Estimation of Growth Rates Based on Tree-ring Analysis of Cryptomeria japonica on Yakushima Island, Japan

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ABSTRACT

Old-growth Cryptomeria japonica forest on Yakushima Island has been affected by large-scale logging activities that began approximately 350 years ago and continued over 300 years. Forests on the island currently consist of 200-300 year-old, regenerated Cr. japonica, and 400- to over 1000 year-old Cr. japonica that survived logging activities. The objective of the present study was to understand the long-term growth patterns of Cr. japonica on Yakushima Island over the last several hundred years. Tree-ring analysis using samples obtained from 28 Cr. japonica individuals that regenerated subsequent to the inaugural year of logging was employed to develop an understanding of long-term growth patterns in regenerated Cr. japonica. Growth rate of basal area increment (BAI) was calculated from tree-ring series and results indicated diversity among individual diameter growth curves. BAI growth rate increased with age until approximately 110 years, a period of increase longer than that observed in Cr. japonica in an artificial forest. BAI growth rate across diameter classes showed an initial rapid increase until 30 cm, followed by a slow increase between 30-50 cm before plateau. Growth patterns beyond 70 cm could not be determined as sample size were inadequate. Comparison of these results with monitoring results suggested that growth rates were higher 100-150 years ago than they were during the last 30 years, which further indicated that gap formation resulting from large-scale logging activity may have had a positive impact on growth rate in Cr. japonica.

Keywords: basal area increment, dendroecology, natural forest, old-growth

INTRODUCTION

The majority of Yakushima Island, southern Japan has been designated a National Park in 1964, Forest Ecosystem Reserve in 1992 and was declared a World Heritage Site in 1993 due to the presence of an anomalous forest ecosystem that is rich in plant diversity. At altitudes of between 700 and 1800 m, the vegetation on the island consists primarily of a mixed conifer-broadleaved forest dominated by old-growth Cryptomeria japonica (L.f.) D. Don (Miyawaki, 1980), which can reach ages of over 1000 years (Suzuki and Tsukahara, 1987). These old-growth Cr. japonica forests have been affected by large-scale logging activities that occurred over a 300-year period beginning in 1642 (Hamaoka, 1933; Kakinoki, 1954; Yoshida and Imanaga, 1990). Gap formations created by logging activities led to regeneration of Cr. japonica (Suzuki, 1997; Yoshida and Imanaga, 1990). Current forest cover on the island consists of 200-300 year-old, regenerated Cr. japonica, as well as 400- to over 1000 year-old Cr. japonica that survived logging activity (Kyushu Regional Forest Office/Yakushima Environment Conservation Center, 1996; Yoshida and Imanaga, 1990). Conservation of a forest such as this requires an understanding of long-term growth in Cr. japonica.

Previous studies regarding growth of Cr. japonica on Yakushima Island have monitored growth since 1973 (Yoshida and Imanaga, 1990; Takashima, 2009), while others have examined growth or dynamics of Cr. japonica over a span of 10-20 years (Kimura, 1994; Takyu et al., 2005); however, 10-30 years might not be long enough to understand long-term growth pattern of this species, which can live for over 1000 years. Furthermore, previous research using stem analysis of Cr. japonica on Yakushima Island employed only 3 sample trees aged 45-149 years (Hamaoka, 1933), and no previous studies have examined a large enough sample of individuals covering a range of ages that spans hundreds of years. The long-term growth pattern of Cr. japonica over the course of several hundred years remains poorly understood.
Using variations in tree-ring width, it is possible to extrapolate information regarding growth rate. In fact, recent studies have used tree-ring widths to identify and quantify growth trends (Cherubini et al., 1998; Ota et al., 2007). The time span of monitoring data is limited to only several decades; however, tree-ring analysis using sample cores enables much more long-term growth patterns to be understood. The objective of the present study was to understand long-term growth pattern of *C. japonica* on Yakushima Island over the last several hundred years. Regenerated *C. japonica*, which ranged in age from about 200-300 years, were examined in order to understand the long-term growth pattern within these individuals so that information pertinent to the sustainable management of *C. japonica* forest on Yakushima Island could be obtained. In the present study, sample cores were collected from *C. japonica* individuals located within four permanent study plots on Yakushima Island in order to provide data for use in the investigation of long-term growth patterns.

**MATERIALS AND METHODS**

**Study area**

Yakushima Island is located at 30° 20' N latitude and 130° 31' E longitude, approximately 60 km off the southern end of Kyushu, southern Japan and has an area of 504.9 km² (Fig. 1). The shape of the island is nearly circular and the boundary length is approximately 130 km. Mt. Miyanoura, located at the center of the island, reaches an altitude of 1936 m and forms the island’s highest point. Precipitation levels on Yakushima Island are some of the highest in the world and range from 2400-5000 mm year⁻¹ on the coast and 5000-7400 mm year⁻¹ within mountainous areas (Takahara and Matsumoto, 2002). This heavy rainfall is caused by ascending air currents under the influence of the warm Pacific current as well as frequent typhoons (Takahara and Matsumoto, 2002). The presence of high precipitation and mild climatic conditions has lead to the development of rich forests, with approximately 90% of the island covered by forest. A difference in elevation of approximately 2000 m exists between the lowlands and the mountain peaks, and within this range can be found subtropical and temperate rainforests, mixed conifer-broadleaved forest containing *C. japonica*, and evergreen dwarf bamboo grassland surrounding the mountain peaks (Kyushu Regional Forest Office/Yaku-shima Environment Conservation Center, 1996).

During 1973-1974, five permanent plots were established by the Kumamoto Regional Forest Office, four of which were used as study sites in the present study (Hanayama plot (HP), Kohanayama plot (KP), Futaridake-no-komichi plot (FP) and Shiratani plot (SP)) (Fig. 1). Study plots were covered in natural, uneven-aged, mixed conifer-broadleaved forest dominated by *C. japonica* (Takashima, 2009). All living trees with diameters at breast height (DBH, approximately 1.2 m) ≥ 4 cm were measured three times at intervals of 10-19 years within each study plot (Table 1). Study plots were located between 850 and 1,250 m above sea level, with SP having the lowest elevation of the four plots, and SP had an area of 0.8 ha (100 m × 80 m), while the other plots had areas of 1.0 ha (100 m × 100 m) (Table 1). All study plots have previously been affected by logging activities (Yoshida and Imanaga, 1990). Growing stock within SP was less than in the other plots (Table 1), which was possibly the result of more recent human activity within the area and was suggested by a record of the mother tree method having been implemented during 1897 within a neighboring section of forest, after which regenerations were rare (Kumamoto Regional Forest Office, 1982). All plots, however, contained almost the same number of *C. japonica* stumps, and the forest structure of these plots may have been similar prior to large-scale logging activities.

![Fig. 1 Location of study plots on Yakushima Island.](image-url)

| Plot name | Altitude (m) | Area (ha) | Monitoring year | Attributes of *C. japonica* at the 3rd monitoring year | Attributes of sample tree |
|-----------|-------------|-----------|----------------|-------------------------------------------------------|--------------------------|
|           |             |           | 1st | 2nd | 3rd | No. | (ha⁻¹) | Mean DBH (cm) | No. (plot⁻¹) | Mean DBH (cm) | Mean ring-width (mm) | Range of estimated age (year) |
| HP        | 1250        | 1.0       | 1974 | 1992 | 2003 | 192 | 67.5 | 10 | 66.3 | 1.17 | 206-302 |
| KP        | 1100        | 1.0       | 1973 | 1988 | 1998 | 195 | 70.6 | 4 | 80.6 | 1.81 | 186-258 |
| FP        | 1050        | 1.0       | 1973 | 1991 | 2002 | 123 | 57.5 | 7 | 57.6 | 1.37 | 170-214 |
| SP        | 850         | 0.8       | 1974 | 1993 | 2004 | 26 | 75.3 | 7 | 61.6 | 1.83 | 100-276 |

DBH: diameter at breast height
Sampling and Cross-dating Trees

Within study plots, DBH distributions obtained from the second measurement interval were normal for Cryptomeria japonica individuals ≤ 100-110 cm, which represented trees that regenerated at around the same time as the gaps were made by large-scale logging activities. DBH distributions were uniform for individuals with DBH greater than 120 cm, which represented old-aged trees that had not been targeted by logging operations (Yoshida and Imanaga, 1990). After the third measurement was conducted, certain trees whose DBH class had been 110 cm during the second measurement interval had grown to a DBH of 120 cm. In the present study, sample cores from trees with DBH ≤ 120 cm were used (Fig. 2).

Permission was obtained from Kagoshima Prefecture authorities, the Forestry Agency, and the Ministry of the Environment, Japan for the collection of sample cores within permanent study plots located in protected areas. During 2005-2008, sample trees more than 30 cm of DBH classes were randomly selected in each plot and one or two samples were cored using an increment borer (80 cm) and diameter of the coring height was measured; at the time of sample tree selection, care was taken to obtain cores from each of the DBH classes (Fig. 2).

Sampled cores were glued onto wooden mounts and sanded until individual tree-rings were clearly visible. Width of each tree-ring was measured on a TA Unislide Velmex...
machine (0.001 mm precision; Velmex Inc.). Dating of raw tree-ring widths and associated measurement errors were evaluated using the COFECHA program (Holmes, 1983). When there were two cores from the same tree, the mean tree ring width of the two cores was used to create a single ring-width series for each tree. Cores were taken from 68 trees, but only 28 trees were analyzed as certain cores were broken or too short for age estimation. The reason for the high proportion of broken cores is unclear, but may be due to the frequent typhoons in the area that shake big trees and may cause them to break inside.

Age Estimation

Sample cores often lacked pith, the chronological center. Missing parts of tree-ring radius were estimated using the two methods outlined below.

1. Measuring arc of inner tree-ring
   When sample cores passed close enough to the chronological center that arcs of the inner rings were visible, missing radius lengths were estimated using the equation (Duncan, 1989):
   \[ r = \frac{L^2}{8h} + \frac{h}{2} \]  
   where \( r \) is the length of the missing radius, \( L \) is the length of an arc, \( h \) is the height of an arc. Estimated lengths of missing radii were divided by the average tree-ring width of the innermost 20 rings in order to obtain an estimate of age. When the length of the missing radius appears to be within 50 mm, then the mean absolute error is ±21 years of age (Duncan, 1989). In this study, the mean length of the missing radius was 30.7 mm.

2. Age-diameter model
   When sample cores had no visible inner ring arcs, the missing lengths, which are calculated by subtracting the length of sample core from the radius at the diameter of the coring height, and then dividing by the average tree-ring width of the 20 innermost rings to obtain an estimate of age (Norton et al., 1987). When there were two cores from the same tree, this age-diameter model was used to calculate tree age using a mean ring-width series. The mean errors are estimated to be less than ±15% where the core length represents 80% of the radius (Norton et al., 1987). For this study, the mean core length was 80.3%.

   Additionally, cores were not taken at ground level; rather, most were taken at 1.2 meters above ground level. The exact age of sampled trees was estimated based on stem analysis of Cr. japonica on Yakushima Island, which consisted of estimating the relationship between tree height and tree-ring number (Togo, 1981).

Growth-rate Calculation

Basal area increment (BAI) was used to estimate growth rate, since growth rates for trees of different ages and sizes should be based on ring-area series, which are less dependent on stem size or age than ring-width series and provide an accurate quantification of wood production (Phipps, 1979; LeBlanc, 1990). BAI is calculated from raw ring-widths as follows:

\[ \text{BAI} = \pi \left( D_t^2 / 2 \right) - \pi \left( D_{t-1}^2 / 2 \right) \]  

where \( D_t \) is the diameter of the coring height for year \( t \). Diameter of the coring height for year \( t \) was calculated using the diameter value at coring height (without bark) collected in the field or from monitoring results. BAI results were grouped into each age class and diameter class, and Tukey's parametric multiple comparison procedures were applied to test whether there are significant differences in pairs of different classes.

We compared recent growth rate obtained from 30-year monitoring data with past growth rate calculated from tree-ring data that was dated from 1850 to 1900, because sample size was less than 20 individuals that have tree rings before 1850. For this comparison, BAI data were grouped into for each of diameter classes, and nonparametric Wilcoxon–Mann–Whitney test was used to test whether there are differences in BAI between recent and past growth rates each diameter class. We did not analyze data from the diameter classes more than 70cm because sample size was very small (less than 2) in these classes for tree-ring data.

RESULTS

Diameter of the coring height of sampled trees was calculated for each year based on tree-ring series (Fig. 3), and age-diameter relationships were inferred from estimated age and tree-ring widths for trees of different age (Fig. 4). For
trees sampled in the present study, diameter classes ranged from 30-120 cm, age classes ranged from 100-300 years, and individual diameter growth curves showed high diversity (Figs. 3 and 4). Standard deviation of tree-ring widths and BAI values also showed a wide range (Figs. 5 and 6), which suggested a high degree of variability between individual growth patterns.

Tree-ring widths of 28 individuals from four study plots were also grouped into 10-year age classes as well as 10 cm diameter classes and averaged for presentation of the results (Fig. 5). Tree-ring growth rates increased and peaked within the 20-50 year age class and the 10 cm diameter class, after which growth rate decreased gradually (Fig. 5). Mean of tree-ring width was greater than 1 mm in individuals below the 160 year age class (Fig. 5(A)).

BAI values of 28 individuals from four study plots were grouped into 10-year age classes as well as 10 cm diameter classes and averaged (Fig. 6). Results of multiple comparisons showed significant differences in BAI growth rate within individuals in age classes below 50 years and diameter classes below 30 cm. In fact, BAI growth rate increased rapidly up until the 50 year age class and the 30 cm diameter class before it reached a ceiling; however, a slow increase in BAI growth rate was observed from the 50 year to the 110 year age class before it gradually decreased (Fig. 6(A)). Furthermore, a slow increase in BAI growth rate from the 50 year age class to the 50 cm diameter class was observed before it reached a ceiling and subsequently showed an increase between the 70 and 80 cm diameter classes; however, the observation of this secondary increase could have been the result of an insufficient number of sample size more than 70 diameter classes (Fig. 6(B)).

Comparing recent 30-year monitoring data and tree-ring analysis from 1850-1900 showed significant differences in mean BAI growth rate in all diameter classes from 10 to 60 cm; the past growth was consistently larger that the recent one (Fig. 7).

**DISCUSSION**

The present study attempted to clarify the long-term growth patterns of *C. japonica* on Yakushima Island over last several hundred years using tree-ring analysis. According to the results of tree-ring analysis, tree-ring width increased until the 20-50 year age class and the 10 cm diameter class, after which point growth rate gradually decreased (Fig. 5). The decline observed within this age class could be typical of tree-ring width growth patterns, which are wide rings near the pith and narrower rings toward outside (Phipps, 1979). *C. japonica* on Yakushima Island are known for their slow growth, and it has been reported that tree-ring width was less than 1 mm (Numata, 1986); however, mean of tree-ring widths of sample trees less than 160 years in age observed in the present study were greater than 1 mm (Fig. 6(A)).

**Fig. 5** Growth rate of tree-ring width for each of age (A) and diameter classes (B). The error bar indicates the standard deviation.

**Fig. 6** Growth rate of basal area increment for each of age (A) and diameter classes (B). The error bar indicates the standard deviation.

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Generally, growth rate ($m^3$ year$^{-1}$) culmination of artificial Cr. japonica forests occurs after approximately 15-40 years (Otomo, 1983); however, this growth pattern has not been well studied in other natural Cr. japonica forests in Japan. The present study demonstrated that BAI growth rate increased rapidly in trees under the 50 year age class and displayed a subsequent gradual rise until it peaked within the 110 year age class, after which point it gradually decreased (Fig. 6(A)). Therefore, the observed growth rate peak in age of the natural Cr. japonica forest on Yakushima Island was significantly greater than that of artificial Cr. japonica forests. However, individual variation in tree growth patterns is a common characteristic of natural forests, because the growing conditions of each individual tree can differ (Kimura, 1994). Wide standard deviations of tree-ring widths and BAI values might also be a characteristic of natural forests (Figs. 5 and 6).

BAI growth rate showed an initial increase under the 30 cm diameter class, a slow increase within the 30 to 50 cm diameter class, and peaked within the 70-80 cm diameter class before increasing again; however, results from more than 70 cm diameter class might have skewed results due to an inadequate sample size (Fig. 6(B)). Typically, in order to make a mean tree-ring chronology, 20-30 trees are required (Cook and Kairiukstis, 1990); however, in the present study, the sample size for the 70 cm diameter class was below 15 while the sample size for the 80 cm diameter class was below 10. At least growth rate increased to the 50 cm diameter class, after which point BAI growth rate was still high (approximately 25 cm$^2$ year$^{-1}$).

Monitoring results obtained over the last 30 years have shown that the mean BAI growth rate of Cr. japonica trees in all diameter classes from 10 to 60 cm consistently had significant differences comparing to mean BAI growth rate of tree-ring analysis from 1850-1900 (Fig. 7). These results indicated that growth over the last 30 years was much slower than growth that occurred several hundred years ago, suggesting that growth conditions of Cr. japonica were better in the past. One possible explanation could be that large-scale logging activities that occurred about 350 years ago and continued about 300 years encouraged growth by providing better light and spatial conditions. There may be other factors causing growth differences over a few hundred years; differences in microclimate conditions and tree-age might be such factors.

In conclusion, the results of the present study emphasized that BAI growth of Cr. japonica on Yakushima Island showed an initial increase and peaked in the 110 year age class and the 50 cm diameter class, while large diameter trees maintained high growth rates. Mean of tree-ring width was greater than 1 mm within individuals below the 160 year age class and growth rate was higher 100-150 years ago than it was within the last 30 years. These results clarified BAI growth patterns of regenerated Cr. japonica after large-scale logging activities; past growth was much better than recent one and it might have been affected mainly by logging activities. This suggests that human or natural disturbances may be very important to encourage growth of Cr. japonica over long-term forest management strategy for old-growth Cr. japonica forest on Yakushima Island or other regions. Further research should focus on using tree-ring data of stumps and fallen logs in order to understand growth patterns prior to extensive logging.

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LITERATURE CITED

Čerubini, P., Dobbertin, M. and Innes, J. (1998) Potential sampling bias in long-term forest growth trends reconstructed from tree rings: a case study from the Italian Alps. For. Ecol. Manage. 109: 103-118
Cook, E.R. and Kairiukstis, L.A. (1990) Methods of dendrochronology: applications in the environmental sciences. Kluwer Acad. Publishers, Dordrecht. 397pp
Duncan, R.P. (1989) An evaluation of errors in tree age estimates based on increment cores in kahikatea (Dacrycarpus dacrydioides). New Zeal. Nat. Sci. 16: 31-37
Hamaoka, T. (1933) Regeneration of Cryptomeria japonica in natural forest of Yakushima Island*. J. Jpn. For. Soc. 15: 150-162 (in Japanese)
Holmes, R.L. (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. 43: 69-78
Kakinoki, T. (1954) A study of Cryptomeria japonica on Yakushima Island*.* Forestry Office of Kagoshima, Kagoshima. 20-44 (in...
Japanese

Kimura, M. (1994) Changes over 10 years in the mixed forest of evergreen conifers and broad-leafed trees in the Yakushima Wilderness Area, Yakushima Island, Japan. In: Nature Conservation Society of Japan (ed) Long term ecological studies in the Yakushima wilderness area and its surrounding areas. Nature Conservation Society of Japan, Tokyo. 21-41 (in Japanese with English summary)

Kumamoto Regional Forest Office (1982) Forest management of the national forest on Yaku-shima Island*. Kumamoto Regional Forest Office, Kumamoto. 140pp (in Japanese)

Kyushu Regional Forest Office/Yaku-shima Environment Conservstion Centre (1996) Forest of Yaku-shima*. Shukosya Co., Ltd., Fukuoka. 89pp (in Japanese)

Leblanc, D.C. (1990) Relationships between breast-height and whole-stem growth indices for red spruce on whiteface mountain, New York. Can. J. For. Res. 20: 1399-1407

Miyawaki, A. (1980) Vegetation of Japan Yakushima*. Shibundo, Tokyo. 376pp (in Japanese)

Norton, D.A., Palmer, J.G. and Ogden, J. (1987) Dendroecological studies in New Zealand 1. an evaluation of tree age estimates based on increment cores. New Zeal. J. Bot. 25: 373-383

Numata, M. (1986) The natural characteristics of Yaku Island. Mem. Shukutoku Univ. 20: 15-20

Ota, T., Masaki, T., Sugita, H. and Kanazashi, T. (2007) Analyzing annual rings to evaluate past growth of natural Cryptomeria japonica trees in Sado Forest Reserve, Akita Prefecture, northeastern Japan. J. Jpn. For. Soc. 89: 383-389 (in Japanese with English summary)

Otomo, E. (1983) Growth of cedar forest and silvicultural operation system*. In: All about the Japanese cedar*. National Forestry Extension Association in Japan, Tokyo. 508-522 (in Japanese)

Phipps, R.L. (1979) Simulation of wetlands forest vegetation dynamics. Ecol. Model. 7: 257-288

Suzuki, E. (1997) The Dynamics of old Cryptomeria japonica Forest on Yakushima Island. Tropics 6: 421-428

Suzuki, E. and Tsukahara, J. (1987) Age structure and regeneration of old growth Cryptomeria japonica forests on Yakushima Island. Bot. Mag. Tokyo 100: 225-241

Takahara, H. and Matsumoto, J. (2002) Climatological study of precipitation distribution in Yaku-shima Island, southern Japan. J. Geogr. 111: 726-746 (in Japanese with English summary)

Takashima, A. (2009) Stand structure and dynamics of old-growth Cryptomeria japonica forest on Yakushima Island. PhD Thesis, Kyushu University. 108 pp

Takkyu, M., Motohashi, H., Imai, N., Ikawa, K., Iyobe T. and Nakamura, Y. (2005) Community dynamics of Cryptomeria japonica forest during 20 years in the Yakushima Wildness Area, Yakushima Island, southern Japan. Annual report of Pro Natura Fund. 14: 51-60 (in Japanese with English summary)

Togo, S. (1981) Forest structure of natural Cryptomeria japonica forest on Yaku-shima Island*. Bachelor Thesis, Kagoshima University. 45pp (in Japanese)

Yoshida, S. and Imanaga, M. (1990) The stand structure and the growth of sugi (Cryptomeria japonica D. Don) natural forests on Yakushima. J. Jpn. For. Soc. 72: 131-138 (in Japanese with English summary)

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