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Summer climate information recorded in tree-ring oxygen isotope chronologies from seven locations in the Republic of Korea

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The Republic of Korea is characterized by its north-to-south stretch and high mountain ranges along the eastern coast, resulting in terrain with higher elevation in the east and lower in the west. These geographical features typically lead to regional climate differences, either based on latitude or from east to west. In the present study, for effectiveness, the entire Korean peninsula was divided into four regions based on the geographical features: The Northeast Coast (NEC), Central Inland (MI), Southeast Coast (SEC), and South Coast (SC). Two test sites were chosen from each region, except for the SC. The linear relationship between the altitude of sites and the mean oxygen isotope ratio ($\delta^{18}O$) revealed a negative correlation; the highest (1,447 m a.s.l.) and the lowest altitude (86 m a.s.l.) sites had a mean $\delta^{18}O$ of 27.03‰ and 29.67‰, respectively. The sites selected from the same region exhibited stronger correlation coefficients (0.75–0.79) and Glk (Gleichläufigkeit) (74–83%) between the tree-ring oxygen isotope chronologies ($\delta^{18}O_{TR}$ chronologies) than those from different regions (0.60–0.69/70–79%). However, subtle variations in pattern were observed in the comparison period during a few selected intervals (approximately 10 years). All the regional $\delta^{18}O_{TR}$ chronologies exhibited positive correlations with either June or July temperatures over Korea, whereas negative correlations with regional summer precipitation and SPEI-3. Moreover, the chronologies showed notable negative correlations with the water condition of western Japan. The findings of this study can be used as a scientific reference for the study of variations of rainfall in East Asia using $\delta^{18}O_{TR}$ chronology.

KEYWORDS

tree ring, oxygen isotope, precipitation, monsoon, East Asia

1 Introduction

Tree rings typically provide annual information on the growth duration of a tree, and therefore, have been used as a significant indicator in a variety of studies, such as tree adaptation, forest events, dating, and climate reconstruction (Fritts, 1976; Speer, 2010). Apart from the traditional tree-ring width, other ring parameters, such as stable isotopes, density, and cells have also been used in many studies (Fritts et al., 1991; Kirdyanov et al., 2008;

Choi et al., 2020b; Siegwolf et al., 2020; Park et al., 2021; Chen et al., 2023; Lopez-Saez et al., 2023; Xu et al., 2023). One advantage of using the tree-ring width is that it allows simple and straightforward method of analysis. However, this width is also influenced by certain factors in the growing environment (Schweingruber, 1996; Larcher, 2003), such as environmental changes, stand dynamics, competition, soil conditions, and insect damage. In such cases, using tree-ring width chronologies for analysis becomes a challenge. Among the various tree-ring parameters, the stable isotopes in the tree rings become more sensitive during the growth period to the environmental changes, specifically the climatic factors than to net growth (Yakir et al., 1990; Roden et al., 2000; Barbour et al., 2004; Kress et al., 2010; Haupt et al., 2011), which involves the non-climatic factors (McCarroll and Loader, 2004; Liu et al., 2009; Young et al., 2012; Sano et al., 2013; Seo et al., 2017, 2019; Li et al., 2022; Mandy et al., 2023).

The three main elements present in wood and commonly employed in research are the oxygen (^{16}O, ^{18}O), carbon (^{12}C, ^{13}C), and hydrogen (^{1}H, ^{2}H) isotopes (Leavitt and Long, 1988; McCarroll and Loader, 2004; Jia et al., 2023; Pandey et al., 2023). Due to different formation mechanisms of these isotopes in the tree rings, each isotope is applied either individually or in combination across various fields (Farquhar et al., 1989; Yakir et al., 1990; Saurer et al., 1997; Roden and Ehleringer, 1999; Roden et al., 2000; Barbour et al., 2004; Saurer and Siegwolf, 2007; Loader et al., 2008; Roden, 2008; Miles et al., 2019; Belmecheri and Lavergne, 2020; Büntgen, 2022). The annual oxygen isotope ratio in a tree ring reflects the isotopic ratio of the water the tree absorbs during its growing season. Such absorption largely depends upon the precipitation during that period. The $\delta^{18}O_{TR}$ chronologies are therefore greatly influenced by the precipitation during the growing season, and any change in annual precipitation patterns causes variation in the oxygen isotope ratio in the tree rings (Seo et al., 2019; Choi et al., 2020a; Preechamart et al., 2023; Watanabe et al., 2023). Therefore, the isotopes in different trees of the same species exhibit similar patterns of change in the same climate zone, thereby making it possible to use them in climate analysis and establish tree-ring oxygen isotope chronologies ($\delta^{18}O_{TR}$ chronologies) over extensive areas (Baker et al., 2015; Young et al., 2015; Choi et al., 2020a). Additionally, it has been confirmed that although the mean value of the oxygen isotope ratio may differ between tree species due to physiological and spatial characteristics, they exhibit the same pattern (Baker et al., 2015; Loader et al., 2019, 2021; Choi et al., 2020a; Xu et al., 2021; Sano et al., 2022). These advantages of the tree-ring isotopes allow us to establish long-term $\delta^{18}O_{TR}$ chronology using data from different tree species over a wide region.

Until now, only four studies in Korea have been published which involved $\delta^{18}O_{TR}$ chronology (Seo et al., 2017, 2019; Choi et al., 2020a; Lee et al., 2023). These studies verified that a chronology built using $\delta^{18}O$ in tree rings between study sites which are about 144 km away can be used as a master chronology for cross-dating (Choi et al., 2020a) regardless of the tree species due to their high synchronization (Seo et al., 2017; Lee et al., 2023). The influence of water condition in western Japan on the $\delta^{18}O_{TR}$ chronology in southern Korea had also been reported (Seo et al., 2017). However, since these results were obtained from restricted regions, the data have limited application across the country. Korea spans along north–south direction (33° to 38°), and the terrain is characterized by higher elevation in the east, with developed mountain ranges, and lower elevations in the west (The Academy of Korean Studies, 2016). Such difference in topography results in difference in the regional climate (Ministry of Land Infrastructure and Transport and National Geography Information Institute, 2020). Therefore, studies using $\delta^{18}O_{TR}$ chronology which consider such topographical features are necessary.

The current study was designed under the hypothesis that local climatic condition is influenced by topographical features and its effect on $\delta^{18}O$ in the tree rings. The main objectives of the present study are to investigate (1) synchronization strength between the $\delta^{18}O_{TR}$ chronologies from different regions, (2) climatic information embedded in the regional chronologies, and (3) the role of topographical and/or meteorological features on the results of (1) and (2). The results should play an important role in advancing our strategy for making a dendrochronological research plan using $\delta^{18}O$ in tree rings.

2 Materials and methods

2.1 Study sites

Korea has several notable topographical features, including (1) an elongated north–south shape, (2) major mountains along the eastern coast (the Taebaek Mountains), and (3) three sides surrounded by ocean (Figure 1). These geographical locations, topographical, and sea distribution characteristics significantly impact the regional climate of Korea. For example, a large temperature difference exists between the northern and southern regions of Korea depending upon the latitude. On the other hand, at the same latitude, the eastern region is cooler in summer and warmer in winter compared to the western region (Ministry of Land Infrastructure and Transport and National Geography Information Institute, 2020). These variations occur because the Taebaek Mountain blocks the cold air from the continent, while the relatively deep East Sea exhibits less fluctuation in the water temperature compared to the Yellow Sea. In the present study, we considered these topographical differences and divided the study areas with respect to latitude and coastal/inland areas. The study sites were subdivided into four regions, namely (1) Northeast Coast (NEC), (2) Mid-Inland (MI), (3) Southeast Coast (SEC), and (4) South Coast (SC) of South Korea. All the sites in these regions were chosen from the National parks located across the country. The NEC comprises Mt. Seoraksan (SA) and Mt. Odaesan (OD), MI consists of Mt. Songnisan (SN) and Mt. Gyeryongsan (GR), SEC includes Mt. Juwangsan (JW) and Mt. Namsan (NS), and SC includes Jirisan (JR) National Park.

According to the monthly mean climate data from 1991 to 2020, the monthly temperature was the lowest in January and highest in August (Figure 1, bottom right). The monthly precipitation was the highest in July and lowest in January (Open MET Data Portal, https://data.kma.go.kr/resources/html/en/aowdp.html, accessed on July 15, 2023). During summer, the precipitation reached 710.9 mm, accounting for 54% of the total annual precipitation (1306.3 mm) in the nation. Since the 1980s, the average annual temperature and precipitation of South Korea showed significant increase, and the increase in the average annual precipitation was attributed to the rise in summer precipitation

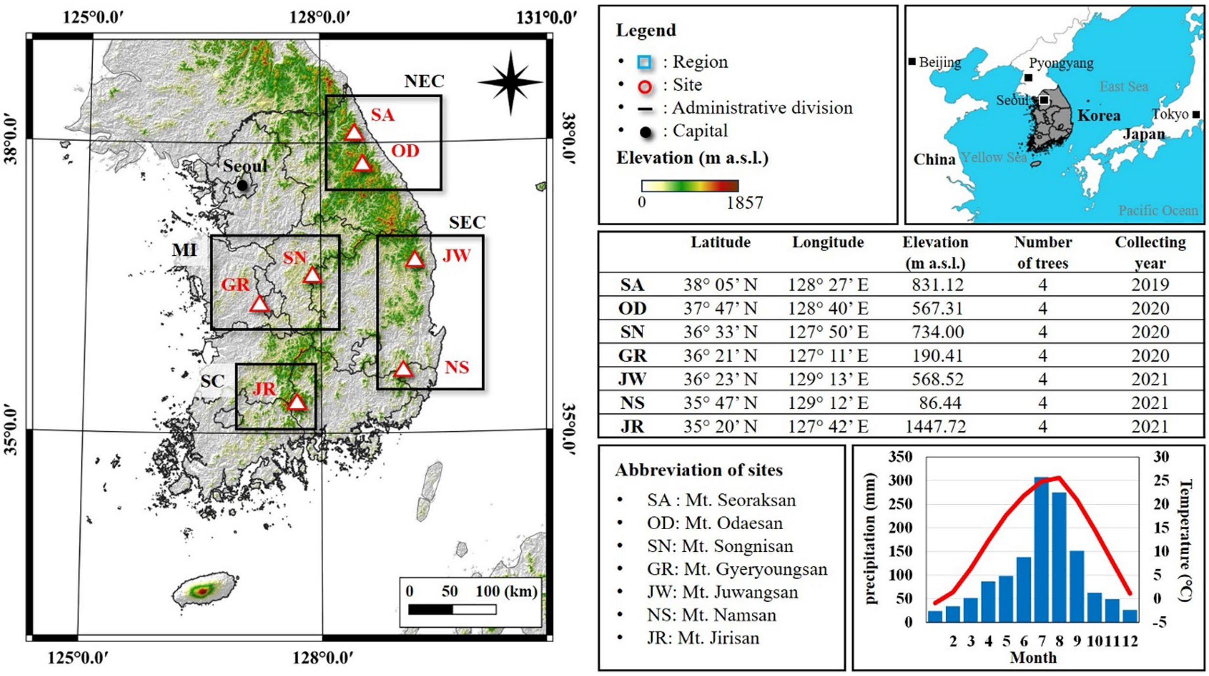

FIGURE 1
Locations (left) and information about the sampling sites. The climate graph was plotted as monthly climate data for 30 years (1991–2020) (right bottom, blue bar: precipitation, and red line: temperature). Blue square boxes represent regions subdivided according to topographical features (NEC, Northeast Coast; MI, Mid-Inland; SEC, Southeast Coast; SC, South Coast).

(National Institute of Meteorological Sciences, 2018; Korea Meteorological Administration, 2020, 2022).

2.2 Tree-ring samples

Pinus densiflora (red pine) was chosen as the sample for the present study which was collected during 2019–2021 (3 years). *P. densiflora* is a coniferous tree species which occupies the largest area (1.5 million ha, 21.9% of all forests) among all the single tree species in South Korea. The red pine is used widely since the ancient times due to its easy accessibility and various applications (Park et al., 2007, 2010; Kim et al., 2013; Kong et al., 2014; Choi et al., 2020a,b). Due to these qualities, the pine forests were designated as protected areas throughout Korea's history (10 C–19 C), and indiscriminate logging is strictly prohibited. In the present study, we have chosen the pine trees in the National parks as the samples because substantial number of tree rings can be obtained from them.

At each study site, cores were collected from minimum 10 trees. A core of 10 mm diameter was extracted for oxygen isotope analysis. All the cores were precisely dated to an accuracy of 0.01 mm using LINTAB (RENNTECH, Germany). Then, tree-ring width chronologies were established which were further used to cross-date each tree, identify any missing or discontinuous rings, and accurately deduce the growth year of each ring. The cross-dating was performed through statistical analysis using the TSAP program (Cook and Kairiukstis, 1990; Speer, 2010). For oxygen isotope measurements, four cores with the longest chronologies and no missing rings were chosen from each study site.

2.3 Tree-ring oxygen isotope chronology

The oxygen isotope ratio was measured for all the selected tree rings. The samples were prepared as described below (Kagawa et al., 2015; Choi et al., 2020a,b). A 1 mm thick plate was first sliced from the selected cores, and α-cellulose was extracted from the plate following Jayme-Wise method (Jayme, 1942; Wise et al., 1946; Green, 1963; Loader et al., 1997; Brendel et al., 2000). From each tree ring of the α-cellulose plate, small specimens weighing between 120 and 250 μg were obtained and wrapped in silver foil. The oxygen isotope ratio ($^{18}O/^{16}O$) in the wrapped samples was measured via pyrolysis using high-temperature conversion elemental analyzer (TC/EA, Thermo Fisher Scientific, Germany) and isotope ratio mass spectrometer (IRMS, Delta V Advantage, Thermo Fisher Scientific, Germany). The ratio was calculated in permil (‰) against Vienna Standard Mean Ocean Water (VSMOW). The measurements were conducted at Nagoya University, Nagoya, Japan.

2.4 Statistical analyses and climate data

The R packages "Dendrochronology Program Library in R (dplR)" and "treeclim" (version 4.3.0) were used for all statistical analyses, namely cross-dating, Expressed Population Singal (EPS), Gleichläufigkeit (Glk) and correlation analysis with climatic parameters, using $\delta^{18}O_{TR}$ chronologies. The climatic parameters used in this study include temperature, precipitation, and SPEI-3. Since Korea lacks meteorological data for more than 100 years, the following data were selected for analysis of the climatic factors spanning over the entire study period. For temperature and precipitation, the

TABLE 1 Information about the established $\delta^{18}O_{TR}$ chronologies.

Site	$\delta^{18}O_{TR}$ chronology			Correlation*	$\delta^{18}O$ (‰)	EPS**
	Length (year)	First year	Last year	Mean (±std)	Mean (±std)	
SA	210	1809	2018	0.79 (±0.06)	27.52 (±1.01)	0.94
OD	393	1628	2020	0.67 (±0.07)	29.11 (±1.12)	0.89
SN	144	1877	2020	0.66 (±0.06)	29.04 (±1.08)	0.89
GR	126	1895	2020	0.65 (±0.05)	29.80 (±0.96)	0.87
JW	103	1918	2020	0.73 (±0.06)	27.75 (±1.24)	0.93
NS	133	1888	2020	0.58 (±0.06)	29.67 (±1.12)	0.86
JR	250	1771	2020	0.74 (±0.03)	27.03 (±1.07)	0.93

*: correlation between individual $\delta^{18}O_{TR}$ chronologies. **: expressed population signal.

Climatic Research Unit gridded Time Series (CRU T.S.) 4.06 data set from 1901 to 2020 provided by the Centre for Environmental Data Analysis (CEDA) was utilized (Harris et al., 2020). For Standardized Precipitation-Evapotranspiration Index (SPEI), data from 1901 to 2018 provided by Consejo Superior de Investigaciones Cientificas (CSIC) were used,[1] and SPEI-3 accumulated in 3-month increments was utilized for the analysis.

3 Results and discussion

3.1 $\delta^{18}O$ of tree ring

The mean and standard deviation of the oxygen isotope ratio varied across regions (Table 1; Figure 2). The altitude of the sites and mean oxygen isotope ratio showed a linear relationship with negative correlation. Specifically, the higher altitude sites, *viz.* JR (1,447 m a.s.l.), showed the lowest mean oxygen isotope ratio of 27.03‰, whereas the lower altitude sites, such as NS (86 m a.s.l.) and GR (190 m a.s.l.) showed the highest oxygen isotope ratio of 29.67‰ and 29.80‰, respectively.

The differences in the mean and standard deviation of the oxygen isotope ratio between various tree species are known to be influenced by complicated physiological and biochemical mechanisms (Roden et al., 2000; Sternberg, 2009). However, in our study, since all the $\delta^{18}O_{TR}$ chronologies were for the same tree species (*P. densiflora*), it is reasonable to state that the spatial factors of a site played a more significant role than the species characteristics. The oxygen isotope ratio of the tree rings is closely related to the temperature and/or precipitation conditions during the tree-ring formation (Hau et al., 2023). Furthermore, for the oxygen isotope ratio of precipitation, fractionation may appear where the relative concentrations of the isotopes vary owing to various factors, such as altitude effect, latitude effect, rainfall, continental effect, surface temperature, and distance from the ocean (Dansgaard, 1964; Rozanski et al., 1993; Bowen and Wilkinson, 2002; Vuille et al., 2003; Aggarwal et al., 2012).

The altitude effect refers to lower oxygen isotope ratio with increasing altitude which occurs due to Rayleigh distillation (Poage and Chamberlain, 2001). The altitude effect occurs mainly because the isotopic ratio of precipitation decreases almost linearly with altitude, and trees at higher altitudes rely mostly on precipitation as the water source during the growing season. Moreover, the neutral isotope ratio of freshwater decreases with increasing latitude and altitude (Dansgaard, 1964; Eriksson, 1965; Poage and Chamberlain, 2001; Aggarwal et al., 2012).

1 https://spei.csic.es/index.html

3.2 Regional tree-ring $\delta^{18}O$ chronologies

From the individual $\delta^{18}O_{TR}$ chronologies, we constructed seven site $\delta^{18}O_{TR}$ chronologies representing the respective sites. The longest site $\delta^{18}O_{TR}$ chronology comprised 393 years (1628–2020) for Mt. Odaesan, while the shortest was for 103 years (1918–2020) for Mt. Juwangsan. The expressed population signal (EPS) for all the sites was above 0.85 for the duration of the $\delta^{18}O_{TR}$ chronology (Table 1). The mean correlation obtained between the individual oxygen isotope ages was 0.69 (maximum SA: 0.79, minimum NS: 0.58, $p < 0.05$).

The EPS in dendrochronology signifies the explanatory power of an infinite population chronology using finite tree-ring data. Usually, EPS > 0.85 is applied to determine the ability of a chronology to explain a common signal (Briffa and Jones, 1990; Buras, 2017; Siegwolf et al., 2020). In the current study, the EPS of all the 7 sites was above 0.85 for the duration of the $\delta^{18}O_{TR}$ chronology. This signifies that the site $\delta^{18}O_{TR}$ chronologies can be utilized to explain a common signal such as climate. Typically, dendroisotope studies urge that minimum four trees should be used to obtain meaningful EPS values (>0.85) for each site (Wigley et al., 1984; Xu et al., 2017; Choi et al., 2020a,b; Li et al., 2020). In the present study, significant EPS > 0.85 was also obtained with four trees for all the sites; EPS between 1918 and 2018 (SA = 0.94, OD = 0.87, SN = 0.89, GR = 0.90, JW = 0.92, NS = 0.85, and JR = 0.93). This indicated that the $\delta^{18}O_{TR}$ chronologies strongly share a common signal with each other and meaningful climatological analysis is possible with these data.

The period of overlap among all the site $\delta^{18}O_{TR}$ chronologies was from 1918 to 2018, i.e., total 101 years. The standardized site $\delta^{18}O_{TR}$ chronologies displayed significant correlations ($p < 0.05$) (Figure 3). The sites in the same region showed higher correlations and Glk values than the sites from different regions, and a clear difference in correlation was observed. Specifically, the correlation and Glk values were 0.75 and 74% between SA and OD in NEC, 0.79 and 83% between SN and GR in MI, and 0.79 and 81% between JW and NS in

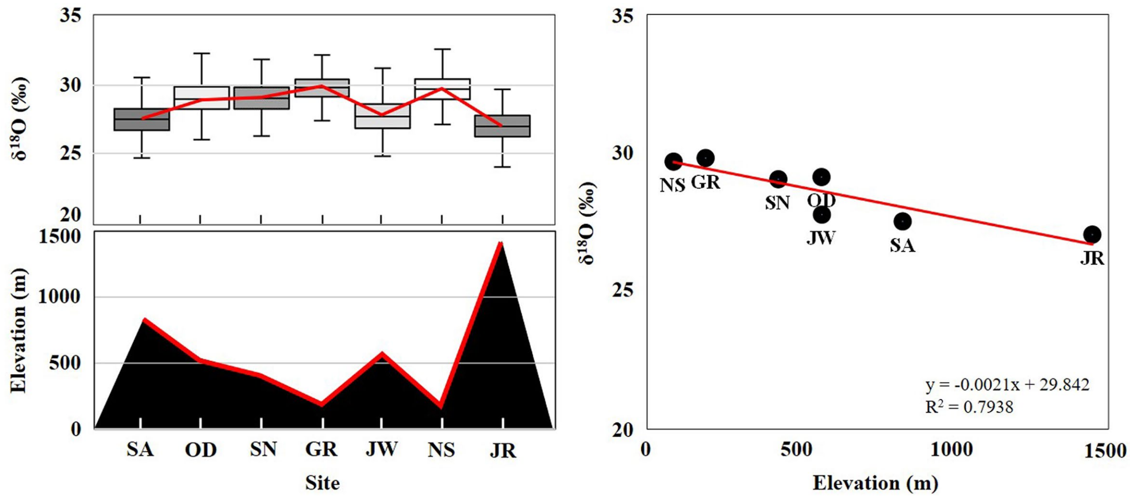

FIGURE 2
Distribution of oxygen isotope ratio according to altitudes of the sites.

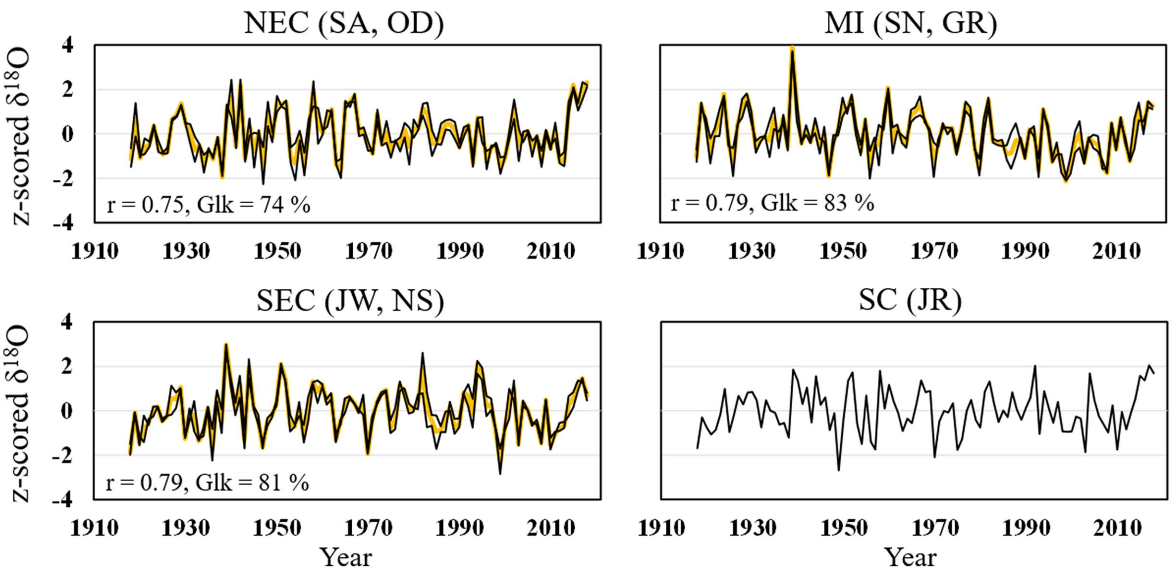

FIGURE 3
Site-$\delta^{18}O_{TR}$ chronology (black line) and regional $\delta^{18}O_{TR}$ chronology (yellow line).

SEC, respectively ($p < 0.05$). Based on these values, three regional $\delta^{18}O_{TR}$ chronologies were constructed. A single site was chosen in the SC; hence, only chronology data from JR were used to construct the SC $\delta^{18}O_{TR}$ chronology.

We also examined the correlations between the regional $\delta^{18}O_{TR}$ chronologies. Most of the regional $\delta^{18}O_{TR}$ chronologies showed statistically significant correlations for the entire comparison period. The NEC exhibited an average correlation and Glk values of 0.64 and 74% with other regions, MI was 0.63 and 77%, SEC was 0.68 and 74%, and SC was 0.65 and 77% ($p < 0.05$). Although the regional $\delta^{18}O_{TR}$ chronologies showed statistically significant correlations for the entire period, the regional chronologies displayed certain differences in patterns between them during certain periods (Figure 4). These subtle differences in patterns during certain periods were attributed to the influence of the same large climatic zone in the study area along with some strong regional climates during certain periods. Therefore, we conducted analyses of climatic factors on a region-by-region basis.

3.3 Climate factors affecting oxygen isotope ratios in tree rings

The regional $\delta^{18}O_{TR}$ chronologies were correlated with temperature, precipitation, and SPEI-3 (Figure 5). All the three climatic factors showed significant correlations ($p < 0.05$), but the strongest correlation

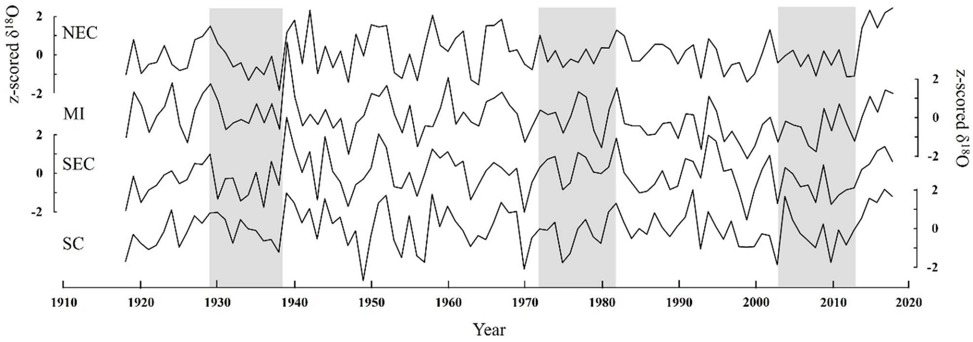

FIGURE 4
Comparison of $\delta^{18}O_{TR}$ patterns between the four composed regional $\delta^{18}O_{TR}$ chronologies. The gray box indicates the period in which subtle pattern differences were observed.

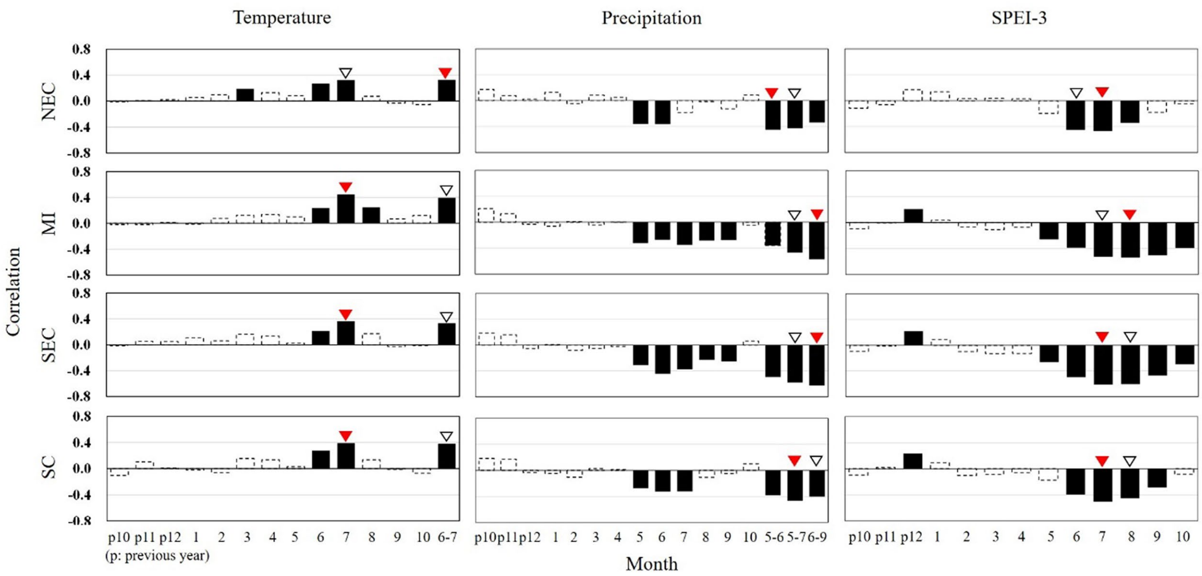

FIGURE 5
Correlation coefficients between regional $\delta^{18}O_{TR}$ chronology and climate data (temperature, precipitation, and SPEI-3) (black bar: $p < 0.05$). The red inverted triangle indicates the highest statistical result, and the white inverted triangle represents the second highest statistical value.

coefficient was obtained for SPEI-3. Specifically, all the regional $\delta^{18}O_{TR}$ chronologies exhibited positive correlations with summer temperatures, and the strongest correlations were observed in either June or July. The NEC displayed the highest correlation with June–July temperatures ($r = 0.33$), as well as with July ($r = 0.32$). For MI, SEC, and SC, the most significant correlations were observed with the July temperatures ($r_{MI} = 0.45$, $r_{SEC} = 0.36$, $r_{SC} = 0.39$), followed by June–July temperatures ($r_{MI} = 0.39$, $r_{SEC} = 0.33$, and $r_{SC} = 0.38$).

The monthly mean precipitation exhibited higher negative correlations with regional $\delta^{18}O_{TR}$ chronologies when the summer precipitation was aggregated by month (Figure 5). This indicated that all the regions were strongly influenced by precipitation during the summer. Specifically, NEC showed a strong negative correlation with the early summer months, May–June ($r_{NEC} = -0.45$) during the overall summer rainfall period. MI and SEC exhibited significant correlation during the entire summer rainfall period, i.e., from June to September, with correlation coefficient of -0.57 (r_{MI}) and -0.62 (r_{SEC}), respectively. For NC, the highest correlation was observed between May and July ($r_{SC} = -0.47$), a significant correlation was also observed from June to September ($r_{SC} = -0.40$). SPEI-3 showed a strong negative correlation in July or August. NEC, SEC, and SC displayed maximum correlation in July ($r_{NEC} = -0.47$, $r_{SEC} = -0.61$, and $r_{SC} = -0.50$), while MI is most highly correlated in August ($r_{MI} = -0.54$).

All the regional $\delta^{18}O_{TR}$ chronologies presented a significant relationship with climate from May to September. These months are typically characterized by the highest temperatures, the most intense precipitation, and maximum growth of most of the trees in Korea. These findings indicate that temperature and precipitation during summer strongly influence the oxygen isotope ratio of the trees in the studied regions. However, even during summer, the regional differences between the climatic factors, especially the precipitation

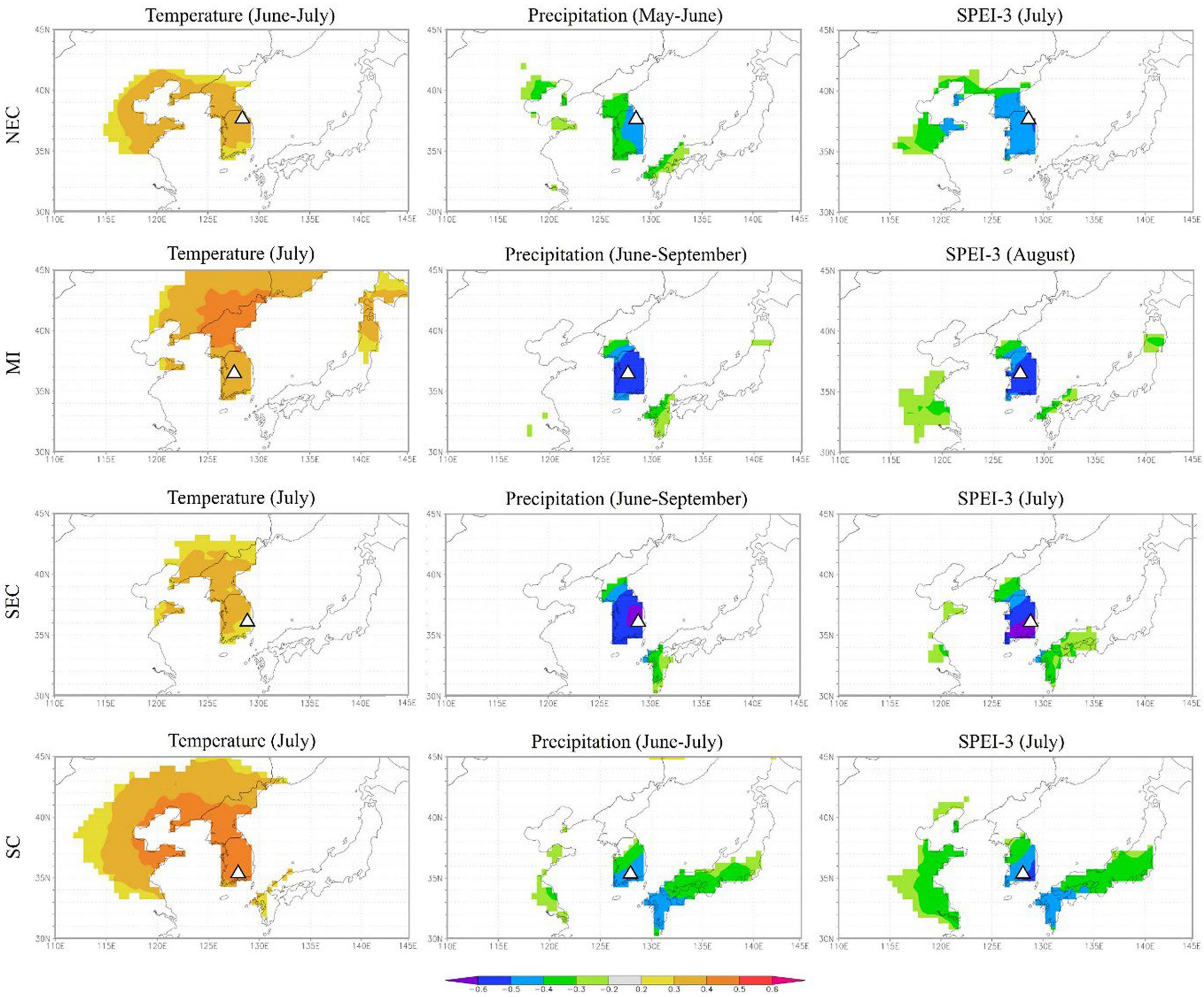

FIGURE 6
Spatial correlations between regional $\delta^{18}O_{TR}$ chronologies and statistically significant climatic factors ($p < 0.01$). The white triangles represent each region (NEC, MI, SEC, and SC).

were evident. Unlike the other regions, NEC exhibited a significant impact mainly during the early summer precipitation period with specific correlations to temperature in June–July, precipitation in May–June, and SPEI-3 in July.

3.4 Spatial correlations between regional $\delta^{18}O_{TR}$ chronologies and climate

Temporal correlation analyses were conducted on the highly correlated periods identified in the previous correlation analysis (Figure 6). A comparison between the regional $\delta^{18}O_{TR}$ chronologies and temperature revealed that the tree-ring $\delta^{18}O_{TR}$ was governed by the July temperature of Korea, whereas that between the chronologies and precipitation or SPEI-3 was governed by the study site regions. Furthermore MI, SEC, and SC also showed high correlations with western Japan.

Previous studies reported that the $\delta^{18}O_{TR}$ chronology of *Taxus cuspidata* from Mt. Jirisan has high correlations with June–July temperature over Korea and May–July precipitation of the study site and western Japan (Seo et al., 2019; Sano et al., 2022). In another study, using the $\delta^{18}O$ data from rainfall, Kurita et al. (2009) interpreted that the high correlation with precipitation in western Japan comes from upstream hydrological processes, such as evaporation and condensation (Kurita et al., 2009). The correlations from MI, SCE, and SC in the present study also support the previous findings, i.e., the role of precipitation in the upstream regions of western Japan (Figure 6). As the altitude increases from the south (SC) to the north (MI), the rain clouds move from SC to MI during June–September. Unlike other regions, early summer climate in NEC is normally influenced by high pressure on the Okhotsk Sea (Lee, 1994). Moreover, the precipitation in NEC located in the east of the Taebaek Mountains is higher than that in the west due to the Föhn effect (WMO, 1992; Choi et al., 1997; Kim and Kim, 2013; Park, 2020). The Taebaek Mountains are located along the eastern edge of Korea. Such meteorological characteristics enhances the effect of early summer precipitation on the $\delta^{18}O$ of the tree rings from NEC (Shin and Lee, 2023).

4 Conclusion

From dendrochronological perspective and based on the comparisons between the seven site $\delta^{18}O_{TR}$ chronologies, several conclusions can be drawn. First, the site chronologies can be used for cross-dating even if they are tens to hundreds of kilometers apart, because the chronologies have similar inter-annual variations. Our findings support that any of the site chronologies can be used for cross-dating tree rings from places where there is no long chronology. Second, although the seven site $\delta^{18}O_{TR}$ chronologies show reliable synchronization pattern, subtle differences exist between the four regions (NEC, MI, SEC, and SC) due to geographical and/or meteorological characteristics. Therefore, at least these four regions should be considered for dendroclimatological study on reconstructing a local paleoclimate.

Temporal correlation analyses between the regional $\delta^{18}O_{TR}$ chronologies and climate data (temperature, precipitation, and SPEI-3) showed different results with respect to temperature and water condition. In the former, all the regional $\delta^{18}O_{TR}$ chronologies were mainly governed by the July temperature over Korea. In the latter, the regional precipitation and SPEI-3 exerted more influences on the corresponding regional $\delta^{18}O_{TR}$ chronologies. The major influences of the local precipitation and SPEI-3 on the $\delta^{18}O$ in tree rings mainly come from the regional precipitation differences. In the three regions except NEC, the month affecting regional tree-ring oxygen chronologies shifted progressively later for higher latitudes of the regions. This is because the rain clouds that affect these regions move inland from the west of Japan to the center of Korea, changing the timing of their impact. Our results can serve as a reference for further studies about variations of rainfall in East Asia using $\delta^{18}O_{TR}$ chronology.

To investigate the effect of drought stress on $\delta^{18}O$ in tree rings, SPEI, calculated from 3-month- increment data was applied since the results from SPEI-3 were better than SPEI-1 in the correlation analysis of regional $\delta^{18}O_{TR}$ chronologies. The trees require time for photosynthesis to build tree rings using water. The higher correlations with SPEI-3 than SPEL-1 can be used as a scientific reference to improve our understanding of tree physiological process.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

E-BC: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing, Methodology. J-HP: Investigation, Methodology, Writing – review & editing. MS: Formal analysis, Writing – review & editing. TN: Writing – review & editing. J-WS: Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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