Dendroclimatological analysis and tree-ring growth prediction of Quercus mongolica

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\textbf{ABSTRACT}

Tree-ring growth of forest trees is closely related to climate and environment changes during growth period, thus it is able to provide precise information on climate changes. Therefore, the current study is intended to estimate growth changes and to develop an estimating formula for ring-growth based on climate factors for Quercus mongolica. The tree-ring data used are from the 5th national forest inventory conducted nationwide, with climate data in a raster format from the Korea Meteorological Administration. Using dendroclimatological method, summary statistics were obtained through cross-dating and standardization, and tree-ring chronology was written. The findings indicate that the variation and fluctuation in the tree-ring growth index are the outcome of complicated effects of diverse climate factors including temperature and precipitation. Also, significant annual variance for Q. mongolica has been observed, with the decreasing temperature efficiency index for it, so that the temperature condition for its growth is getting worse. The statistical analysis to estimate the relationship between tree-ring growth and climate factors is expected to contribute to evaluating changes in productivity which will be affected by climate change in the future.

\textbf{1. Introduction}

Tree-ring growth of forest trees provides precise information on climate change, thus it can be used as fundamental information to evaluate its impact on forest ecology because tree-ring growth is deeply related to climate in growth period and environmental change. Most of all, to understand structural and function changes in forest ecosystem, figuring out major elements and the relationship between tree growth and climate factors should be preceded (Speer 2010). According to the report of Intergovernmental Panel on Climate Change (IPCC 2014), the annual average temperature increased by 0.85°C from 1880 to 2012, and the forecast indicated that the increasing tendency was not limited to certain areas but prevailing all over the earth. Especially, forest ecosystem has been experiencing the damages from droughts, typhoons, and heavy rainfalls which may cause the changes in ecosystem, and as a result, it may put many species in danger of extinction (Ministry of Environment 2010). As such, climate change is one of the most serious environmental changes that mankind faces.

Specifically, how vegetation distribution would be affected by it is the most pressing earth-wide research topic (Clark et al. 2001; Davis and Shaw 2001; Jackson et al. 2009; Loarie et al. 2009; Dawson et al. 2011). Therefore, climate change requires multi-dimensional research from almost every field of science including forestry to act properly in response to it. From this context, IPCC (2007) reported that the forest structure will experience shift of vegetation belt from low to high latitude because of acceleration of global warming. In addition, tree species will no longer be in optimal environment for growth, thus, the competitiveness among species will also change. Previous researches anticipated higher possibility of withering and damages from disease and insect pest as global warming causes phenological response such as vascular plant growth anticipation higher possibility of withering and damages from disease and insect pest as global warming causes phenological response such as vascular plant growth, and insect appearance (Parmesan and Yohe 2003; Crozier 2004; Yim 2009; Kim 2012; National Institute of Forest Science 2014).

Monitoring research (Korea Meteorological Administration 2016) reported that the forest distribution change occurs as annual average temperature increases but varies according to local specific characteristics. Especially, forest distribution model applying climate change scenario forecasted that deciduous forest increases while coniferous forest and mixed forest decrease. The results indicate the possibility that productivity may be reduced as potential forest distribution of Korea switched from coniferous forest to deciduous forest (Ministry of Environment 2014). Oaks are known to be the second most prevailing species...
following pines in Korean peninsula, and they take about 25% of entire forest (Kim 1995). However, oaks of Europe, Japan, and Korea recently experienced withering damages because of increased Platypus kuroenisis population and dry weather conditions of high temperature and low rainfall, which led to the spread of forest denudation (Lee 2013).

This study aims at developing an equation to estimate tree-ring growth for Quercus mongolica based on climate factors by projecting changes in growth of forest trees through a dendroclimatological analysis with the data for its tree-ring growth from the 5th National Forest Inventory (NFI).

On the other hand, a Korean Quercus species is of ecologic and geologic importance because it is horizontally distributed across the Korean Peninsula from a perspective of phytogeography as well as its inland areas. Furthermore, a need to conserve Quercus forests is emphasized by the fact that they not just contribute to forest preservation and esthetic landscapes but also provide food for animals and trees to grow mushrooms. In particular, Q. mongolica, one of Korean native and typical deciduous species, is of great value as a forest resource which is highly exploited (Kim et al. 2016). However, Q. mongolica is included in the list of 100 forest plant species that are vulnerable to climate change (National Institute of Forest Science 2014). Hence, there is a need for a thorough examination of changes in growth of Q. mongolica by climate change and relevant management plans in order to minimize damages climate change might cause in the future.

It is considered as temperature and precipitation that are most important among climate factors affecting growth of a forest tree (Sander 1971; Kira 1977; Woodward 1987; Woodward and Rochefort 1991; Son and Chung 1994; Shin et al. 2001), and the latter is known as having the most significant impact on tree-ring growth (Zobel and Van Buijtenen 1989). Given the fact that tree-ring growth is delayed by lack of moisture (Larson 1963), 80% of this variation in growth can be explained by changes in precipitation (Zahner 1968). The clear correlation between precipitation and tree-ring growth has been found out by two dendroclimatological studies for Acer saccharum, Fagus grandifolia, Tsuga canadensis in Quebec, Canada and for coniferous species in California in the US, respectively (Larsen and Macdonald 1995; Tradif and Bergeron 2001). Concerning effects of climate change on vegetation distribution, there has been the literature based on the correlation analysis between temperature and precipitation of previous and current years for tree-ring growth to identify climate factors affecting the tree-ring growth (Andreu et al. 2007; Hart et al. 2010; Martin-Benito et al. 2010; Lebourgeois et al. 2013). Hence, there is the need for a thorough examination of environmental changes by climate change to growth of a forest tree. The ultimate goal of this paper is to estimate variations in growth of Q. mongolica through a dendroclimatological analysis and then to find out a relationship between its tree-ring growth and climate factors. To this end, the present study was conducted through the following stages; (1) an examination of its tree-ring growth was made by employing data for growth cores taken as samples in the 5th NFI; (2) its tree-ring chronology was made out after computing basic statistics through processes of cross-dating and standardization in order to predict the changes in tree-ring growth for Q. mongolica; (3) lastly, an equation was devised to calculate its tree-ring growth according to the climate factors.

2. Materials and methods

2.1. Data collection

The subject of this study is Q. mongolica, one of Korean native oaks, to examine the relation between tree-ring growth and climate factors. Quercus mongolica is deciduous broadleaved tree and makes pure forests on upper mountainside nationwide in Korea. Quercus mongolica appears in the range of 100–1800 m in vertical positions, and it features strong drought resistance and thrives even on dry soil. In addition, Q. mongolica has sprouting and natural regeneration abilities, and is usually populated in mountain regions of high elevation (Korea Forest Service 1992).

The areas in which a set of tree-rings had been collected were classified by city and county units and then organized by utilizing the data for growth cores obtained at permanent sample plots established for the 5th NFI (Figure 1). In the light of statistical characteristics, only the data was reorganized for the regions with more than 30 tree-ring units estimated. As shown in Figure 1, the number of the regions in question is 67. It was found out that the samples regarding Q. mongolica were gathered relatively more from both Gangwon province and Gyeongbuk province with larger forest areas. A dendroclimatological analysis was conducted in the study to find out a correlation between tree-ring growth of forest trees, precipitation, and temperature. The base year was set as 1951 when the data obtained for temperature and precipitation can be well matched with those for tree-ring growth. Thus, the relationship between climate factors and tree-ring growth was confirmed by using the tree-ring chronology for the past 60 years. Overall, a database for the growth cores of Q. mongolica was built in this research by exploiting a total of 9487 samples (Table 1).

Table 1 describes summary statistics of data on growth core of Q. mongolica sampled from permanent sample plot by the 5th NFI. It gives specific information on the analysis results of core data which inform the number of core samples, the average age, average diameter at breast height (DBH), average height, and the average growth of sample trees. Also, it is needed to analyze the climate characteristics of the regions where the samples were collected to examine the relation between tree-ring growth and climate factors. For this purpose, after the regions where cores were collected were divided according to administrative
regional divisions, the average monthly temperature and precipitation for each region were calculated from the daily raster data of Korea Meteorological Administration using GIS, Arc GIS 101, and R 3.0.1.

### 2.2. Tree-ring growth analysis

Prior to analyzing data of tree-ring, cross-dating was conducted to prevent the incorrect results by missing data and error. First, graphing methodology was implemented such that the variations in tree-ring growth graphed and compared to figure out the period that tree-ring was generated based on the overall growth of forest tree (Park and Kong 2001). The qualities of cross-dating and tree-ring data were assured using COFECHA program provided by Dendrochronology Programs Library (DPL) of University of Arizona in USA.

To understand the impact of climate appeared in tree-ring, diverse factors affecting tree-ring growth should be considered comprehensively. Standardization is the process to remove biological growth tendency according to tree age, the variation of width of tree-ring by the competition for a long period of time, and low-frequency genetic variation in diameter growth.

Standardized curve for the width of each tree-ring series is obtained using statistical functions such as negative exponential curve or spline curve. And, the tree-ring

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**Figure 1.** Spatial distribution of data on growth core.

**Table 1.** Summary of tree-ring growth database of *Quercus mongolica*.

| Species            | No. of samples | Mean tree age (year) | Mean dbh (cm) | Mean tree height (m) | Growth amount of last 5 years (mm) |
|--------------------|----------------|----------------------|---------------|----------------------|----------------------------------|
| Quercus Mongolica  | 9,487          | 39                   | 16.4          | 10.9                 | 8.6                              |
growth estimates and the real growth ring width were compared and the index chronology of each core is written. Standardization index formulated on the process of standardizing is as in the below equation:

\[ I_t = \frac{W_t}{\bar{Y}_t} \tag{1} \]

\( I_t \) represents the standardized index of year \( t \) when the annual ring generated; \( W_t \) is the measured tree-ring growth; \( \bar{Y}_t \) is the tree-ring growth estimate by standardized curves; and \( t \) is the year that tree-ring was generated.

This study employed the double-detrending method considering Korean forest conditions of high crown density and keen competition to standardize core growth data. Using negative exponential curve, first-standardization was processed to remove biologic growing tendency by tree age; the second process was conducted to re-standardize the variation tendency by using spline curve of 60 years of response cycle and forest stand competition and disturbance. And, standardized chronology has autocorrelation that affects growth by carryover of nutrition produced prior to the year of growth (Cook 1985; Cook and Holmes 1986; Speer 2010). This research used autoregressive model of ASTAN program (Cook and Holmes 1986) and removed biological continuity, and residual chronology was written with autocorrelation removed.

To test normality of index chronology and to understand inherent climate sign degree and validity, mean, variance, kurtosis, skewness, mean sensitivity, autocorrelation coefficient, cross-correlation coefficient, signal to noise ratio (SNR), expressed population signal (EPS), etc. were computed. Based on the results, tree-ring chronology of \( Q. mongolica \) was developed for the 60 years from 1951 to 2010 when tree-ring growth core were collected.

### 2.3. Correlation analysis between climate factors and tree-ring growth

The last step for the current research, to build the model that estimate the tree-ring growth of \( Q. mongolica \) based on the data of temperature and precipitation, the study on the relation climate factors tree-ring growth was conducted. For this, tree-ring chronological information of \( Q. mongolica \) were used. Also, calculated are Growing Degree Days (GDD) and Standardized Precipitation Index (SPI) which represent the relation between growth and temperature and precipitation (Yim 1977; Lim 1998), and derived a formula to estimate the tree-ring growth. GDD is the measure of temperature for growth, it is used to identify the range of the plant distribution according to the regional temperature or to estimate the growing phase of the currently distributed plants, and calculated as in the below equation:

\[ GDD = \sum (T_i - T_b), \quad \text{when} \quad T_i - T_b > 0 \tag{2} \]

In Equation (2), \( T_i \) means the average daily temperature of the year; \( T_b \) is growth critical temperature which is 5°C in this study (Kira 1977; Chang et al. 2019). Also, Warm Index (WI) suggested by Yim (1977) and \( GDD = 30.838 \, WI \), the equation suggested by Lim (1998), the whole range of \( Q. mongolica \) and the optimal growth range were computed. The temperature effect on forest tree growth is determined by the parabola function of \( Q. mongolica \) and is calculate by Equation (3). The current research named the measure Temperature Efficiency Index (TEI), and the value is between zero and one:

\[ TEI = \frac{4(GDD - GDD_{min}) (GDD_{max} - GDD)}{(GDD_{max} - GDD_{min})^2} \tag{3} \]

\( GDD \) means the Growing Degree Days in a specific region; \( GDD_{min} \) is the minimum GDD for specific tree species; \( GDD_{max} \) is the maximum GDD for specific tree species for whole range. Standardized precipitation index (SPI), which represents the relation between precipitation and growth, is calculated SPI analysis program developed by Colorado Climate Center (2004). SPI takes value between –3 and 3, and the higher value means the better moisture condition. This study calculated Precipitation Efficiency Index (PEI) based on cumulative probability of SPI and evaluates the impact of precipitation on growth with it.

### 2.4. Formulating estimation equation for tree-ring growth by climate factors

This study used estimation model with independent variables including multiplied TEI and PEI, which are the measures of temperature and precipitation, and made square of the multiplication to develop the estimation equation for \( Q. mongolica \) (Table 2).

As above, when developing estimation equation with regression model, the validity of regression model is needed to be tested. A statistical test requires additional cost and effort, thus currently available estimation and test materials were alternatively used.

| Model no. | Model form |
|-----------|------------|
| 1         | \( GI = b_0 + b_1 (TEI \times PEI) \) |
| 2         | \( GI = b_0 + b_1 TEI + b_2 (TEI \times PEI) \) |
| 3         | \( GI = b_0 + b_1 TEI + b_2 (TEI \times PEI)^2 \) |
| 4         | \( GI = b_0 + b_1 TEI + b_2 (TEI \times PEI) + b_3 (TEI \times PEI)^3 \) |

\( GI \): tree-ring growth index; \( TEI \): temperature efficiency index; \( PEI \): precipitation efficiency index; \( b_0, b_1, b_2, b_3 \): regression coefficients to be estimated.

In such case, usually estimation material and test material should be 50–50% for statistical efficiency (Snee 1977). However, the research uses 70% of estimate material and 30% of test material that have not been used for regression equation estimate. Statistics used for test are estimation bias of the model, precision of the model, and mean square error type of measure that considers errors of these two (Shin 1990; Arbanatzis and Burkhart 1992). Thus, the current study made final tree-ring growth index using combined materials of annual estimation and test materials.
Table 3. Summary of basic statistics for tree-ring data of Quercus mongolica.

| No. of tree-ring | Mean tree-ring width (mm) | SD | Skewness | Kurtosis | Mean sensitivity | Auto correlation | Signal to noise ratio | Expressed population signal |
|-----------------|--------------------------|----|----------|----------|------------------|------------------|-----------------------|---------------------------|
| 8508            | 2.203                    | 0.998 | 1.052 | 5.026 | 0.308 | 0.401 | 5.886 | 0.739 |

3. Results and discussion

3.1. Estimating basic statistics and writing tree-ring chronology

Table 3 describes basic statistics on index chronology of Q. mongolica with low-frequency of non-climate factors removed using cross-dating and standardization based on tree-ring growth materials collected by 5th NFI.

Average measured tree-ring growth was 2.203 mm and its standard deviation was 0.998, which means Q. mongolica with higher age of stand has relatively small tree-ring growth. Skewness and kurtosis, the statistics to test normality, were 1.052 and 5.026, respectively. Average sensitivity, which tells deviation between adjacent tree-rings, was 0.308, and the autocorrelation, the index for biological continuity of tree-ring growth, was 0.401. From these results, it can be implicated that autocorrelation is mostly removed (Box et al. 1994). Also, using cross-correlation coefficient between forest trees, signal-to-noise ratio which indicates the signal strength for each period of chronology was estimated to be high, 5.886. And, signal strength was appeared to be 0.739, generally, if it is higher than 0.85, then local chronology has high confidence level (Arabatzis and Burkhart 1992; Shin et al. 1996). The EPS, which indicates the signal intensity for a population, is found to show its adequate reliability. It has been suggested that, if the EPS is above 0.85, index chronology is of significantly statistical confidence (Briffa 1984; Wigley et al. 1984; Briffa and Jones 1990). In two studies by the National Institute of Forest Science (2016) and Park and Kong (2001), the values of the EPS were 0.58 for Quercus acutissima and 0.75 for Taxus cuspidate, respectively, which ensures the use of the EPS as data for index chronology. However, this paper is different from the previous literature at stand-level, because a chronicle for the relatively wider area is produced after collecting data at city-province level based on growth amount of tree-ring obtained nationwide. Hence, it does not appear improper to utilize the EPS estimations as data for a tree-ring chronicle analysis nationwide by species, although the EPS estimations by species are relatively low in the study.

In this research, as national level data for tree-ring growth were used, it is different from previous research with stand level. Therefore, the analyzed values show signal strength for population and have strong confidence level. Also, tree-ring chronology for Q. mongolica was estimated for 60 years from 1951 to 2010. Table 4 describes its summary statistics.

Average tree-ring growth index estimate of Q. mongolica was 0.975, which was close to the expectation and showed small variance from 1. Considering climate factors that affect tree-ring growth, there have existed the slow but increasing tendency of average temperature distribution due to climate change. As a result, the variance and ups and downs on the tree-ring growth distribution was interpreted as the outcome of diverse climate factors including temperature and precipitation.

3.2. Correlation analysis of temperature and tree-ring growth

The overall range of the GDD for Q. mongolica was calculated to identify the correlation between temperature and growth before devising the tree-ring equation (Table 5).

In the aspect of GDD, the whole range of Q. mongolica, cold temperate tree species, is showed broad range of growth between 555.1 and 3423.0.

As mentioned above, GDD of 60 years from 1951 to 2010 was calculated yearly and the results are as in Figure 2.

GDD of Q. mongolica had remained within the range of optimum growth except the recent three years, but it has shown slowly increasing tendency since 1980. Therefore, not only it went out of the range of optimum growth as time went by, but also there exists the possibility that GDD of some regions are approaching to the margin of the whole range or can go out of it. Figure 3 shows the change in yearly TEI estimates using parabola function with yearly GDD values.

During the first half period observed, the TEI had been 0.8 or higher indicating a good temperature condition, but over the second half it had continued to fluctuate and was below 0.5 in 2010. In overall, Q. mongolica has significant yearly variation and showed gradually decreasing TEI, which informs that the temperature condition for growth has been becoming worse.

3.3. Correlation analysis between precipitation and tree-ring growth

Meteorological drought indicates the degree of dryness or dry conditions and is analyzed based on generally
Figure 2. Yearly changes of growing degree days.

Figure 3. Yearly changes of temperature efficiency index.

Figure 4. Yearly changes of standard precipitation index.
Standardized Precipitation Index (SPI) or Palmer Drought Severity Index (PDSI) (Guttman 1998). In this research, to study the moisture condition that affects tree-ring growth of *Q. mongolica*, yearly SPI was computed for the 60 years from 1951 to 2010 that tree-rings were generated (Figure 4).

The regional distribution of *Q. mongolica* shows high variations fluctuating around 0. Overall, the first half of the investigated 60 years shows bigger deviations in SPI than the second half.

SPI takes the value between −3 and 3 changed to standardized normal distribution from gamma cumulative probability distribution SPI (Mckee et al. 1993). This research used SPI and estimated Precipitation Efficiency Index (PEI) to analyze the impact of moisture condition on tree-ring growth (Figure 5).

The tendency of PEI shows repeating yearly fluctuations, and the second half of the 60 years have greater average PEI than the first half. This is the result that shows the moisture condition in recent 30 years has changed more significantly than the previous 30 years. Since moisture condition is deeply related to growth (Fritts 1976), it can be inferred that tree-ring growth would be more positively affected during the second 30 years. However, precipitation has huge variations year-to-year, so it should be noted that PEI of a year would have direct effect on growth in that specific year (Table 5).

### 3.4. Developing estimation equation tree-ring growth index by climate factors

A test is generally required for the utility of a finally proposed regression equation in the case of developing an equation based on a regression model. The applicability of the proposed equation to estimate tree-ring growth was evaluated in this paper based on the test data. The best model among four tree-ring growth equations was identified by the overall score of each one, after prioritizing them regarding their own performances based on three evaluation statistics for the four models (Table 6).

All the values of the MAD for the four models were below 0.08, which implies the capability of the equations to estimate tree-ring growth correctly. Similarly, the values of the SDD and the SED were relatively low in all models despite a slight difference among them. Therefore, the relationship between climate factors and tree-ring growth can be well explained by the proposed equation to estimate tree-ring growth in the study.

A final equation to estimate tree-ring growth was generated according to the integrated data in which both the test data and the fit ones were organized by year. It is found out that the model 1 was the best based on the maximum and minimum value of the evaluation statistics. The analysis result of the final equation is as follows (Table 7).

The coefficient of determination was 0.66 for the final equation developed in this paper to estimate tree-ring growth, thereby indicating a good power of explanation.
3.5. Comprehensive contemplation

The results obtained from this research can contribute as materials for forest stand dynamics to interpret the mechanism of forest ecosystem and for understanding the impact of climate change on forest ecosystem. If the limitations appeared during developing final estimation equation are resolved, it can be useful in making policies regarding afforestation or management in response to climate change.

First, regarding tree-ring growth and climate factors, forest tree growth is known to be greatly affected by temperature and moisture conditions. Previous researches studied the impact of seasonal temperature conditions on tree-ring growth (Vieira et al. 2009; Wigley et al. 1984; Huang et al. 2010), and precipitation among the climate factors is known to have the most significant impact on tree-ring growth (Zobel and Van Buijtenen 1989). Especially, in the case of short in moisture, tree-ring growth becomes slow (Larson 1963), 80% of this variation can be explained by precipitation (Zahner 1968).

This research developed the relation formula to estimate growth by the multiplication of independent variables of TEI and PEI calculated from temperature and precipitation. For future research, to be more precise on estimating relation between climate factors and ring-growth, Photosynthetically Active Radiation (PAR) would provide useful information. In some countries, not only GDD but also biophysical variables including Soil Moisture Index and Photosynthetically Active Emissions are included to analyze the impact of climate changes on the distribution of forest species and to give research support for policies (Sykes and Prentice 1996; Bourque and Hassan 2008; Bourque et al. 2010).

To add more precision to tree-ring growth estimate, which was developed in this research, comprehensive climate information is needed to explain the change in tree-ring growth from diverse aspects. For example, given a climate factor in the climate change scenario, it can be useful to estimate not only change in tree-ring growth because of climate change but also predicting following change in potential distribution.

4. Conclusion

Recent radical changes in global climate require Korea as well to establish the three policy responses in forestry. To minimize the damages from climate change, the recent change in climate should be reflected and the future impact of the change should be estimated. This process will give the foundation for the proper responses. To that end, it must be preceded to identify the relation between tree-ring growth and climate factors for the major tree species in Korea.

In the current research, dendroclimatological analysis was employed to enlighten the impact of climate factors on tree-ring growth with the subject of Q. mongolica, one of the mostly populated Korean native oak species. For this, the methods of cross-dating and standardization were used with information on tree-ring growth of Q. mongolica, and summary statistics and tree-ring growth were conducted. Also, the tree-ring growth estimate equation was developed with independent variable of climate factors to show the relation between tree-ring growth and climate factors. As a result, the multiplication of TEI and PEI as an independent variable was identified as the most reliable model.

The data segmentation is required before calculating the GDD to enhance the accuracy of the tree-ring equation for Q. mongolica developed in this paper. Since the NFI data used here were obtained nationwide, it is necessary to compute the GDD values for each group and to reflect them on the development of the equation after the cluster analysis for similar chronicles to be categorized. In the future, a statistical approach to compare tree-ring growth models seems a prerequisite for future research on a variety of tree species.

The results obtained from the current research can make contribution as impact evaluation material for the impacts of climate change on forest ecosystem and as support for forest policy. In addition, based on the statistical analysis between tree-ring growth and climate factors, it can be helpful to estimate the change in productivity due to climate change in the future.

Disclosure statement

No potential conflict of interest was reported by the authors.

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