



# Article The Relationship between Tree-Ring Growths of *Pinus densiflora* and Climate from Three Mountains in Central Region, the Republic of Korea

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**Abstract**: To analyze the relationship between climatic factors (monthly mean temperature and total precipitation) and tree-ring growths of *Pinus densiflora* from the central region of the Republic of Korea, more than 20 trees were sampled from three national parks. The tree-ring chronology of Mt. Bukhan covering the period of 1917–2016 was assessed, as well as that of Mt. Seorak across 1687–2017 and Mt. Worak across 1777–2017. After cross-dating, each ring-width series was double-standardized by first fitting a logarithmic curve and then a 50 year cubic spline. Climate-growth relationships were computed with bootstrap correlation functions. The result of the analysis showed a positive response from the current March temperature and May precipitations for tree-ring growth of *Pinus densiflora*. It indicates that a higher temperature supply during early spring season and precipitation during cambium activity are important for radial growths of *Pinus densiflora* from the central region in the Republic of Korea.

Keywords: Pinus densiflora; tree-ring; climate; bootstrap correlation functions; Republic of Korea

# 1. Introduction

The growth of a tree is determined by the tree's genetic potential and its environment, and tree-rings are formed by the repetition of length and diameter growth that occurs annually [1]. Although genetic factors can be artificially manipulated, environmental factors are almost impossible to manipulate artificially due to the drastic and broader variation [2]. Therefore, environmental factors exert a significant influence on the growth of trees, and climate factors among such environmental factors are closely related to the growth of trees [3,4]. Tree-ring data from locations where trees are sensitive to climate variation are among the most important sources of proxy climate data [5]. These tree-ring data can be analyzed by dendrochronology, one of the biological proxies that provides annual climate data resolutions with characteristics, and this has contributed to the past climate reconstruction [6]. Therefore, understanding of the spatial patterns in climate change variability is required to expand the tree-ring data in various areas [7].

Climate reconstruction using dendroclimatology is conducted around the world. Opala-Owczarek studied *Juniperus* in Pamir and found a high correlation between May–September minimum temperatures and juniper growth [8]. Corona et al. studied the climate-growth relationship of *Larix decidua* and *Pinus cembra* at the upper timber line in the Alps and could reconstruct the climate for the past 1000 years [9]. Cerrato et al. performed a May–September mean temperature reconstruction via the maximum density of *Pinus cembra* in the Rhaetian Alps [10]. Another study restored the summer temperature of up to



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the past 7500 years using Scotch pine (*Pinus sylvestris* L.) growing in the northern regions of Finland [11]. In Republic of Korea, Park et al. studied the relationship between climate and standardized chronologies on Korean firs (*Abies koreana* Wils.) growing on Janggun Peak and Jung Peak in Mt. Jiri [12]. Seo et al. studied death years and inter-annual growth reduction in Korean firs at Yeongsil in Mt. Halla by using the tree-rings of Korean fir that withered in the region [13].

Being a mountainous region with 70% of its landmass covered in mountains, the Republic of Korea has most of its forest areas spread along the Taebaek and Sobaek mountain ranges. The total forest area of Republic of Korea is 6.55 million ha, which consists of various species. The representative types of trees are oak (*Quercus* spp.) and pine (*Pinus densiflora*) [3]. *P. densiflora* is one of the major tree species growing across the whole country, which is distributed along areas at an altitude of lower than 1300 m a.s.l. and preferably grows in sunny areas [14]. In addition, the tree-rings of pine species have shown a good agreement with climatic variables, and conifers are known for their dendroclimatic potential [15–17]. However, due to human interference, it is difficult to obtain long tree-ring chronologies in Republic of Korea. The centuries-old trees (up to 300–400 years) with high potential for the development of tree-ring chronologies are located national parks.

Therefore, we chose Mt. Bukhan, Mt. Seorak, and Mt. Worak for this study, which have experienced relatively low human intervention and are mountainous. The aim of our study was to establish tree-ring chronologies of *P. densiflora* from three mountains in the Republic of Korea, and to compare the growth of trees across each mountain. We evaluated the influence of temperature and precipitation on *P. densiflora* tree-rings, the stability of responses in the past century, and the potential for climate reconstruction.

# 2. Materials and Methods

### 2.1. Study Site and Sampling

The sampling took place at three mountains (Mt. Bukhan, Mt. Seorak, and Mt. Worak), all located in central Korea (Figure 1). Mt. Bukhan is located in the northwestern part of Seoul, the capital of Republic of Korea. It is composed of granite, intrusive during the Mesozoic era, and the dominant species are *Q. mongolica* and *P. densiflora* [18]. Mt. Seorak is located in the Taebaek Mountains in northeastern Korea. Since granite intrusion at the end of the Cretaceous, Mt. Seorak rose up high together with the formation of the Taebaek Mountains about 23 million years ago in the Cenozoic era. This area has been designated by world organizations (UNESCO, IUCN) for the conservation of nature for its various ecosystems, and the dominant species are *Q. mongolica* and *P. densiflora* [19]. Mt. Worak is located in the Sobaek Mountains in central Korea. This area is composed of limestone silicate rock from the Paleozoic era and biotite granite from the Mesozoic era [20]. It is a mountainous area similar to Mt. Seorak, and the dominant species are the same (Table 1).

**Table 1.** Site characteristics and sample replication.

	Bukhan	Seorak	Worak	
Latitude, longitude	37°39′ N, 126°58′ E	38°07′ N, 128°28′ E	36°59′ N, 128°15′ E	
Area (km <sup>2</sup> )	76.92	398.24	287.57	
Highest altitude (m a.s.l.)	835	1708	1097	
Angle of slope	$10.5^{\circ}$ – $30.5^{\circ}$	15.3°-31.6°	8.9°-35.5°	
Geology	Granite	Granite	Biotite granite	
Exposition	E-NE	E-NE	E-NE	
No. of cores for tree-ring analysis	33 cores (16 trees)	30 cores (14 trees)	40 cores (20 trees)	
Altitudes (m a.s.l.)	318–720	383-840	351–940	



**Figure 1.** Location of study sites (triangle) and overview of sampling sites ((**A**): Mt. Bukhan, (**B**): Mt. Seorak, (**C**): Mt. Worak).

We usually sampled from below the timber line of *P. densiflora* (between 300 and 1000 m a.s.l.), and sampled at least 2 cores in one tree from fewer than 20 trees (adult wood) over 50 years of age-class, as the KNPS (Korea National Park Service) limited the number of specimens to 20 for the protection of the national park's natural landscapes and ecosystems.

#### 2.2. Method of Analysis

## 2.2.1. Tree-Ring Chronologies

Tree-ring cores, which were sampled at breast height from *P. densiflora* using an increment borer, were mounted on wooden boards and sanded. The core samples, which had the tree-ring width clearly visible, were observed to the nearest 0.01 mm using an increment measurement table, LINTAB linear table (Frank Rinn Company, Heidelberg, Germany), connected to a LEICA-S4E stereo microscope and the software TSAP-Win Scientific. The cross-dating process was carried out to assign accurate dates to each tree-ring. The representative cross-dating methods utilized in dendrochronology involve a statistical method that calculates the mutual conformity in the tree-ring chronology and a graphic method in which the conformity in tree-ring chronology is visually confirmed [4].

To remove age and other non-climatic trends, the measured series of individually dated samples was standardized to ring width indices by employing ARSTAN software [6,21]. Standardization in dendrochronology was used for the removal of age and other non-climatic trends and for creating an index chronology using the trend curve of growth-acquired aggregation function and the measured difference of each tree-ring width [22]. This study utilized the double detrending method, which firstly removes the biological growth trend acquired using a logarithmic curve and then estimates the stand competition and growth rate based on disturbances using spline (50% response cycle of 50 years) to go through re-standardization [23]. Within the standardized chronologies

exists autocorrelation, in which nutrients produced prior to the years of growth get carried over, and this study utilized residual chronology to remove such autocorrelation.

Usually, the mean sensitivity (MS) measures the year-to-year variation in tree-ring width and is thus considered an estimate of the extent to which the chronology reflects local climate variation [24,25]. However, the MS parameter is a confusing and ambiguous statistic for describing variations in tree growth, as MS is largely dependent on the autocorrelation and standard deviation of a series [26]. Therefore, the subsample signals' strengths (SSS), which are statistical data used to evaluate the dendrochronological value of the chronologies acquired through standardization, were analyzed. The subsample signal strength (SSS), which is computed from data on sample size and between tree correlations, is a guide to assessing the likely loss of reconstruction accuracy, which occurs when the chronology is formed from a limited number of series [27–29]

Additionally, regional differences among the standardized chronologies in each national park proceeded with cross-dating. The functions used in the TSAP-Win program (RINNTECH, Germany) were graphic method and  $t_{BP}$  calculated using the coefficient of correlation and Glk% (Gleichläufigkeit), where the sign test was applied [4,30–32].

# 2.2.2. The Tree-Ring Chronology and Climate Relationship

Response function analysis allows a more accurate understanding of the relationship between dependent variables and independent variables since it analyzes the relationship after removing the multicollinearity existing between each independent variable [22,23]. Therefore, the correlations between tree-ring chronologies and climate variables (monthly total precipitation, temperature) were analyzed.

The climate data used were from the Climatic Research Unit gridded Time Series (CRU-TS). CRU-TS is a widely used climate dataset on a 0.5° latitude by 0.5° longitude grid over all land domains of the world except Antarctica [33]. All chronologies and the climate data correlations were analyzed using the climate data from October of the previous year to December of the current year (15 months). The DENDROCLIM 2002 software developed by Biondi et al. was used for statistical analyses [34]. The correlation between climatic data and tree-ring chronology was calculated using DENDROCLIM2002 that were tested by a bootstrap response function analysis at the 95% significant confidence level.

#### 3. Results

#### 3.1. Tree-Ring Chronologies

Chronologies covering the period of 1917–2016 were developed for pine trees from Mt. Bukhan (Figure 2), and the number of samples that could be cross-dated was 32 cores from 16 trees. The mean tree-ring width of the individual series constituting the regional chronology ranged from 1.53 to 3.20 mm. The results of the basic statistics are shown in Table 2. The residual chronologies and the sample size (the number of trees) through time are illustrated along with the running subsample signal strength (SSS) and running mean series intercorrelation (Rbar) using 50-year moving windows with 25-year overlapping [35]. The mean sensitivity within the entire dataset was 0.164, and the SSS exceeded 0.85 over the nine trees after 1939. This adds confidence to the speculation that further growthclimate analyses for the developed chronologies represent the population signal quite well. The Mt. Seorak chronology (Figure 3) was composed of 28 cores from 14 trees, and the period of chronology was 1687–2017. The mean tree-ring width of the individual series constituting the regional chronology was quite similar, ranging from 0.49 to 2.13 mm. The mean sensitivity within the entire dataset was 0.161, and the SSS exceeded 0.85 over the seven trees after 1796. The period of Mt. Worak's chronology was 1777–2017, and the number of sample cores that could be cross-dated was 20. The mean tree-ring width of the individual series constituting the regional chronology was wider, ranging from 1.22 to 3.58 mm. The mean sensitivity within the entire dataset was 0.160, and the SSS reached a value of 0.85 after 1900 (eight trees). Typical of these pines of the three mountains is low mean sensitivity, which indicates complacent, non-sensitive growth (0.16). The period of

SSS equal to or above 0.85 was longer for Mt. Seorak (after 1779) than for Mt. Worak (after 1833), despite the fact that Mt. Seorak had a lower sample depth than Mt. Worak (Figure 4).

The Mt. Bukhan chronology correlated well with the Mt. Worak chronology ( $t_{BP} = 6.4$ , GLK = 72%, overlap = 100 years) and to a lesser extent with the Mt. Seorak chronology ( $t_{BP} = 4.6$ , GLK = 69%, overlap = 100 years). Comparison between the Mt. Worak and Mt. Seorak chronologies showed relatively high  $t_{BP}$  and GLK% values, especially when taking into account the very long overlap ( $t_{BP} = 8.2$ , GLK = 68%, overlap = 241 years).



Figure 2. The chronology and sample depth of *P. densiflora* from Mt. Bukhan (dotted line is  $SSS \ge 0.85$ ).

	Mt. Bukhan	Mt. Seorak	Mt. Worak
Number of samples (cores)	16 (32)	14 (28)	20 (40)
Time span	1917–2016	1687–2017	1777–2017
Year	100	331	241
Average ring width (mm)	2.38	1.15	2.06
Mean sensitivity	0.16	0.16	0.16
RBAR	0.367	0.354	0.398
Standard deviation	0.20	0.18	0.18
First-order autocorrelation	0.48	0.39	0.36
Signal-to-noise ratio	9.07	6.49	12.76
Agreement with population chronology	0.90	0.86	0.92
Variance in 1st Eigenvector (%)	46.24	52.44	45.44
SSS of 0.85 attained (trees)	1939 (9)	1796 (7)	1900 (8)
SSS of 0.90 attained (trees)	1946 (13)	1884 (12)	1924 (13)

Table 2. Statistics of tree-ring chronologies of *P. densiflora* from three mountains.



**Figure 3.** The chronology and sample depth of *P. densiflora* from Mt. Seorak (dotted line is SSS  $\geq$  0.85).



**Figure 4.** The chronology and sample depth of *P. densiflora* from Mt. Worak (dotted line is SSS  $\geq$  0.85).

# 3.2. The Tree-Ring Chronology and Climate Relationship

The chronology of Mt. Bukhan start from 1917, but unfortunately, the SSS reached a value of 0.85 after 1939 and 0.90 after 1946. Therefore, the climate data and tree-ring growth correlation were analyzed by using the climate data from the period 1939–2016. The chronology of Mt. Seorak corresponded to a minimum sample depth of seven trees and the period was A.D. 1796–2017, and the chronology of Mt. Worak involved eight trees in the period A.D. 1900–2017. Therefore, the tree-ring growth of Mt. Seorak and Mt. Worak and the climate data correlation were analyzed by using the climate data from the period 1901–2016.

The tree-ring growth of pines at the three mountains is strongly positively correlated with the current March temperature and May precipitation. These results show that the high temperature in March and the precipitation in May had a positive effect on the growth of pine tree-rings in the three mountains. Mt. Seorak showed a significant positive correlation with temperature during current February. Mt. Bukhan showed a significant positive correlation both previous December and current September. Moreover, negative correlations with current January precipitation were found for our Mt. Bukhan chronology, as well as positive correlations with previous November precipitation (Figures 5–7).



**Figure 5.** The correlation between climate data and tree-ring chronology of *P. densiflora* from Mt. Bukhan (significant correlations (p < 0.05) are indicated with black dots).



**Figure 6.** The correlation between climate data and tree-ring chronology of *P. densiflora* from Mt. Seorak (significant correlations (p < 0.05) are indicated with black dots).



**Figure 7.** The correlation between climate data and tree-ring chronology of *P. densiflora* from Mt. Worak (significant correlations (p < 0.05) are indicated with black dots).

## 4. Discussion

# 4.1. Tree-Ring Chronologies

*P. densiflora* is a long-lived endemic pine species in Republic of Korea having a wide distribution [3]. From a dendrochronological point of view, the longevity and durability of the tree are what makes *P. densiflora* potentially important for dating purposes in cases where wood originating from this species was used in buildings or other wooden constructions. When comparing the *P. densiflora* tree-ring chronology from each site, we obtained relatively high statistic values. Although the statistics between Mt. Bukhan and the other mountains were relatively low because of regional differences, the others matched with high t<sub>BP</sub> and GLK% values. This could be explained by the fact that Mt. Seorak and Mt. Worak are mountainous areas that are less subject to human intervention and are connected to one mountain range. Each mountain has corresponding dates of more than 10 samples where the SSS value is 90%, and Mt. Seorak is the oldest at 1884. In particular, the SNR (signal-to-noise ratio) value of Mt. Seorak is higher than that of other mountains. Therefore, it is considered more suitable for use in past climate reconstruction than Mt. Bukhan and Mt. Worak.

#### 4.2. The Tree-Ring Chronology and Climate Relationship

The correlation coefficients between the residual chronology and monthly precipitation data for the years 1901–2016 were calculated. However, the SSS value of the Mt. Bukhan chronology reached 0.85 after 1939 and was compared for the years 1939–2016. We found relationships between the tree-ring chronologies and climate conditions, including a strong correlation between the tree-ring chronology of the three mountains and the climate data (temperature, precipitation) of March and May. It can be understood that *P. densiflora* react more sensitively to the temperature in March before which cambial activities are initiated. The result is also similar to the conclusions drawn in previous studies, which stated that the initiation or termination of cambial activities of coniferous trees located in temperate and boreal regions with clear seasonal change is mostly determined by the temperature condition [36–38]. The May precipitation of each mountain was determined to affect tree-ring growth by providing the required moisture in the initial growth phase in *P. densiflora*. Mt. Bukhan showed a significant positive correlation with the previous December temperature and a negative correlation with the current January precipitation. Based on such a result, it can be assumed that for the *P. densiflora* from Mt. Bukhan, an

appropriate increase in temperature during winter strengthens the soil's ability to retain by reducing snow fall and leads to a positive influence on the growth of trees. However, if this phenomenon continues, it can be estimated that the amount of snowfall will be significantly reduced and moisture stress will occur in January, which will lead to a negative influence on the growth of trees. In addition, Mt. Bukhan was found to have a more significant correlation than the other mountains, which is considered to be due to the fact that the *P. densiflora* tree-ring chronology from Mt. Bukhan is much shorter than the other *P. densiflora* tree-ring chronologies. It could be that the tree-ring chronology was too short, and more trees need to be sampled to obtain a better climate signal. However, we obtained relatively high correlations among the *P. densiflora* tree-ring chronologies of each mountain, despite a relatively short chronology of Mt. Bukhan. Therefore, while a sufficient number of samples are important to solve these problems, it is necessary to expand *P. densiflora* tree-ring chronologies in terms of time scale and space. Through this, a database could be created for monitoring the climate change from the past to the present and to predict the climate in the future.

# 5. Conclusions

Living tree samples were collected from three National Parks in the central region of the Republic of Korea, and they were then processed through dendrochronological techniques. The tree-ring width data showed the conventional acceptance quality to construct the chronologies. The dendroclimatological investigation on pine growing in the central region in the Republic of Korea showed that thermal and pluvial conditions in spring (March and May) have the most important influence on the radial growth of this species in that region. A simultaneous analysis of the three chronologies revealed the climate situations, which caused similar reactions in the central region and, thus, can be used for detailed reconstruction. The general lack of reliable data on climate variability in Republic of Korea during the past and the potential to construct extensive tree-ring chronologies from *P. densiflora* promote future dendrochronological work.

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