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The Relationship between Tree-Ring Growth in *Pinus densiflora* S. et Z. and the Corresponding Climatic Factors in Korea

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ABSTRACT

To analyze the relationship between climatic factors (mean monthly temperature and total precipitation) and tree-ring growths of *Pinus densiflora* S. et Z. from National Parks (according to region) of the Korea, 20 trees were sampled from 13 National Parks. Only trees that were successfully cross-dated were used for dendrochronological analysis, and at least 11 trees were included. The tree-ring chronology of Mt. Bukhan (covering the shortest period of 1917–2016 [100 years]) was assessed, as well as that of Mt. Seorak (covering the longest period of 1687–2017 [331 years]). After cross-dating, each ring width series was double-standardized by first fitting a logarithmic curve and then a 50-year cubic spline. The relationships between climate and tree-ring growth were calculated with response function analysis. The results show a significant positive correlation between a given year's February-March temperature, May precipitation levels, and tree-ring growth. It indicates that a higher temperature in early spring and precipitation before cambium activity are important for radial growths of *Pinus densiflora* in the Korea.

Keywords: *Pinus densiflora* S. et Z., National Parks, tree rings, climate, response functions analysis

1. INTRODUCTION

The total area of Korea forests is 6,550,000 ha, and the majority of these are distributed along the Taebaek and Sobasek Mountains. These forests can be categorized into warm temperate, temperate southern, and temperate central forests. The main tree species found there are *Quercus* spp. and *P. densiflora* (Park *et al*., 2003). The growth and development of wild trees in various forests are affected by environmental and genetic factors and undergo both annual stretch growth and thickening growth. The climate (as the typical environmental factor) is closely related to the growth and development of the trees (Park *et al*., 2003; Schweingruber, 1988). Thus, variations in anatomical features, such as the microfibril angle of the cell, exist according to the

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climatic factor of the region (Kim *et al*., 2020a; Kim *et al*., 2020b). The annual ring composed of cells manifests in unique patterns depending on the region. Such regional variations can be investigated with dendrochronology.

Dendrochronology in Korea is in general performed with *P. densiflora* S. et Z (hereafter, *P. densiflora*). Wooden cultural heritage is actively dated using standard dendrochronology, which was first developed during the Koryo Dynasty (Lee *et al*., 2021). Following this, analysis of the relationship between climate and annual ring growth was also conducted. For example, Seo *et al.* (2000) analyzed the relationship between the diameter growth of *P. densiflora* in the Woraksan Mountains and the climate factors according to the topographical features, which is a typical type of study of the relationship between the annual ring growth and climate. Subsequently, research was conducted on the effects of climatic factors on the annual ring growth of *P. densiflora* in different regions using cluster analysis (Lee *et al*., 2008), along with research on the relationship between the annual ring growth of *P. densiflora* and the climate in the Baekdudaegan Mountain Range Marugeum (Park *et al*., 2010). Moreover, further research analyzed the correlation between annual ring growth and climate, including *Larix kaempferi* and *P. densiflora* in Gangwon-do, Gyeongsangbuk-do, and Chungcheong-nam-do (Chung *et al*., 2017). However, most of this research was limited to regional units or the northern region of Chungcheong-do. It is necessary to secure a long-term standard chronicle for each region that could be used to calculate the relationship between climate and annual ring growth and work towards climate restoration in the future.

This study dendrochronologically compared the regional differences in annual ring growth of *P. densiflora* in domestic national parks, where the human disturbance is comparatively low and a long-term standard chronicle could be obtained. Through the response function with the climate data, the factors affecting domestic *P. densiflora* annual ring growth were determined.

2. MATERIALS and METHODS

2.1. Study site and sampling

P. densiflora S. et Z. is a tree species that is found across all regions of Korea in sunny regions of altitudes 1,300 m or below (Lee, 1997). Samples were collected from *P. densiflora* in major national parks in Seoul, Gyeonggi-do, Gangwon-do, Chungcheong-do, Jeolla-do, and Gyeongsang-do (Fig. 1). For dendrochronological analysis, a minimum of 50 years of annual rings was required and 20 mature trees of 7–20 m in height, > 39 –72 cm in diameter were selected from each national park. Most trees had 50 years or more of annual rings, but some juvenile trees were found (less than 50 rings) and eliminated from the annual ring analysis. Therefore, 11–20 trees from each national park were used in the

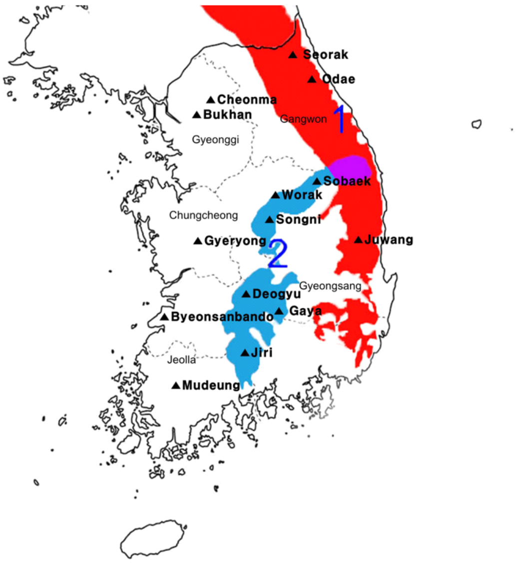

Fig. 1. Location of the National Parks (triangle, National Park: red line, Taebaek Mountains: blue line, Sobaek Mountains).

annual ring analysis, according to the number of rings. The samples were extracted bidirectionally at chest height, where the wood could be avoided, using an increment borer (Fig. 2 and Table 1).

Fig. 2. Extracting an increment core (Ø5.15 mm) from an experimental tree (*Pinus densiflora*) at chest height.

2.2. Analysis method

2.2.1. Annual ring width measurement and cross-dating

The annual ring cores sampled from each site were adhered and fixed to a U-shaped specimen mount and polished with a belt sander until the boundary of the annual ring was visible. The width of each annual ring was measured within a 0.01 mm accuracy using LINTAB (Rinntech, DEU) connected to a computer, and cross-dating was performed to assign an accurate period of growth and development to each annual ring. Cross-dating was performed using the graphic method, which compares the tendencies of growth and development of the *t*-value using the coefficient of correlation (Equation 1), and the *G*-value (similarity) (Equation 2), which were used in the sign test (Baillie and Pilcher, 1973; Eckstein and Bauch, 1969; Rinn, 2011; Schweingruber, 1988). For this purpose, the TSAP-Win program, which is often used in dendrochronology, was used.

Table 1. Description of study sites and sample trees (*Pinus densiflora*)

Region	National park	Latitude / longitude	Number of trees (cores)	Highest altitude (m a.s.l.)	Range of sampling altitude (m a.s.l.)
Seoul	Bukhan	37°39'N/126°58'E	20 (40)	836	318-720
Gangwon	Seorak	38°07'N/128°28'E	20 (40)	1,708	383-840
	Odae	37°48'N/128°41'E	11 (22)	1,577	298-520
Chung cheong	Worak	36°59'N/128°15'E	20 (40)	1,161	351-940
	Songni	36°33'N/127°51'E	20 (40)	1,057	348-890
	Gyeryong	36°20'N/127°11'E	13 (26)	847	627-732
Gyeong sang	Juwang	36°24'N/129°11'E	20 (40)	923	305-884
	Sobaek	36°57'N/128°29'E	20 (40)	1,439	548−1,274
	Gaya	35°48'N/128°06'E	20 (40)	1,433	388-988
Jeolla	Jiri	35°16'N/127°33'E	19 (38)	1,915	310−1,024
	Byeonsan	35°36'N/126°35'E	12 (24)	508	30-413
	Mudeung	35°09'N/126°59'E	18 (36)	1,187	138-629
	Deogyu	35°50'N/127°44'E	20 (40)	1,614	418-989

$$t = |r| \frac{\sqrt{(n-2)}}{\sqrt{1-r^2}} \qquad (1)$$

(r: correlation coefficient)

$$\triangle_i = (X_{i+1} - X_i) \ \ when \ \ \triangle_i > 0 : G_{ix} = +\frac{1}{2}$$
$$\triangle_i = 0 : G_{ix} = 0$$
$$\triangle_i < 0 : G_{ix} = -\frac{1}{2}$$
$$\text{for } two\ curves \ \ G_{(x,y)} = \frac{1}{n-1} \Sigma |G_{ix} + G_{iy}| \qquad (2)$$

2.2.2. Standardization and residual chronology

Standardization was performed in order to eliminate the unique biological trends of the tree, according to the age of the sampled tree. Standardization in dendrochronology refers to the elimination of the biological trend according to long-term competition and disturbance, creating a chronology index using the ratio between the biological trendline obtained with the statistical function and the annual ring width (Fritts *et al*., 1976). The double detrending method was used, in which the biological trend was primarily eliminated using the exponential curve and also the growing stock competition using spline (50% response cycle 50 years). Additionally, the biological trend according to disturbance was predicted for standardization (Seo, 1999). Autocorrelation, in which the nutrients created in years before the growth and development were carried over, exists in standardized exponential chronicles, but this study used residual chronology in which autocorrelation was eliminated. The ARSTAN program (Cook, 1985) was used to obtain the residual chronology.

2.2.3. Statistical analysis of dendrochronology

The mean sensitivity (MS) and subsample signal strength (SSS) were analyzed through standardization as statistical data that could evaluate the dendrochronological value of the obtained chronicles. The MS was calculated (as shown in Equation 3) as the statistical factor that measures high-frequency fluctuation, the size of change between the two consecutive annual ring widths and indicates the annual fluctuation for each chronicle (Cook and Kairiukstis, 1990). However, the average sensitivity is heavily reliant on autocorrelation and the standard deviation, and it partially lacks the statistics for describing the change in annual ring growth, for which the SSS (Equation 4) was analyzed (Bunn *et al*., 2013). The SSS is the value that is calculated based on the correlation between the dendrochronology (measured by the annual ring width of each tree) and is used to determine the suitability of the data during the climate restoration and climate data analysis. In general, an average sensitivity of 0.20 or above is required, and an SSS of 0.85 or above is required (Akkemik *et al*., 2005; Buras, 2017; Speer, 2010). The ARSTAN program (Cook, 1985) was used for the analysis.

$$MS_x = \frac{1}{n-1} \Sigma \left| \frac{2(X_{t+1} - X_t)}{X_{t+1} + X_t} \right| \qquad (3)$$

(X_t = tree-ring index at t year, X_{t+1} = tree-ring index at t+1 year)

$$SSS = \frac{t'(1+(t-1)r)}{t(1+(t'-1)r)} \qquad (4)$$

(r: mean interseries correlation for the chronology, t: No. of cores in the full set, t': No. of cores in a subset of the whole population)

2.2.4. Response function with climate

A response function analysis was performed to analyze the relationship between the standardized dendrochronology of the trees and the climate of each national park. In the analysis, the multicollinearity between the independent variables was eliminated in order to analyze the interrelation between the dependent and independent variable, which could itself be more accurately identified

(Fritts *et al*., 1976; Seo, 1999). The mean monthly temperature and total monthly precipitation were used as independent variables, and the annual ring index was used as the dependent variable. The DENDROCLIM 2002 program (Biondi and Waikul, 2004) was used for the response function analysis. To survey the relationship between the forest tree growth and development and the climate, climate data measured from the nearby meteorological station was required. However, due to the absence of meteorological stations in any of the national parks, climate data from the Climate Research Unit Gridded Time Series (CRU-TS) was used. CRU-TS segments all terrestrial areas of the world (excluding Antarctica) with a grid of 0.5° latitude and longitude, constructed from 1901 to date (Harris *et al*., 2020). The independent variables used in the response function were the mean monthly temperature and total monthly precipitation from October in the preceding year to October in the given study year. The analysis period included the chronicle sections with SSS values ≥ 0.85 from each park's chronicles.

3. RESULTS and DISCUSSION

3.1. Regional dendrochronology cross-dating

The *t* and *G*-values were used to perform cross-dating based on the *P. densiflora* S. et Z. samples from 13 national parks (Table 2). The annual ring patterns of *P. densiflora* found in the Seoul and Gyeonggi regions, Gangwon-do, Chungcheong-do, and Gyeongsang-do show relatively high statistical values within identical regions, indicating similar annual ring patterns. However, the annual ring patterns of *P. densiflora* in Jeolla-do national park have relatively low statistical values, despite the annual ring patterns of this variety in the same region. Low statistical values from Deogyu national park indica-

Table 2. *t*-values and *G*-values between local tree-ring chronologies of *Pinus densiflora* from each national park (Where the *t*-value is 3.5 more and G-value is 55% more)

National Park		Seoul	Gangwon		Chungcheong			Gyeongsang			Jeolla		
		Bukhan	Seolark	Odae	Worak	Songni	Gye-ryong	Juwang	Sobaek	Gaya	Jiri	Byeon-san	Mu-deung
Gang-won	Seolark	4.6/69											
	Odae	3.9/66	7.9/66										
Chung-cheong	Worak	6.4/72	8.2/68	5.4/63									
	Songni	3.9/68	3.8/65	2.6/61	7.3/75								
	Gyeryong	6.0/69	4.9/62	4.7/60	5.6/62	3.1/60							
Gyeong-sang	Juwang	2.7/67	3.9/66	4.8/63	5.0/75	3.5/68	2.8/68						
	Sobaek	2.3/66	2.6/61	3.8/67	2.1/68	2.2/68	3.5/64	4.5/67					
	Gaya	4.5/66	2.8/60	4.0/66	3.1/65	5.6/74	5.3/62	4.0/66	3.7/74				
Jeolla	Jiri	4.4/64	3.2/64	3.3/65	3.1/66	3.7/63	4.1/66	4.0/68	3.4/68	3.3/65			
	Byeonsan	1.5/60	0.5/57	1.0/58	3.5/62	1.6/53	2.6/61	0.5/60	0.5/53	3.5/61	3.8/65		
	Mudeung	2.8/61	3.0/55	3.7/60	5.2/60	4.0/56	3.7/65	3.7/66	1.8/56	3.5/60	3.8/65	3.6/61	
	Deogyu	4.8/65	1.7/58	2.9/58	2.6/59	1.9/58	2.0/53	3.6/61	0.9/61	4.1/63	1.7/55	0.2/47	2.1/54

ted a strong regional annual ring pattern, unlike other national parks. In addition, high statistical values were exhibited among the trees in Seoul and Gyeonggi-do, Gangwon-do, and Chungcheong-do national parks, indicating similar annual ring patterns. A *t*-value of around 3.5 was calculated for the Gayasan Mountain region of Gyeongsang-do, indicating similar patterns to all the other regions. In the case of Juwang Mountain, the annual ring patterns were identical to the national parks near Worak Mountain and Songni Mountain or in the Taebaek Mountains. However, Sobaek Mountain showed relatively low statistical values compared with other regions, showing a strong regional annual ring pattern. Byeonsan Peninsula and Deogyu Mountain in the Jeolla-do national park had lower statistical values compared to other regions, indicating a strong regional annual pattern. The Jiri and Mudeung Mountains were found to have similar annual ring patterns to the national parks south of the center in Chungcheong-do and Gyeongsang-do. This corresponds to the outcome of the previous studies that found similar annual ring patterns in *P. densiflora* in the northern and central regions with a high *t*-value, but a low similarity with the annual ring patterns of southern regions (Park *et al*., 2010). Currently, there is a lack of studies on the annual ring pattern of *P. densiflora* in southern regions. With further research in this region, an accurate conclusion could be derived on the difference in annual ring patterns of *P. densiflora* between the northern, central, and southern regions.

The longest chronicle identified was in Seorak Mountain at 331 years, and the shortest, at 100 years, was in the Bukhan Mountain region. The majority of trees over 200 years old were sampled in Gangwon-do and Chungcheong-do Worak Mountain (Fig. 3). *P. densiflora* from the Taebaek Mountains were found to have more rings than artificially affected regions, such as Chungcheongnam-do and Gyeongsangbuk-do coasts. Thus, it could be determined that the oldest *P. densiflora* were distributed in mountainous areas with relatively low artificial influence in comparison to coastal areas (Chung *et al*., 2017; Lee *et al*., 2008).

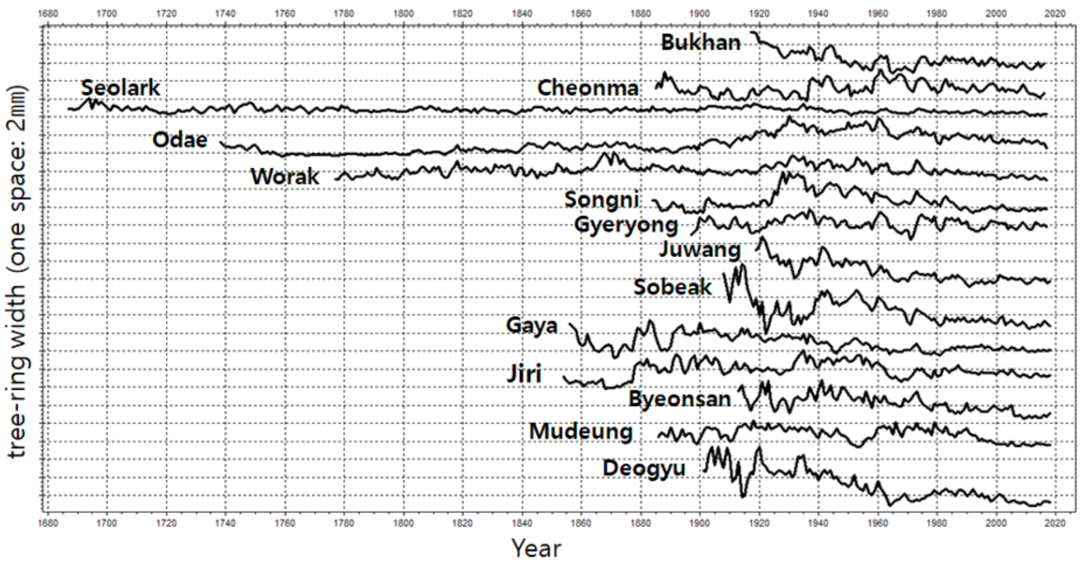

Fig. 3. Individual tree-ring chronologies of *Pinus densiflora* of each national park after cross-dating.

3.2. Statistical characteristics of regional dendrochronology

The average sensitivity and SSS were analyzed for the dendrochronology developed from domestic national parks (Table 3). The average sensitivity of the chronicles of most national parks was between 0.14 and 0.26, which is generally thought to be high sensitivity, as shown in a previous study (Seo *et al*., 2000). In addition, most national park chronicles had a value of 0.2 or above, while the Seorak, Odae, and Worak Mountains had values below 0.2, where numerous rings were observed. This was attributed to the narrow annual ring width with increasing tree age, and the average sensitivity being low given the proximity in annual ring width.

Among the 16 individual *P. densiflora* included in the Bukhan Mountain dendrochronology, nine trees had SSS values of 0.85 or above since 1939. The dendrochronology of 1939–2016 was found to be applicable to research on its relationship to the climate. The dendrochronology obtained in the Gangwon and Chungcheong regions all had SSS values of 0.85 or above, suggesting its suitability for research on its relationship to climate. Segments of 0.90 or above were identified from the Bukhan, Seorak, and Worak Mountain national parks, indicating a reasonable possibility for climate restoration research. The dendrochronology obtained in Gyeongsang-do and Jeolla-do mostly had SSS values of 0.85 or above. However, in six *P. densiflora*, the SSS values of 0.80 after 1937 and 0.75 in the Juwang Mountain dendrochronology in the Gyeongsang region after 1943 led to its omission in the research on the relationship to the climate. It was decided that subsequent research could proceed with the addition of samples with 60–70 annual rings.

Table 3. Statistical information about the tree-ring chronologies of *Pinus densiflora* from each national park

Region		Number of trees	Time span	Length	Average ring width (mm)	Mean sensitivity	SSS of 0.85 attained (trees)	SSS of 0.90 attained (trees)
Seoul	Bukhan	16	1917-2016	100	2.38	0.20	1939 (9)	1946 (13)
Gangwon	Seorak	14	1687-2017	331	1.15	0.16	1796 (7)	1884 (12)
	Odae	11	1738-2017	280	2.68	0.14	1950 (10)	-
Chung cheong	Worak	20	1777-2017	241	2.06	0.16	1900 (8)	1924 (13)
	Songni	12	1884-2017	134	2.08	0.23	1934 (10)	-
	Gyeryong	11	1897-2017	121	2.34	0.23	1955 (8)	-
Gyeong sang	Juwang	7	1918-2018	101	2.44	0.20	-	-
	Sobaek	12	1908-2018	111	3.04	0.23	1955 (10)	-
	Gaya	10	1856-2018	163	1.82	0.22	1926 (10)	-
Jeolla	Jiri	12	1854-2018	165	2.51	0.20	1948 (12)	-
	Byeonsan	5	1913-2018	106	2.28	0.26	1947 (5)	-
	Mudeung	8	1886-2018	133	2.05	0.24	1906 (7)	-
	Deogyu	6	1901-2018	118	2.70	0.20	-	-

SSS: subsample signal strength.

3.3. Response function

Response function analysis was performed for *P. densiflora* in 11 national parks, excluding the Juwang and Deogyu Mountains where the standardized dendrochronology SSS value was 0.85 or below (Tables 4 and 5).

The results show that most *P. densiflora* had a higher defining relationship ($p < 0.05$) during the initial stages of growth and development in February and March. Such results suggest, through Liebig's law of the minimum, that "plant production is determined by the minimum nutrients necessary for growth and development", i.e., the temperature before or during the initial development of the cambium determines the annual ring growth (cambium activity) of *P. densiflora* (Fritts *et al*., 1976). This was similar to the results derived from previous research in which the formation or end of the cambium of conifers located in temperate and subpolar regions, where the seasonal changes were well-defined (Park *et al*., 2015; Rossi *et al*., 2008; Seo *et al*., 2008).

In the Byeonsan Peninsula, Sobaek Mountain, Gaya Mountain, and Bukhan Mountain, positive responses were identified with winter temperature during the resting phase of growth and development, from November to January of a given year. The *P. densiflora* in the Worak Mountain highlands reacted to winter temperature most sensitively in the year before growth and development (Seo *et al*., 2000). In previous research on domestic *P. densiflora*, only the positive effect of the winter temperature on the growth and development was identified, not the cause (Lee, 2003; Park *et al*., 2010; Yoon *et al*., 2013). Lee (2018) stated that conifers photosynthesize annually, and the sugar content recorded for the mugho pine was highest in January and lowest between April and July, while the sprouts grew. Thus, *P. densiflora* as a typical xylophyte that undergoes fixed growth (the number of leaves of the branch during the year of growth is fixed to the number of phyllogens formed during the winter snow in the previous year) was estimated to affect the commencement of the cambium activity as the increase in winter temperature increases

Table 4. The correlation coefficients between mean monthly temperature and tree-ring index chronologies of *Pinus densiflora* from each national park, which are higher than the significant level ($p < 0.05$)

Region	National park	Month												
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.
Seoul	Bukhan			0.21			0.34						0.22	
Gangwon	Seolark					0.22	0.21			−0.19				
	Odae					0.39	0.34							
Chung cheong	Worak						0.20							
	Songni						0.28	0.22						
	Gyeryong					0.23	0.34							0.38
Gyeong sang	Sobaek		0.23	0.27	0.34	0.23	0.41	0.44			0.24			
	Gaya			0.30	0.22	0.25								
Jeolla	Jiri					0.27	0.21							0.26
	Byeonsan			0.32										
	Mudeung					0.22								

Table 5. The correlation coefficients between monthly total precipitation and tree-ring index chronologies of *Pinus densiflora* from each national park, which are higher than the significant level (p < 0.05)

Region	National Park	Month												
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.
Seoul	Bukhan		0.26		-0.26				0.23					
Gangwon	Seolark			0.19					0.42					
	Odae								0.29					
Chung cheong	Worak								0.34					
	Songni								0.20		−0.21			
	Gyeryong								0.24					
Gyeong sang	Sobaek									−0.26	−0.27			
	Gaya				0.23									
Jeolla	Jiri								0.28					
	Byeonsan				0.22	0.22	0.27						0.34	−0.21
	Mudeung			0.20					0.20					

the carbohydrates reserved through photosynthesis. Since this is only a hypothesis, further research is required for validation.

The regional monthly temperature was also found to affect the growth of *P. densiflora*, however, no regional similarities were found. Even when tree species are identical, the difference in climatic responses among trees in a forest can be attributed to the environmental and locational factors (Hofgaard *et al*., 1999; Larsen and MacDonald, 1995). In addition, there have been numerous studies conducted using the sum of temperature rather than the average temperature in relation to cambium activity, and additional research is necessary to properly elucidate the relationship between the regional sum of temperature and the annual ring width (Sarvas, 1972; Seo *et al*., 2008; Seo *et al*., 2017; Yoo *et al*., 2021).

Precipitation in May positively affected the growth and development of *P. densiflora* in all regions, excluding the Byeonsan Peninsula in Jeolla-do and Gyeongsang region, suggesting that moisture supply during the initial growth stage of *P. densiflora* is important. The trees selected for this study were mostly found on/in rocky slopes or regions, and moisture supply during growth was critical to the formation of annual rings. This is consistent with the results of previous research, which showed that precipitation in May (during the commencement of growth of trees exposed to slopes or rocks) affected cambium activity (Seo *et al*., 2000). In contrast, the *P. densiflora* of certain national parks in Gyeongsang-do were mostly found near valleys or plains (Sobeak Mountain: Huibang waterfall, Geumgye stream, Gaya Mountain: Gayga stream), and were not so affected by precipitation.

A positive correlation was identified between precipitation in June to July in Sobaek Mountain and the July rainy season in Songni Mountain with precipitation in Byeonsan Peninsula in October. During tree growth, precipitation was linked with a decrease in sunlight levels, which therefore results in decreased photosynthesis (Park and Seo, 1999). In the case of the Byeonsan Peninsula, precipitation in January to March and September positively affected annual ring growth. Thus, the *P. densiflora* in the relative lowlands in the Byeonsan Peninsula was more affected by precipitation than the temperature, and its effects were investigated prior to growth (January to February), from the start of growth (March), and until the growth process was complete (September).

Winter precipitation from November to December in the previous year and January in the study year were found to positively affect the growth and development of *P. densiflora* in the Bukhan, Seorak, Gaya, and Mudeung Mountains. The increase in winter precipitation or snowfall could supply the necessary moisture for spring tree growth, positively affecting the annual ring growth. In addition, previous research found that if the soil temperature was not so low as to inhibit growth, the precipitation between November and December would accelerate the root growth of *P. densiflora* along with the annual ring growth of the following year (Yoon *et al*., 2013). However, in Bukhan Mountain, a positive relationship with the precipitation in January of the relevant year was identified, which was not identified in other regions. Therefore, growth conditions, such as root exposure and stress, in combination with excessive moisture likely affected the outcome.

4. CONCLUSIONS

Samples from *P. densiflora* S. et Z. in 13 national parks were extracted to examine the relationship between the difference in annual ring growth for each region through dendrochronological analysis and the climate. A statistically significant agreement between the annual ring patterns among the *P. densiflora* in Seoul, Gangwon-do, and Chungcheong-do national parks was identified. However, the annual ring patterns of *P. densiflora* in the Jeolla-do and Gyeongsang-do national parks only partially matched that of other national parks. This was considered to stem from the difference in climate in the central and southern regions, for which the correlation between the annual ring growth and climate was analyzed based on 11 sites. The results showed that the annual ring growth of *P. densiflora* native to the central and southern regions was mostly affected by the temperature in spring (February and April) and precipitation in May. Moreover, the winter (November to January) temperature and precipitation before and during the year of growth and development were found have an effect in some regions, except for Gangwon and Chungcheong. The increase in precipitation near the valley or lowland plains was found to restrict diameter growth. Thus, the effect of region on the annual ring growth pattern was significant, whereas in the relationship between the annual ring growth and climate, the growth conditions were found to have a significant effect.

The chronicles developed through this research could be used as critical data for expanding the dendrochronology of *P. densiflora* in each region. The dendrochronology of *P. densiflora* native to Bukhan, Seorak, and Worak Mountains could be utilized in specific restoration studies on the variability of past climate in Korea.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

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