Choi *et al. J Wood Sci* (2020) 66:53
https://doi.org/10.1186/s10086-020-01901-3

Journal of Wood Science

ORIGINAL ARTICLE Open Access

Synchronizations of tree-ring δ^{18}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 δ^{18}O (hereafter $\delta^{18}O_{TR}$) 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 $\delta^{18}O_{TR}$ 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 Songnisan National Park for which the value is 0.83 calculated by only two $\delta^{18}O_{TR}$ time series. Based on the statistical results, we concluded that a $\delta^{18}O_{TR}$ 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

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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 $\delta^{18}O$ time series, which has been established using the ratios between ^{18}O and ^{16}O for each year, is considered as a reliable reference chronology, and has been used in dating tree-ring $\delta^{18}O$ time series without considering the tree species [30, 31]. For instance, Li et al. [32] published that tree-ring $\delta^{18}O$ 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 $\delta^{18}O$ time series established within 1000 km in Bolivia also showed good correlations. Apart from such attractive advantage, a tree-ring $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ chronology for cross-dating and/or dating tree-ring $\delta^{18}O$ time series for other regions.

In the current study, we aimed to test synchronizations of tree-ring $\delta^{18}O$ (hereafter $\delta^{18}O_{TR}$) 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 to the north from Jirisan National Park.

In order to establish tree-ring $\delta^{18}O$ (hereafter $\delta^{18}O_{TR}$) 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 $\delta^{18}O_{TR}$ time series for living trees.

The $\delta^{18}O_{TR}$ time series

Only one core per tree was used to establish the $\delta^{18}O_{TR}$ 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

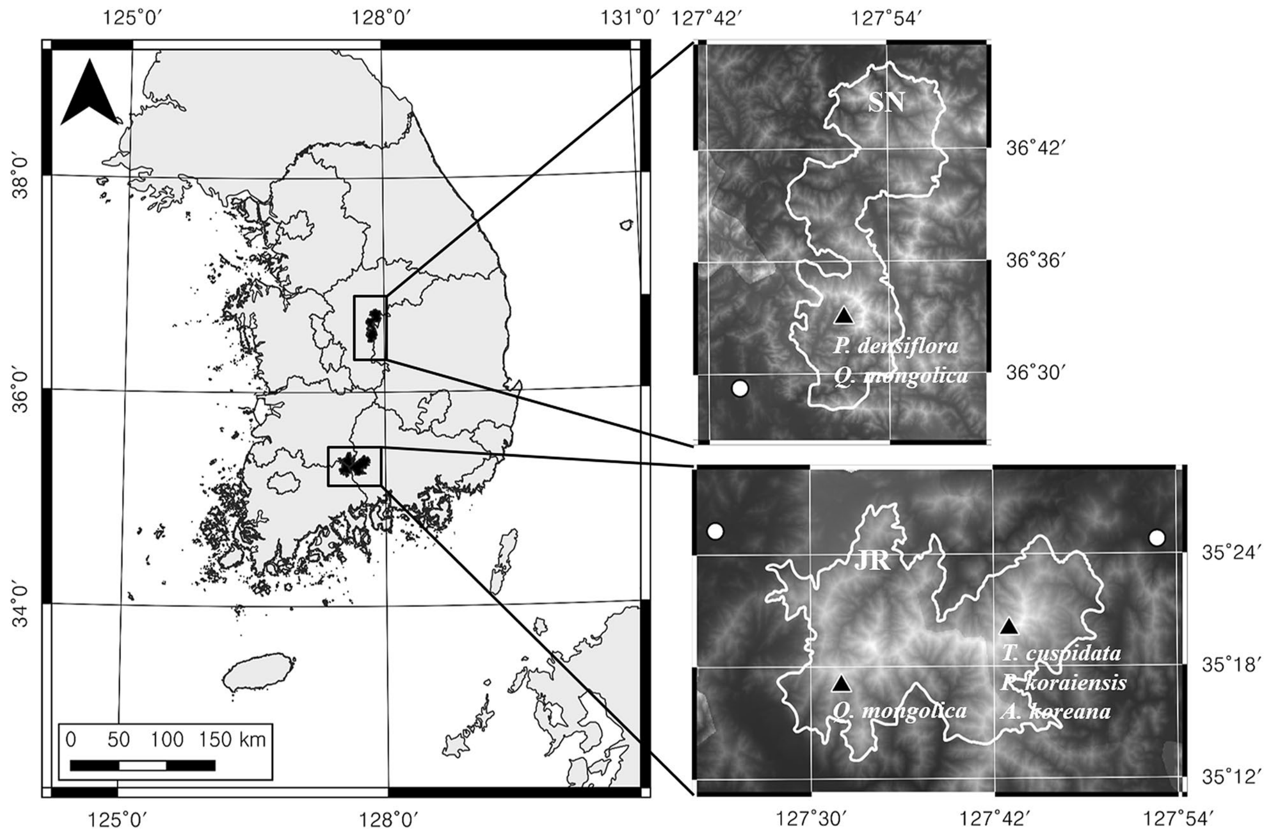

Fig. 1 Locations of the sampling sites (triangles) and the meteorological stations (open circles) close to the sampling sites (SN: Songnisan National Park, JR: Jirisan National Park)

Table 1 Details of the experimental sites and trees used to establish the $\delta^{18}O_{TR}$ time series

Site	Location		Altitude (m a.s.l)	Species	DBH (cm)			No. of samples
	Latitude	Longitude			Ave.	Min	Max	
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° 20′ N	127° 43′ E	1310–1645	*A. koreana*	47.6	43	53	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

respect to the international oxygen isotope standard (Vienna Standard Mean Ocean Water) as follows:

$$\delta^{18}\mathrm{O}(‰) = \left(\frac{R_{\mathrm{sam\,p|e}}}{R_{\mathrm{standard}}} - 1\right) \times 1000, \tag{1}$$

where R_{sample} and R_{standard} are the $^{18}\mathrm{O}/^{16}\mathrm{O}$ 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

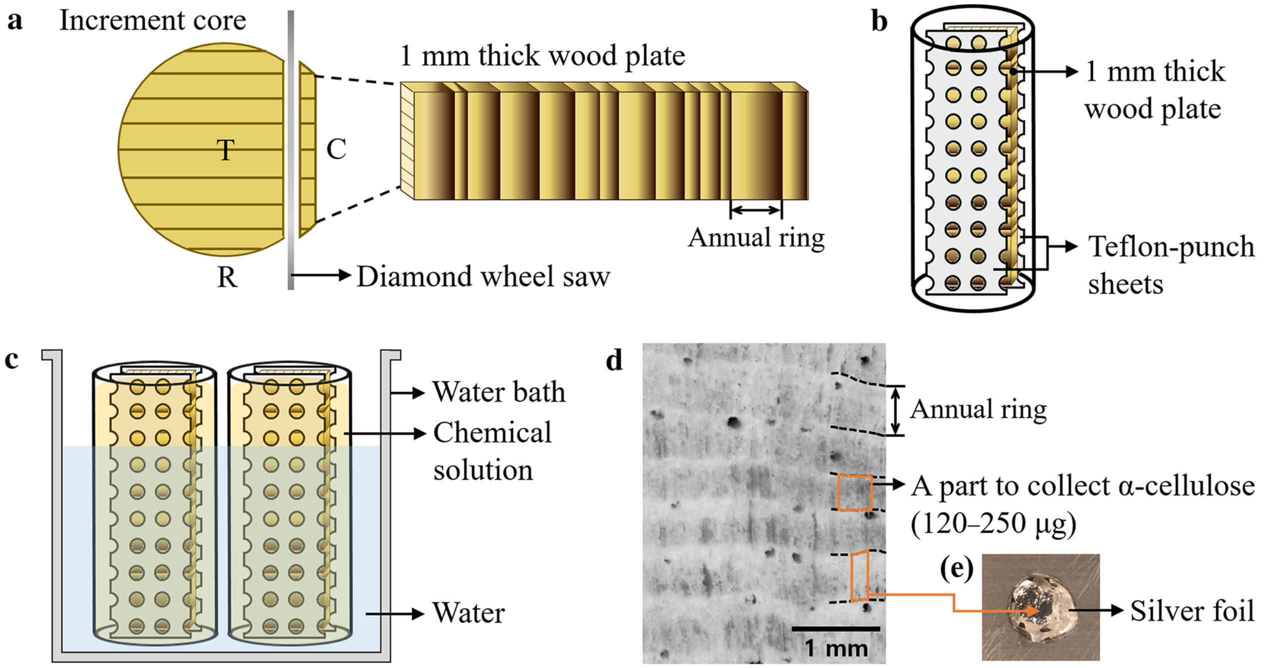

Fig. 2 Preparation process to measure δ^{18}O of α-cellulose in each tree ring: **a** cutting an increment core of 1 mm thickness (C: cross plane, R: radial plane, T: tangential plane); **b** vial with a thin wood plate fixed between Teflon-punch sheets; **c** chemical treatment to extract lignin and hemicellulose in solutions of NaClO$_2$ and NaOH in a water bath at temperature 70 and 80 °C, respectively; **d** separating α-cellulose from each tree ring of same width from early- to latewood at 120–250 μg, and **e** wrapped α-cellulose in a thin silver foil

(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).

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

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

$$G_{(x,y)} = \frac{1}{n-1} \sum_{i=1}^{n-1} \left[G_{ix} + G_{iy} \right] \tag{3}$$

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 δ^{18}O$_{\mathrm{TR}}$ time series. Fifty-year δ^{18}O$_{\mathrm{TR}}$ 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:

$$\mathrm{EPS} = n * R_{\mathrm{bar}} / (n * R_{\mathrm{bar}} + (1 - R_{\mathrm{bar}})), \tag{4}$$

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 α-cellulose from each tree ring was done so that we could establish δ^{18}O$_{\mathrm{TR}}$ 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 δ^{18}O$_{\mathrm{TR}}$ time series were used for further analysis (Table 2).

Synchronization tests within and between tree species

From the synchronization test of δ^{18}O$_{\mathrm{TR}}$ time series within tree species, the mean *t*-values (min.–max.) for *P.*

Table 2 The *t*-values and Glk scores of $\delta^{18}O_{TR}$ time series within tree species

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

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 $\delta^{18}O_{TR}$ time series within the tree species showed similar patterns (Fig. 3).

In the synchronization test of $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ chronologies of individual tree species (Fig. 4).

In all the synchronization tests of $\delta^{18}O_{TR}$ 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 ^{18}O, which was modulated by relative humidity at the site [26, 27]. Non-climatic factors such as ecological competition did not alter annual variations in $\delta^{18}O_{TR}$ values of individual trees significantly. In fact, the $\delta^{18}O_{TR}$ 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 (R_{bar}) and expressed population signal (EPS)

R_{bar} and EPS of $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ chronologies established using more than four trees could serve as a promising chronology in dendroclimatic reaches based on EPS. In this result, the R_{bar} from each group, consisting of the same tree species showed high values, so that EPS higher than the threshold value (0.85) could

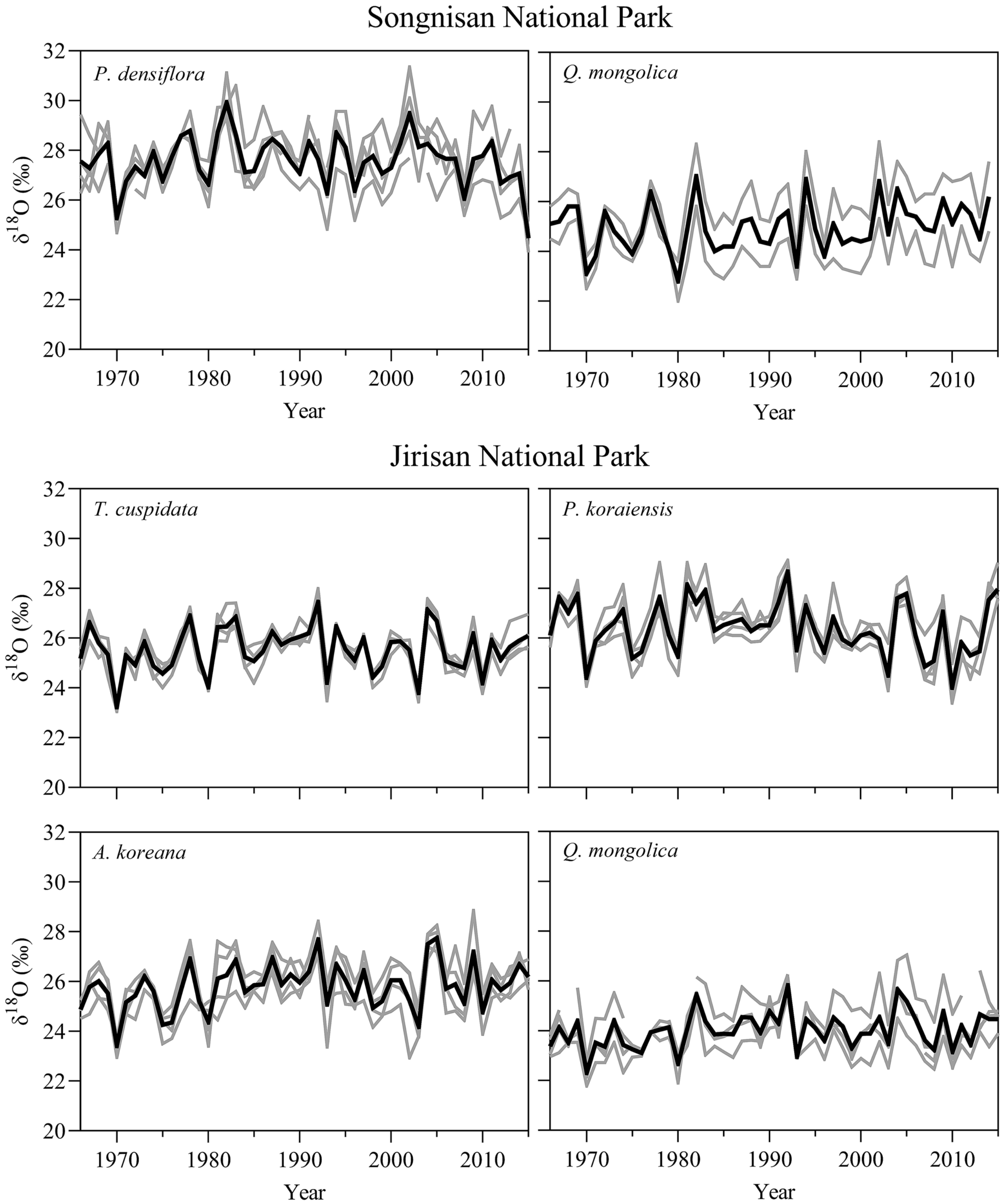

Fig. 3 Synchronization tests of the $\delta^{18}O_{TR}$ time series within tree species (gray lines) and their mean inter-annual variations (solid bold lines)

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

Glk scores *t*-values		SN		JR			
		P. densiflora	*Q. mongolica*	*T. cuspidate*	*P. koraiensis*	*A. koreana*	*Q. mongolica*
SN	*P. densiflora*		73.0**	68.0**	72.0**	71.0**	74.0**
	Q. mongolica	6.6**		72.0**	68.0**	75.0**	78.0**
JR	*T. cuspidate*	4.9**	4.7**		80.0**	81.0**	76.0**
	P. koraiensis	4.3**	3.6**	10.3**		81.0**	73.0**
	A. koreana	3.9**	4.4**	13.2**	8.3**		74.0**
	Q. mongolica	4.6**	5.4**	8.8**	6.1**	8.9**	

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

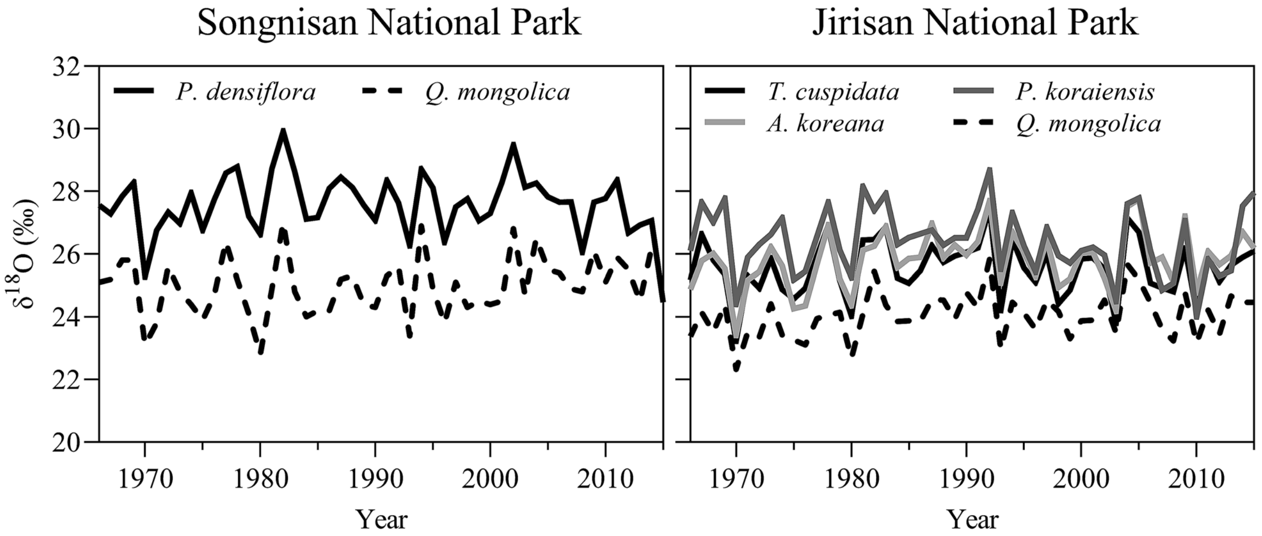

Fig. 4 Synchronization tests of the $\delta^{18}O_{TR}$ chronologies between the tree species

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

Site	Tree species	No. of samples	R_{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

be obtained (Table 4). Only EPS from *Q. mongolica* at Songnisan National Park, which was calculated using R_{bar} from two trees, was lower than the threshold due to insufficient sample size.

Synchronization tests between the study regions

Comparing the $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ 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

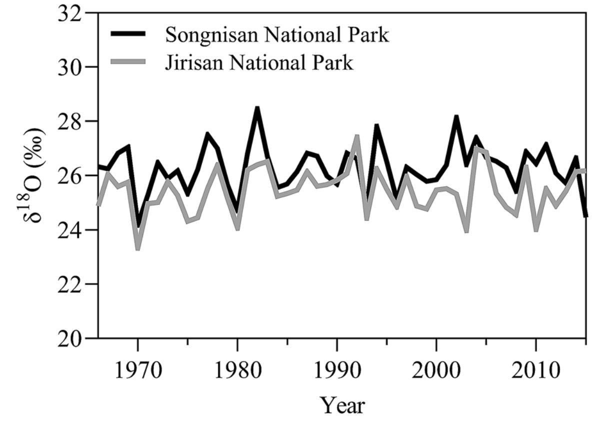

Fig. 5 Synchronization tests of local $\delta^{18}O_{TR}$ chronologies between Songnisan and Jirisan National Parks

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 $\delta^{18}O$ 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 $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ chronologies were also found between different provinces in Bolivia which are about 1000 km far from each other [33].

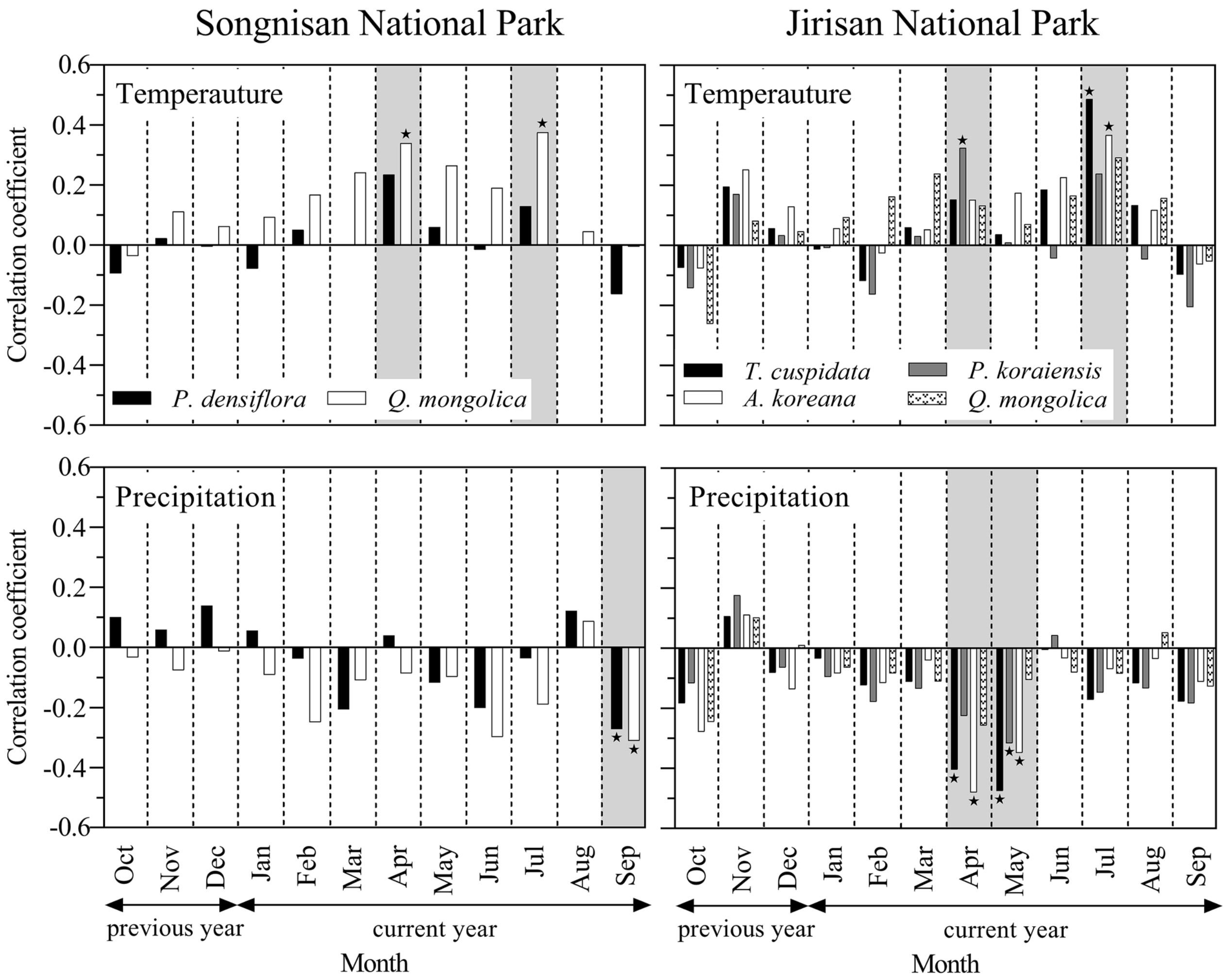

Fig. 6 Correlation coefficients between individual $\delta^{18}O$ chronologies and monthly temperature and precipitation from October in the previous year to September in the current year from Boeun meteorological station close to Songnisan National Park and Sancheong and Namwon meteorological stations close to Jirisan National Park for the last 43 years (1973–2015)

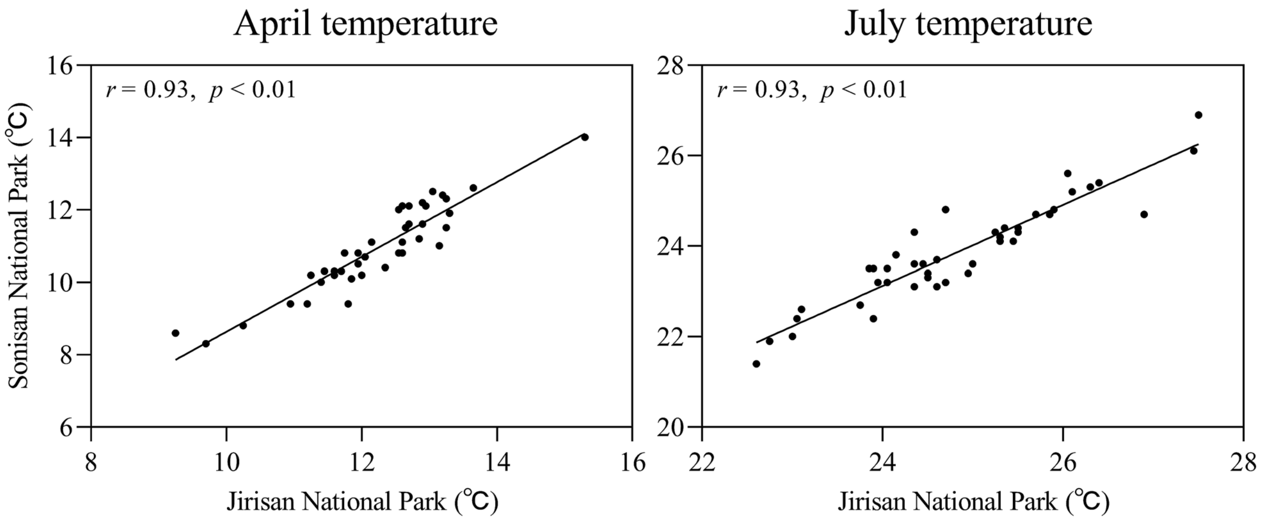

Fig. 7 Linear relationships between April temperatures and between July temperatures of Songnisan and Jirisan National Parks

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 $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ time series, we tested synchronization between and within-tree species in the Songnisan and Jirisan National Parks, which are about 144 km apart. The $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ chronologies showed significant correlations with one another irrespective of species and locations. In addition, the EPS from the four $\delta^{18}O_{TR}$ 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 $\delta^{18}O_{TR}$ 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

$\delta^{18}O_{TR}$ chronology: Tree-ring $\delta^{18}O$ time series; Glk: Gleichläufigkeit; EPS: Expressed population signal; SN: Songnisan National Park; JR: Jirisan National Park; DBH: Diameter at breast height.

Acknowledgements

This study was supported by the Ministry of Environment (MOE), the Republic of Korea, through the Korea National Park Research Institute as the "The monitoring Project of Ecosystem in National Park according to climate change", by Research Institute for Humanity and Nature (RIHN: a constituent member of NIHU) Project No. 14200077 (Historical Climate Adaptation Project), and Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (23242047, 26244049, 17H02020 and 17H06118).

Authors' contributions

All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 2 March 2020 Accepted: 20 July 2020

References

1. Schweingruber FH (1988) Tree rings. Kluwer, Dordrecht, p 276
2. Nash SE (2002) Archaeological tree-ring dating at the millennium. J Archaeol Res 10:243–275
3. Ohyama M, Ohwada M, Suzuki M (2007) Chronology development of Hiba arbor-vitae (*Thujopsis dolabrata* var. *hondae*) and dating of timbers from an old building. J Wood Sci 53:367–373
4. Park W-K, Kim Y, Seo J-W, Lee J-H, Wazny T (2007) Tree-ring dating of Sinmumun, the north gate of Kyungbok Palace in Seoul. Tree-Ring Res 63(2):105–109
5. Jeong H-M, Kim Y, Kim J-Y, Seo J-W (2016) Tree-ring dating of the Palsangjeon wooden pagoda at the Beopjusa temple in Boeun, South Korea. J Korean Wood Sci Technol 44(4):515–525
6. Sano Y, Matono T, Ujihara A (1977) Growth of *Pinus pumila* and climate fluctuation in Japan. Nature 266:159–161
7. Park W-K, Yadav R (1998) Reconstruction of May precipitation (A.D. 1731–1995) in west-central Korea from tree rings of Korean red pine. J Korean Meteor Soc 34(3):459–465
8. Abrams MD, Copenheaver CA, Terazawa K, Umeki K, Takiya M, Akashi N (1999) A 370-year dendroecological history of an old-growth *Abies-Acer-Quercus* forest in Hokkaido, northern Japan. Can J For Res 29(12):1891–1899
9. Grudd H (2008) Torneträsk tree-ring width and density AD 500–2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summer. Clim Dyn 31:843–857
10. Seo J-W, Park W-K (2002) Reconstruction of may precipitation (317 years: A.D. 1682–1998) using tree rings of *Pinus densiflora* S. et. Z. in Western Sorak Mt. Korean J Quat Res 16(1):29–36 **(in Korean with English Abstract)**
11. Choi JN, Yu KB, Park W-K (1992) Paleoclimate reconstruction for Chungbu mountainous region using tree-ring chronology. Korean J Quat Res 6:21–32 **(in Korean with English Abstract)**
12. Park W-K (1993) Increasing atmospheric carbon dioxide and growth trends of Korean subalpine conifers. J Korean For Soc 82(1):17–25
13. Park W-K, Kim Y-J, Lee J-H, Seo J-W (2001) Development of tree-ring chronology of Pinus densiflora from Mt. Sorak and dating the year of construction of the Kyunghoe-ru Pavilion in Seoul. J Korean Phys Soc 39:790–795
14. Park W-K, Kim Y-J (2005) Tree-ring dating of korean traditional furniture: a case study on cabinet and chest. J Korean Wood Sci Technol 33(3):1–10 **(in Korean with English Abstract)**
15. Park W-K, Kim SK, Kim Y-J (2007) Tree-ring dating for Korean wood furniture: a case study on medicine cabinets. J Korean Wood Sci Technol 35(6):57–64 **(in Korean with English Abstract)**
16. Lee K-H, Kim S-K, Park W-K (2008) Tree-ring dating of wood elements used for the Jeongjagak and Bigak buildings of Kangrung (King Myoung-jong's Tomb). J Korean Furnit Soc 19(3):219–228 **(in Korean with English Abstract)**
17. Park W-K, Yoon S-J, Lee Y-J (1999) Species identification of peat woods from Hyunwhari, Pyungtack. Mokchae Konghak 27(2):1–6 **(in Korean with English Abstract)**
18. Park W-K, Lee K-H (2007) Changes in the species of woods of used for Korean ancient and historic architectures. AURC 16(1):9–28 **(in Korean with English abstract)**
19. Park W-K, Oh J-A, Kim Y, Kim S-K, Park S-Y, Son B-H, Choi S (2010) Species of wooden Buddhist statues of the late Joseon Dynasty in Jeollado, South Korea. J Korean Furnit Soc 21(1):72–82 **(in Korean with English abstract)**
20. Son J-A, Park W-K (2010) Species of Korean furniture in the late Choseon Dynasty (I). KFS J 21(6):486–498
21. Lee K-H, Seo J-W, Han G-S (2018) Dating wooden artifacts excavated at Imdang-dong site, Gyeongsan, Korea and interpreting the paleoenvironment according to the wood identification. J Korean Wood Sci Technol 46(3):241–252 **(in Korean with English Abstract)**
22. Nam T-G, Hong G-H, Lee J-H (2017) Radiocarbon dating of a wooden board from Mado shipwreck No. 4 using wiggle matching. J Conserv Sci 33(4):275–281 **(in Korean with English Abstract)**
23. Nam T-G, Yoon Y-H, Kim E-H (2018) Species identification and Radiocarbon dating for the wooden board from Daebudo shipwreck No. 2 using wiggle matching. J Conserv Sci 34(5):359–368 **(in Korean with English Abstract)**
24. Garćia-González I, Eckstein D (2003) Climatic signal of earlywood vessels of oak on a maritime site. Tree Physiol 23(7):497–504
25. Seo JW, Eckstein D, Jalkanin R (2012) Screening various variables of cellular anatomy of Scots pines in subarctic Finland for climatic signals. IAWA J 33(4):417–429
26. Roden JS, Lin G, Ehleringer JR (2000) A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose—evidence and implications for the use of isotope signals transduced by plants. Geochim Cosmochim Acta 64(1):21–35
27. McCarroll D, Loader NJ (2004) Stable isotopes in tree rings. Quat Sci Rev 23(7–8):771–801
28. Esper J, Frank DC, Battipaglia G, Büntgen U, Holert C, Treydte K, Siegwolf R, Saurer M (2010) Low-frequency noise in $\delta^{13}C$ and $\delta^{18}O$ tree ring data: a case study of *Pinus uncinata* in the Spanish Pyrenees. Global Biogeochem Cycles 24(4):1–11
29. Kagawa A, Sano M, Nakatsuka T, Ikeda T, Kubo S (2015) An optimized method for stable isotope analysis of tree rings by extracting cellulose directly from cross-sectional laths. Chem Geol 393–394:16–25
30. Sano M, Tshering P, Komori J, Fujita K, Xu C, Nakatsuka T (2013) May-September precipitation in the Bhutan Himalaya since 1743 as reconstructed from tree ring cellulose $\delta^{18}O$. J Geophys Res Atmos 118(15):8399–8410
31. Hartl-Meier C, Zang C, Büntgen U, Esper J, Rothe A, Göttlein A, Dirnböck T, Treydte K (2015) Uniform climate sensitivity in tree-ring stable isotopes across species and sites in a mid-latitude temperate forest. Tree Physiol 35(1):4–15
32. Li Z, Nakatsuka T, Sano M (2015) Tree-ring cellulose $\delta^{18}O$ variability in pine and oak and its potential to reconstruct precipitation and relative humidity in central Japan. Geochem J 49(2):125–137
33. Jessica B, Sarah H, Santiago C, Robert N, Simnon B, Melanie L, Timnothy H, Gerhard H, Jaime A, Manuel G, Roel B (2015) Oxygen isotopes in tree rings show good coherence between species and sites in Bolivia. Glob Planet Change 133:298–308
34. Xu C, Masaki S, Nakatsuka T (2011) Tree ring cellulose $\delta^{18}O$ of *Fokieneia hodginsii* in northern Laos: a promising proxy to reconstruct ENSO? J Geophys Res 116:D24109
35. Seo J-W, Sano M, Jeong H-M, Lee K-H, Park H-C, Nakatsuka T, Shin C-S (2019) Oxygen isotope ratios of subalpine in Jirisan National Park, Korea and their dendroclimatological potential. Dendrochronologia 57:1–7
36. Seo J-W, Jeong H-M, Sano M, Choi E-B, Park J-H, Lee G-H, Kim Y-J, Park H-C (2017) Establishing tree ring $\delta^{18}O$ chronologies for principal tree species (*T. cuspidata, P. koraiensis, A. koreana, Q. mongolica*) at subalpine zone in Mt. Jiri National Park and their correlations with the corresponding climate. J Korean Wood Sci Technol 45(5):661–670 **(in Korean with English abstract)**
37. Jeong H-M, Kim Y-J, Seo J-W (2017) Relationships between vessel-lumen-area time series of *Quercus* spp. Mt. Songni and corresponding climatic factors. J Korean Wood Sci Technol 45(1):72–84 **(in Korean with English abstract)**
38. Yu J-E, Lee J-H, Kwon K-W (2003) An analysis of forest community and dynamics according to elevation in Mt. Sokri and Odae. Korean J Agric For Meteorol 5(4):238–246
39. Gwon J-H, Sin M-K, Kwon HJ, Song H-K (2013) A study on the forest vegetation of Jirisan National Park. J Korean Env Tech 16(5):93–118 **(in Korean with English abstract)**
40. Cho M-G, Chung J-M, Im H-I, Il Noh, Kim T-W, Kim C-Y, Moon H-S (2016) Ecological characteristics of sub-alpine coniferous forest on Banyabong in Mt. Jiri. J Clim Change Res 7(4):465–476
41. Loader NJ, Robertson I, Barker AC, Switsur VR, Waterhouse JS (1997) An improved technique for the batch processing of small wholewood samples to α-cellulose. Chem Geol 136(3–4):313–317
42. Brendel O, Iannetta P, Stewart D (2000) A rapid and simple method to isolate pure alpha-cellulose. Phytochem Anal 11(1):7–10

43. Eckstein D, Bauch J (1969) Beitrag zur Rationalisierung eines dendrochronologishen Verfahrens und zur Analyze seiner Aussagesicherheit. Forstw Cbl 88:230–250
44. Nasswettrová A, Krvankov S, Smira P (2017) Comparison of the results of dendrochronological measuring based on different images of a historical wood sample of silver fir (*Abies alba*) from the Czech Republic. Wood Res 62(1):113–124
45. Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J Climate Appl Meteror. 23:201–213
46. Hartl-Meier C, Zang C, Büntgen U, Esper J, Rothe A, Göttlein A, Dirnböck T, Treydte K (2014) Uniform climate sensitivity in tree-ring stable isotopes across species and sites in a mid-latitude temperate forest. Tree Physiol 35(1):4–15
47. Xu C, Zhu H, Nakatsuka T, Sano M, Li Z, Shi F, Liang E, Guo Z (2017) Sampling strategy and climatic implication of tree-ring cellulose oxygen isotopes of *Hippophae tibetana* and *Abies georgei* on the southeastern Tibetan Plateau. Int J Biometeorol 63:679–686
48. Li Q, Liu Y, Nakatsuka T, Zhan Q-B, Ohnishi K, Sakai A, Kobayashi O, Pan Y, Song H, Liu R, Sun C, Fang C (2020) Oxygen stable isotopes of a network of shrubs and trees as high-resolution paleoclimatic proxies in Northwestern China. Agric For Meteorol 285–286:107929
49. Fritts HC (1976) Tree rings and climate. Academic Press, New York

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