectively (Table 4). By contrast, for the Jirisan National Park, the former was higher than 0.70 and the latter higher than 0.90. Except Q. mongolica at Songnisan National Park, the EPS from the four trees showed higher than the threshold value 0.85 [27, 45]. The δ18OTR chronologies from the four trees therefore were verified as a promising chronology for dating of the undated archaeological woods, as well as for capturing past climate condition.

Through previous publications on dendroclimatic researches [47, 48], it was verified that δ18OTR chronologies established using more than four trees could serve as a promising chronology in dendroclimatic reaches based on EPS. In this result, the Rbar from each group, consisting of the same tree species showed high values, so that EPS higher than the threshold value (0.85) could

| Site | Tree species | No. of samples | t-values | Glk scores (%) |
|------|--------------|----------------|----------|----------------|
|      |              |                | Ave. | Min | Max | Ave. | Min | Max |
| SN   | P. densiflora | 4              | 5.2   | 4.2**| 6.4**| 74   | 66**| 83** |
|      | Q. mongolica | 2              | 6.9   | –   | –   | 79   | –   | –   |
| JR   | T. cuspidata | 4              | 9.5   | 5.9**| 15.6**| 78   | 68**| 87** |
|      | P. koraiensis| 4              | 11.2  | 7.5**| 14.0**| 83   | 78**| 86** |
|      | A. koreana  | 4              | 7.3   | 4.9**| 11.3**| 76   | 65**| 84** |
|      | Q. mongolica | 4              | 6.4   | 4.0**| 11.0**| 69   | 62**| 86** |

SN Songnisan National Park, JR Jirisan National Park, *: 95.0%, **: 99.0%

–: no data due to the number of samples
**Fig. 3** Synchronization tests of the $\delta^{18}O_{\text{p}}$ time series within tree species (gray lines) and their mean inter-annual variations (solid bold lines)
be obtained (Table 4). Only EPS from Q. mongolica at Songnisan National Park, which was calculated using $R_{\text{bar}}$ from two trees, was lower than the threshold due to insufficient sample size.

### Table 3 The $t$-values and Glk scores of $\delta^{18}$OTR time series between tree species in the same national parks (gray backgrounds) and both national parks (white background)

|                   | SN                | JR                |
|-------------------|------------------|------------------|
| Site              | P. densiflora    | Q. mongolica     |
|                   | T. cuspidate     | P. koraiensis    |
|                   | A. koreana       | Q. mongolica     |
| SN P. densiflora  | 6.6**            | 68.0**           |
| Q. mongolica      | 72.0**           | 75.0**           |
| JR T. cuspidate   | 4.9*             | 10.3**           |
| P. koraiensis     | 3.9**            | 8.3**            |
| A. koreana        | 4.3**            | 6.1**            |
| Q. mongolica      | 6.6**            | 6.6**            |

*SN Songnisan National Park, JR Jirisan National Park, *: 95.0%, **: 99.0%

### Table 4 Mean correlation coefficients ($R_{\text{bar}}$) and expressed population signal (EPS) of $\delta^{18}$OTR time series within tree species

| Site  | Tree species | No. of samples | $R_{\text{bar}}$ | EPS   |
|-------|--------------|----------------|-----------------|-------|
| SN    | P. densiflora| 4              | 0.610           | 0.862 |
|       | Q. mongolica | 2              | 0.717           | 0.835 |
| JR    | T. cuspidata | 4              | 0.841           | 0.955 |
|       | P. koraiensis| 4              | 0.704           | 0.905 |
|       | A. koreana   | 4              | 0.869           | 0.964 |
|       | Q. mongolica | 4              | 0.759           | 0.926 |

*SN Songnisan National Park, JR Jirisan National Park

### Synchronization tests between the study regions

Comparing the $\delta^{18}$OTR chronologies originating from Songnisan National Park and Jirisan National Park, the mean $t$-values and Glk scores (min.–max.) were 4.5 (3.6–5.4) and 72% (68–78%), respectively (Table 3, white background). To verify the synchronization strength between the two regions regardless of tree species, we compared the local $\delta^{18}$OTR chronologies between Songnisan and Jirisan National Parks. It turned out that the mean $t$-value and Glk score were 3.5, and 65%, respectively. In addition, the local chronologies showed a significant correlation of 0.60 ($p<0.01$) (Fig. 5).

According to the correlation analysis between individual $\delta^{18}$OTR chronologies and monthly temperature and precipitation from meteorological stations close to Songnisan and Jirisan National Parks (Fig. 1) for the last 43 years (1973–2015), all chronologies at both the national parks showed relatively high positive correlation.
coefficients with April and July temperatures of the current year (Fig. 6). These results signify that these monthly temperatures at both the research areas play an important role in modulating δ18O of the source water and local humidity [27, 32]. It should also be noted that there are significant linear relationships between April temperatures of Songnisan and Jirisan National Parks, and between the July temperatures of them as well (Fig. 7). Although Songnisan and Jirisan National Parks are about 144 km apart from each other, our results indicate that the δ18OTR was controlled by large-scale variations in the growing season temperature as well as variations in the April and July temperatures (Fig. 6). Significant correlations of δ18OTR chronologies were also found between different provinces in Bolivia which are about 1000 km far from each other [33].

Fig. 5 Synchronization tests of local δ18OTR chronologies between Songnisan and Jirisan National Parks

Fig. 6 Correlation coefficients between individual δ18O chronologies and monthly temperature and precipitation from October in the previous year to September in the current year from Boeun meteorological station close to Songnisan National Park and Sancheong and Namwon meteorological stations close to Jirisan National Park for the last 43 years (1973–2015)
Application to dendroarchaeology and dendroclimatology

In order to date wooden materials using tree-ring chronology, establishing a long chronology using the same tree species growing under similar environmental condition is a fundamental requirement [49]. Dendrologists in Korea have a limitation in making such a long chronology. This is due to the chance of finding a living tree older than 300 years being rare, as well as, it is difficult to find archaeological woods to extend the chronology from the living trees. Based on the current results, it was verified that a δ18OTR chronology established using four trees could play a promising reference in dating archaeological woods excavated from a region between Songnisan and Jirisan National Parks, and in research on reconstructing the past climate of the region.

Conclusions

Based on a 50-year δ18OTR time series, we tested synchronization between and within-tree species in the Songnisan and Jirisan National Parks, which are about 144 km apart. The δ18OTR time series was established using increment cores from *Pinus densiflora* and *Quercus mongolica* in the Songnisan National Park, and *Taxus cuspidata*, *Pinus koraiensis*, *Abies koreana* and *Quercus mongolica* in the Jirisan National Park. All the δ18OTR chronologies showed significant correlations with one another irrespective of species and locations. In addition, the EPS from the four δ18OTR time series were higher than 0.85, which is the threshold value in research on climate in the past. Based on the statistical results, we conclude that a δ18OTR chronology established using more than four trees could play a promising reference for dating an undated wood without considering the tree species, as well as for research on climate in the past, where the regions are from Songnisan to Jirisan National Parks.

Abbreviations

δ18OTR chronology: Tree-ring δ18O time series; Glk: Gleichläufigkeit; EPS: Expressed population signal; SN: Songnisan National Park; JR: Jirisan National Park; DBH: Diameter at breast height.

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Competing interests

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Fig. 7 Linear relationships between April temperatures and between July temperatures of Songnisan and Jirisan National Parks
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