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Original article

Evaluation of the effects of climatic and nonclimatic factors on the radial growth of Yezo spruce *(Picea jezoensis* Carr*)* by dendrochronological methods

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Abstract – The responses to climatic and nonclimatic factors of Yezo spruce (*Picea jezoensis* Carr) trees growing in a natural forest in Tomakomai, Hokkaido were analyzed by dendrochronological methods. The effects of climatic factors were examined by response function analysis. More than 70 % of the variance of ring-width and maximum-density indices was explained by climatic data from 1924 to 1965. The effect of nonclimatic factors on radial growth from 1966 to 1990 was analyzed by comparing actual indices with the estimated indices of ring width and maximum density calculated from the climatic data. Actual ring-width indices were lower than the estimated indices every year from 1969 to 1977. Actual maximum-density indices were lower than the estimated indices every year from 1971 to 1974. These results indicate that some nonclimatic factors might have affected both ring width and maximum density in the 1970s. (© Inra/Elsevier, Paris.)

***Picea jezoensis* Carr / ring width / maximum density / X-ray densitometry / response function analysis**

Résumé – Évaluation des effets des facteurs climatiques et non climatiques sur la croissance radiale de l'épinettes de yezo (*Picea jezoensis* Carr) par les méthodes dendrochronologiques. Les réponses aux facteurs climatiques et non climatiques de l'épinette de yezo (*Picea jezoensis* Carr) ont été étudiées dans des forêts naturelles du Tomakomai, dans l'île d'Hokkaido, par les méthodes dendrochronologiques. Les effets des facteurs climatiques ont été examinés par l'analyse de fonctions de réponse. Plus de 70 % de la variance des indices de lar-

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geur des cernes annuels et de densité maximale ont été expliqués par les données climatiques de 1924 à 1965. L'effet des facteurs non climatiques sur la croissance radiale de 1966 à 1990 a été étudié par la comparaison des indices actuels et des indices estimés de largeur des cernes annuels et de densité maximale, calculés d'après les données climatiques. Les indices actuels de largeur des cernes annuels pour les années 1969 à 1977 sont inférieurs aux indices estimés. Les indices actuels de densité maximale pour les annés 1971 à 1974 sont inférieurs aux indices estimés. Les résultats indiquent que des facteurs non climatiques affectent probablement les largeurs de cernes annuelles et la densité maximale au cours des années 1970. (© Inra/Elsevier, Paris.)

***Picea jezoensis* Carr / largeur de cerne annuel / densité maximale / densitométrie au rayon-X / fonctions de réponse**

1. INTRODUCTION

Climate is one of the most important factors that influences the variance of ring widths and wood densities [14]. Statistical methods have been widely used to assess relationships between climatic data and ring widths or wood densities [3–5, 10, 14, 28]. However, nonclimatic factors, such as air pollution, also affect the variance of ring widths and wood densities [12, 13, 19, 24, 26, 32]. Thus, ring widths and wood densities provide records of the effects of both climatic and nonclimatic factors on the radial growth of trees. It is possible to evaluate the effects of nonclimatic factors on the radial growth of trees in the past by comparing actual ring-width or wood-density indices with estimated indices calculated from the climatic data [6, 9].

Previous studies have shown that variations in ring widths, ring densities or maximum densities of Sakhalin spruce (*Picea glehnii* Mast) [23, 31], Japanese ash (*Fraxinus mandshurica* Rupr var *japonica* Maxim) [30] and Norway spruce (*Picea abies* Karst) [20] trees, which are growing in Hokkaido, are correlated with monthly temperature or precipitation. Yezo spruce (*Picea jezoensis* Carr) is one of the species that provides the longest tree-ring chronologies in Hokkaido, Japan. However, no dendrochronological approach to an understanding of the effects of climatic and nonclimatic factors on Yezo spruce has been reported. Our previous study [21, 22] revealed an abrupt decrease in ring width of Yezo spruce and Norway spruce trees in the Tomakomai forest, which is located near an industrial district, from the late 1960s to the mid 1970s. This decrease might have been due to nonclimatic factors, such as air pollution. However, the variance in ring widths due to nonclimatic factors has not been evaluated by statistical analysis. Thus, it is necessary to characterize the effects of nonclimatic factors on radial growth by a statistical elimination of the variance in ring widths or maximum densities that is due to climate.

In this study, the statistical relationships between climatic data and ring-width or maximum-density indices were investigated by response function analysis [14], which has been widely used to assess relationships between climatic data and ring widths or wood densities. We investigated the influence of nonclimatic stress factors by comparing actual ring-width or maximum-density indices with estimated indices calculated from the response functions that corresponded to the period prior to the onset of exposure to putative, nonclimatic stress factors.

2. MATERIALS AND METHODS

2.1. Study sites

We examined Yezo spruce trees at five sites in the natural forest at the National Forest of the

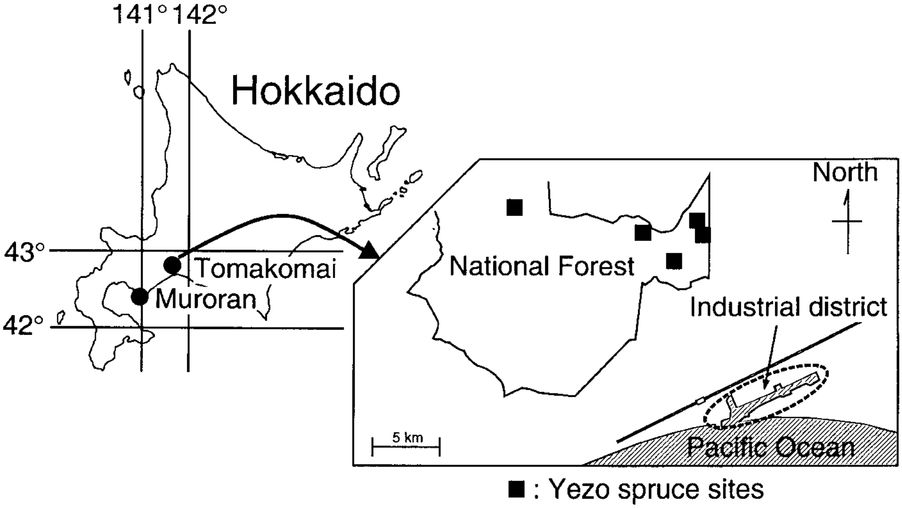

Figure 1. Map of the study area showing the locations of the natural stands of Yezo spruce and the industrial district.

Japan Forestry Agency (Tomakomai District Office, Tomakomai City, Hokkaido, Japan; *figure 1*). The cores used in this study were sampled from naturally growing Yezo spruce trees with little human treatment such as thinning and cutting. The topography and geology of the five sites are quite similar. Soils are composed of shallow A horizons, with infertile volcanogenous regosols. The Tomakomai Industrial District, where factories began operation in 1968, is located on the coast in Tomakomai city. The distance from the industrial district to the nearest site was approximately 10 km, and that to the most remote site was approximately 20 km. All sites were frequently exposed to winds from the industrial district from April to September.

2.2. Collection and treatment of samples

Fifteen Yezo spruce trees were selected from the five natural sites (*table I*). The trees were selected to represent similar site conditions throughout all sites to minimize any variability due to extraneous factors. Thirty cores in all were collected, with two cores taken from different directions in each tree at breast height. The cores were cut into 2-mm-thick strips, and then they were dried and irradiated with soft X-rays at 15 kV and 5 mA for 240 s from a distance of 1.5 m. The X-ray films were scanned with a microdensitometer (PDS-15; Konica, Japan). Ring-width and maximum-density series were obtained by application of the Tree-Ring Analysis Program (Y. Nobori, Faculty of Agriculture, Yamagata University, 1989).

2.3. Crossdating and standardization

All cores were crossdated visually by skeleton plot procedures [11, 29] and crossdating was later verified by a statistical method using the COFECHA program [18]. The COFECHA program tests each individual ring-width and maximum-density series against a master dating series (mean of all series) on the basis of correlation coefficients. Careful crossdating eliminates absent and false rings, as well as measurement errors, which reduce the statistical accuracy of site chronologies of ring width and maximum density. Twenty-four cores from 13 trees were successfully crossdated (*table I*). All 24 series are plotted in *figure 2*.

Table I. Statistical characteristics of ring-width and maximum-density series.

	Ring-width series	Maximum-density series
Sampled trees (cores)	15 (30)	15 (30)
Measurements		
Number of trees (cores) in the chronology	13 (24)	13 (24)
Mean width (mm) or density (g·cm^{-3})	1.88	0.87
Mean sensitivity	0.25	0.10
Mean first-order autocorrelation	0.72	0.51
Residual chronology		
Span of the chronology	1828 – 1993	1828 – 1993
Fitting curves for detrending	70-year spline	Horizontal line
Standard deviation	0.18	0.05
Mean correlation between trees*	0.22	0.21
Signal to noise ratio*	2.85	2.69
Variance in first eigenvector (%)*	30.03	27.86

* Calculated for the common interval (1906 – 1993).

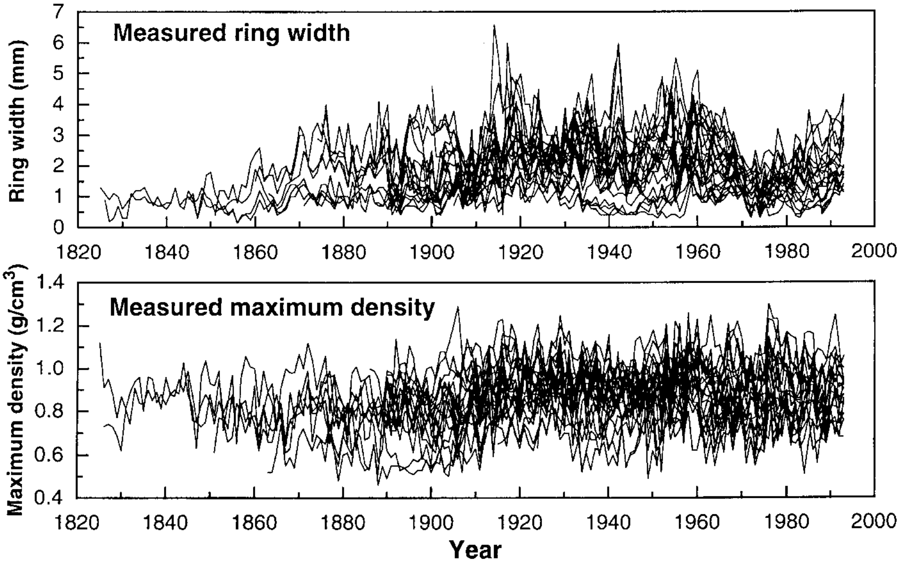

Figure 2. Measured ring-width and maximum-density series of Yezo spruce cores that were used in the chronologies.

Crossdated ring-width and maximum-density series were standardized to eliminate individual growth trends, such as age-related declines and low-frequency variance due to natural disturbance. The ring-width and maximum-density series were standardized by first fitting a trend line and then dividing the measured data by the corresponding fitted data for the given year. A stiff spline-function [8], passing 50 % of the variance of the measured series at frequencies greater than 70 years, was adapted to the ring-width series. A horizontal line that crossed the mean maximum-density values of each series was adapted to the maximum-density series. Remaining autocorrelations in the ring-width and maximum-density series that might adversely affect significance tests in the response function analysis were removed by pooled autoregressive modeling [7]. Thus, the common variance in ring-width and maximum-density series of all cores that was due to climatic and regional nonclimatic factors was extracted by this standardization procedure. Standardization of the ring-width and maximum-density series was performed using the ARSTAN program (R.L. Holmes, Laboratory of Tree-Ring Research, University of Arizona, 1996). Standardized individual ring-width and maximum-density indices were averaged using the arithmetic mean to establish the master chronologies of Yezo spruce at Tomakomai from 1828 to 1993 (*figure 3*). Statistics for the master chronologies of ring-width and maximum-density indices are presented in *table I*.

2.4. Response function analysis

The growth–climate relationship for the period from 1924 to 1965 ($n = 42$ years) was calculated by response function analysis [2, 14, 17]. Response function analysis is a multiple-regression technique that uses principal components of monthly climatic data as predictors of ring-width and maximum-density indices (the predictands). The principal components of monthly climatic data were originally used to eliminate the intercorrelations between the predictor variables [14]. The calculation of response functions was performed with the PRECON program (H.C. Fritts, Dendro-Power, Tucson, Arizona, 1996) [15]. Simple correlation was also calculated to confirm the results of response functions since response

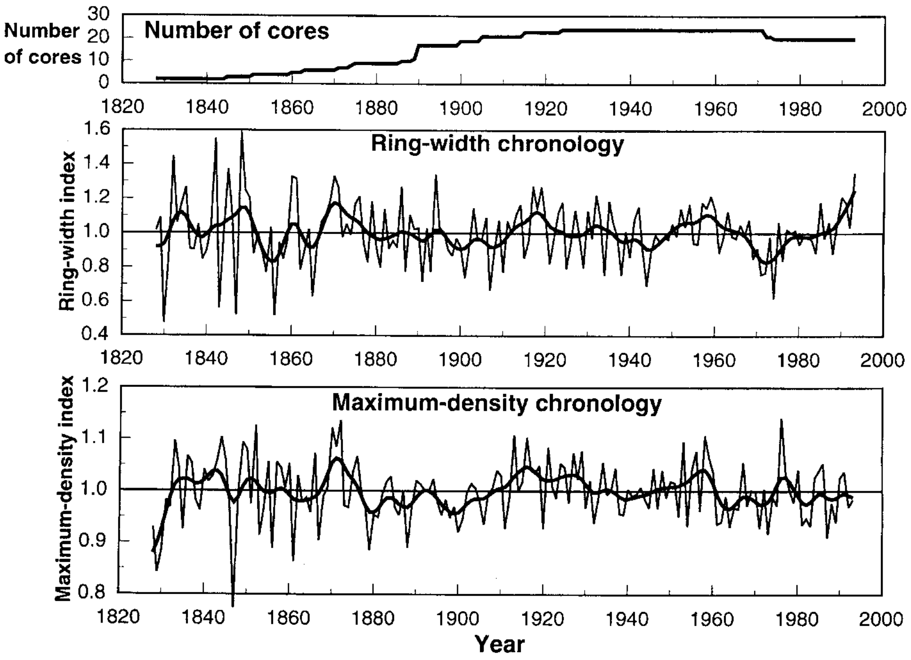

Figure 3. Master chronologies for ring width and maximum density of Yezo spruce at Tomakomai, Hokkaido. The upper curve shows the number of cores used in the chronologies. The bold line is a 10-year smoothing spline.

functions are sensitive to various parameters, such as the confidence level, number of eigenvectors and climatic variables [1].

Monthly mean temperatures and monthly total precipitation at the Muroran Meteorological Observatory of the Japan Meteorological Agency (Sapporo District Meteorological Observatory, 1991), located approximately 60 km southwest of Tomakomai city, were used for response function analysis. We used the data from Muroran because of the longer weather records at Muroran (1924 – 1990) as compared to those at the Tomakomai Weather Station (located approximately 10 km south of the study sites). Monthly climatic data at Muroran were strongly correlated ($R \geq 0.6$, $P \leq 0.0001$) with those at Tomakomai.

Estimated ring-width and maximum-density indices were calculated by substituting climatic data into the regression equations of the response functions. The response functions used for the calibration of estimated indices were calculated for the period from 1924 to 1965 (calibration period), namely for the period before the factories at the industrial district became operational. Estimated ring-width and maximum-density indices were compared with the actual ring-width and maximum-density indices for the period from 1966 to 1990 (verification period). Nonclimatic variations in ring-width and maximum-density indices were investigated by comparing the actual and estimated indices.

3. RESULTS AND DISCUSSION

3.1. Response function analysis

The results of response function analysis showed that 78 % of the variance in ring-width indices could be explained by climate (*figure 4*). Ring width exhibited a negative response to temperature in the previous September, which was significant with respect to both the response function and simple correlation. Ring width also exhibited a significant positive response to temperature in the current April and a negative response to temperature in the current June.

Seventy-four percent of the variance in maximum-density indices could be explained by climate (*figure 4*). Maximum density exhibited a significant positive response to temperature in the previous July. In addition, the maximum density exhibited a significant positive response to precipitation in the previous October.

Our results show the influences of temperature in the previous autumn and current spring on ring width of Yezo spruce growing at Tomakomai. Ring width of Sakhalin spruce growing close to our experiment site shows a similar positive response to temperature in the current April [23]. However, the response of ring width to other climatic data differed between Yezo spruce and Sakhalin spruce. On the other hand, both maximum density of Sakhalin spruce growing in northern Hokkaido [31] and latewood density of Sakhalin spruce growing at Tomakomai [23] show a similar positive response to temperature from the current August to September. However, this response to temperature in the current summer was not evident in the maximum density of Yezo spruce growing at Tomakomai. Therefore, the radial growth of Yezo spruce and Sakhalin spruce, which are growing at Tomakomai, may respond differently to seasonal climate. Previous studies have also indicated that dissimilarities in growth responses to climate are related to species differences rather than to site differences [16, 25].

3.2. Comparison between actual and estimated indices

The influence of nonclimatic factors from 1966 to 1990 was investigated by comparing the actual indices and the estimated indices for both ring width and maximum density. *Figure 5* shows the actual indices and estimated indices for ring width and maximum density. Shaded areas indicate actual indices that were lower than estimated indices. During the

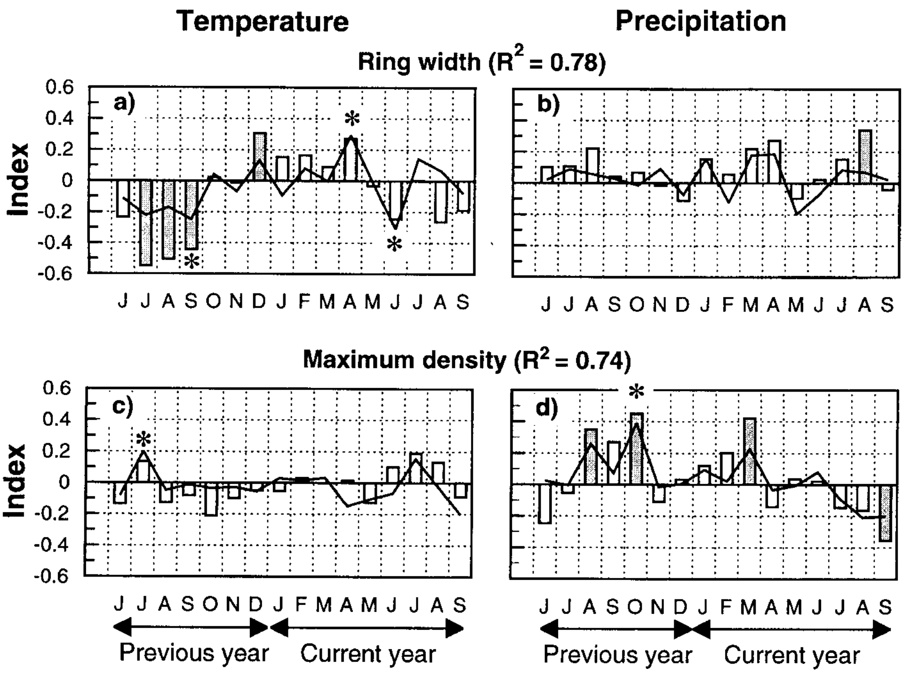

Figure 4. Response functions (lines) and simple correlation coefficients (columns) of ring-width (a, b) and maximum-density (c, d) indices of Yezo spruce for the mean temperature and total precipitation from the previous June to the current September (1924 – 1965). R^2 indicates the variance explained by climatic variables. Asterisks and shaded columns indicate the variables that are significant at the 5 % level.

verification period, both actual ring-width indices and maximum-density indices were very low as compared to estimated indices. Actual ring-width indices were lower than estimated indices from 1966 to 1967, from 1969 to 1977, from 1981 to 1984 and from 1988 to 1989. Actual maximum-density indices were lower than the estimated indices in 1966, in 1969, from 1971 to 1974, from 1978 to 1979, from 1981 to 1982, in 1987 and in 1989. In particular, actual ring-width indices were lower than estimated every year from 1969 to 1977 and actual maximum-density indices were lower than estimated every year from 1971 to 1974. The climatic data show that the August precipitation in 1981 was extremely high. This climatic event might have caused the overestimation of ring-width and maximum-density indices from 1981 to 1982. However, climatic events that might reduce the radial growth of Yezo spruce trees in the 1970s are not shown in the climatic data. These results indicate that nonclimatic stress factors reduced the radial growth of Yezo spruce trees in the 1970s.

Our previous study [22] revealed an abrupt reduction in ring width of Yezo spruce from 1969 to 1979, with an increasing extent of reduction from 1972 onwards. Norway spruce trees growing in the same region also showed an extreme reduction in ring width around 1970. The

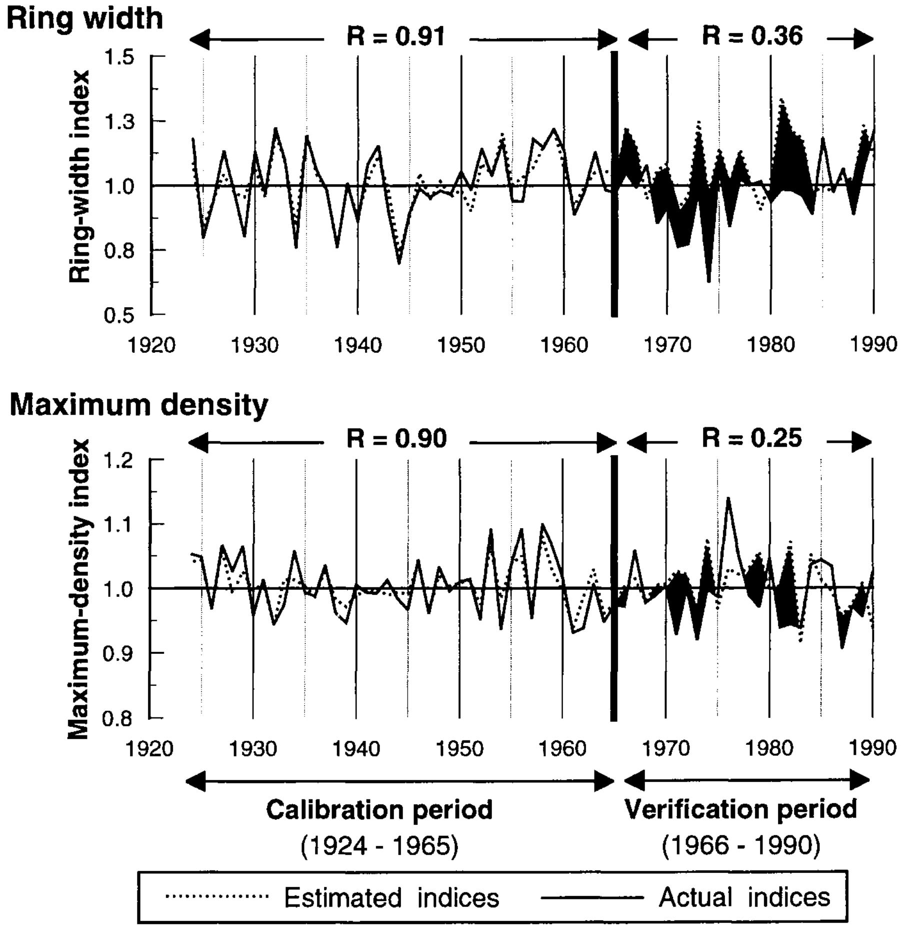

Figure 5. Plots of the actual and estimated indices of ring width and maximum density of Yezo spruce, based on response functions. The calibration period extends from 1924 to 1965 and the verification period extends from 1966 to 1990. The shaded areas shows the periods when the actual tree-ring or maximum-density indices were lower than the estimated indices. Correlation coefficients (R) were calculated from the actual and estimated indices for the calibration period and the verification period.

extent of this growth reduction was related to the distance from the industrial district [21, 22]. These reductions in ring width in Yezo spruce and Norway spruce in the 1970s reflect the records of industrial activity near the forest. During this period, neither the meteorological data nor the forest management record shows the evidence of typhoon effects, insect pests or tree disease that might reduce the radial growth of the trees. Therefore, we postulated that air pollution from the industrial district might have caused the reductions in ring width of Yezo spruce and Norway spruce since 1969 [22]. The present results of our statistical analysis support the hypothesis that nonclimatic stress factors, such as air pollution, became important in the 1970s.

Response function analysis revealed that ring-width and maximum-density indices of Yezo spruce exhibited significant responses to climatic data. We were also able to estimate the effects of nonclimatic stress factors, such as air pollution, by comparing actual and estimated indices of ring width or maximum density. Thus, it is apparently possible to estimate the effects of nonclimatic stress factors on the radial growth by applying the statistical techniques that are used in dendrochronology. This method might be useful to assess the effects of nonclimatic stress factors on tree growth in the past when historical evidence of a reduction in tree growth is not available.

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