Identifying Dendroecological Growth Releases in Old-growth Cryptomeria japonica Forest on Yakushima Island, Japan

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ABSTRACT

Old-growth Cryptomeria japonica forests on Yakushima Island, Japan have been affected by logging activities. The most ancient record related to logging of Cr. japonica on Yakushima Island dates back to 1563. Systematic large scale logging activities of Cr. japonica occurred over a 300 year period starting in 1642. Forests on the island currently consist of 200–300 year-old regenerated Cr. japonica, although 400 to over 1000 year-old trees have survived logging activities. The objective of the present study was to identify the points in time and the scale of past disturbances and to verify of ancient records of logging activities using dendroecological approaches. Tree-ring analysis using samples obtained from eight Cr. japonica individuals was employed to develop an understanding of and pinpoint the time of past disturbances. Percent growth change (%GC) was calculated to detect release events caused by gaps created by human or natural disturbances and basal area increments (BAI) were calculated to detect growth rates. One older sample tree showed evidence of release events from the middle of 1700s to about 1800 and at the end of the 1900s, and another old-aged sample tree showed similar evidence from 1600 to the middle of 1900s. The BAI value showed an increase for one old-aged sample tree from the middle of 1700s to the beginning of 1900s and the other old-aged sample tree from 1800 to the end of 1900s; thus both trees showed high BAI values for 150 years after releases. Germination year of six regenerated trees subsequent to the inaugural year of logging was estimated within the relatively narrow range between 1791 and 1835. This germination timing was consistent with release events followed by high BAI values of old-aged trees. Evidence showing all regenerated samples germinated on stumps and logs indicates the detected releases might have been caused by large scale of logging activities. This study clarified that large scale of logging activity encouraged the growth rate of approximately 500 to 600 years old trees, and also large scale of disturbance was important for regeneration of Cr. japonica.

Keywords: basal area increment, boundary line, disturbance, logging activity, natural regeneration

INTRODUCTION

Cryptomeria japonica (L.f.) D. Don occurs naturally from the northern limit of Aomori Prefecture to the southern limit of Yakushima Island in Kagoshima Prefecture, but because of ancient logging activity, extensive natural forests of Cr. japonica currently only exist in Akita and Kochi prefectures and on Yakushima Island (Maeda, 1983). Logging records do not exist for most of these forests and little is known about how the current forest structure developed. Cr. japonica on Yakushima Island live more than one thousand years (Suzuki and Tsukahara, 1987). These old-growth Cr. japonica forests on Yakushima Island had been affected by logging activities (Yoshida and Imanaga, 1990). Canopy gap formation by logging activities led to regenerations of Cr. japonica (Suzuki, 1997). Currently this forest consists of 200–300 year old, regenerated Cr. japonica as well as 400 to over 1,000 year old Cr. japonica that survived logging activities (Kyushu Regional Forest Office/Yaku-shima Environment Conservation Centre, 1996; Yoshida and Imanaga, 1990).

These old-growth forests on Yakushima Island have been conserved as Forest Ecosystem Protected Area (FEPA), which includes the world heritage-listed area (Tagawa, 1994). FEPA is divided into the core and buffer areas under the concept of biosphere reserves, which has been evolved by UNESCO's Man and Biosphere Program (Tagawa, 1994). In the core area, no human activity such as logging is allowed. In the buffer area surrounding the core area, human activities are restricted, and selective logging is allowed only in Cr. japonica.

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plantations (Kagoshima Prefecture, 2012). Such plantations in the buffer zone are expected to be transformed to naturally regenerated stands (Kyushu Regional Forest Office, 2013). Outside FEPA, there is production area of Cr. japonica, and clearcutting system or selection system have been carried out mainly in plantations (Kyushu Regional Forest Office/Yakushima Environment Conservation Centre, 1996). Conservation of old-growth Cr. japonica forests requires an understanding of the effects of human disturbances on the growth of Cr. japonica and dynamics of Cr. japonica forest, because it may help researchers elucidate past forest structure and provide useful information for the long-term forest management strategy in the buffer and production areas. Historical descriptions related to logging have been in existence since 1563 (Kanetani and Yoshimaru, 2007). However scale of logging activity, its effect on growth of the surviving trees and the germination years of Cr. japonica which thrived because of gap formation have not been studied.

Dendroecological approaches have been proven to be extremely useful in evaluating the disturbance history of a stand with complex age structure over time and one of the fundamental dendroecological approaches to evaluating the disturbance history is identification of releases (Lorimer and Frelich, 1989). Calculation of releases is a powerful and unique tool that reflects disturbances at a high temporal resolution (Black and Abrams, 2003). Regional studies of disturbance regimes have been useful in understanding species dynamics and have served as guides for restoring natural vegetation complexes (Bonnicksen and Stone, 1980). The objectives of the present study were; 1) to pinpoint the time and the scale of disturbances to verify ancient records of logging activity, 2) to determine the effects of logging on growth of old-aged Cr. japonica and 3) to reveal the germination year of regenerated Cr. japonica through gap formations using dendroecological approaches and positional information.

MATERIALS AND METHODS

Study Area

Yakushima Island is located at 30°20’ N, 130°31’ E, about 60 km from the southern end of Kyushu, southern Japan and has an area of 504.9 km² (Fig. 1). This nearly circular island has about 130 km of shoreline. Mt. Miyanoura, located at the center of the island, reaches an altitude of 1,936 m and forms the island’s highest point. Precipitation levels on Yakushima Island are some of the highest in the world and range from 2,400–5,000 mm year⁻¹ on the coast to 5,000–7,400 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). Within the roughly 2,000 m elevational difference between the flatlands and mountain peak forests range from sub-tropical and temperate rainforests, mixed conifer-broadleaved forest containing Cr. japonica, to evergreen dwarf bamboo grassland surrounding mountain peaks (Kyushu Regional Forest Office/Yaku-shima Environment Conservation Centre, 1996). The presence of high precipitation and vertical distribution has led to about 90% of the island developing rich forests with high diverse flora, which contain old Cr. japonica, many endemic and endangered species (Kanetani and Yoshimaru, 2007).

At altitudes between 700 and 1,800 m, the vegetation on the island consists primarily of a mixed conifer-broadleaved forest dominated by old-growth Cr. japonica (Miyawaki, 1980). The most ancient record related to logging of Cr. japonica from Yakushima Island is from 1563 when logging was done to rebuild the Kagoshima shrine (Kanetani and Yoshimaru, 2007). Systematic large scale of logging activities of Cr. japonica occurred over a 300 year period beginning in 1642 (Hamaoka, 1933; Kakinoi, 1954; Yoshida and Imanaga, 1990).

Four permanent plots were established in 1973–1974 by the Kumamoto Regional Forest Office, named the Hanayama (HP), Kohanayama (KP), Futaridake-no-komichi (FP) and Shiratani (SP) plots (Fig. 1). Study plots were covered in natural, uneven-aged, mixed conifer-broadleaved forest dominated by Cr. japonica (Takashima, 2009). Study plots were located between 850 and 1,250 m a.s.l., 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). For this study we focused on detecting releases in the FP study plot. The FP area has been designated as recreation forest since 1971. Tree-ring data from four study plots were used to calculate release criteria.

Sampling and Cross-dating Trees

During 2005–2008, sample trees more than 30 cm of DBH classes were randomly selected in each plot. One or two samples from each of the DBH classes were cored using an increment borer with 80 cm length and diameters at breast height were measured where the sampling cores were obtained. Sampled cores were glued onto wooden mounts and sanded until individual tree-rings were clearly visible. Each tree-ring width was measured on a TA Unislide Velmex machine (0.001 millimeter precision; Velmex Inc., Bloomfield, NY, USA). 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.

To detect releases for the last 550 years we used tree-ring data from FP study plot and succeeded in obtaining two long sample cores, while taking cores from large diameter trees was so difficult that mostly innermost of cores were broken. In FP study plot, two old-aged trees that might be regenerated before the starting year of large scale logging activity in 1642 and six regenerated trees that were expected to have regenerated after 1642, were used to detect releases (Tables 2 and 3). A large data set of tree ring measurements was needed to calculate species-specific release criteria. Therefore, we supplemented our data with 34 tree-ring data sets from the four study sites.

### Standing Tree Monitoring and Mapping

Diameter and species name of all living trees with diameter at breast height (DBH, approximately 1.2 m height from the ground) ≥ 4 cm have been recorded three different times since 1973 or 1974 within each study plot (Takashima, 2009) (Table 1). Elevations were measured on a 20 m grid at corners of the sub-blocks and positions of all softwood and dominant broad-leaved trees were mapped (Takashima, 2009). For C. japonica trees in the FP study plot regeneration types were also recorded; trees regenerated from the ground, logs or stumps. Within the FP study plot C. japonica snags and stumps (DBH ≥ 10 cm) were mapped and their DBH were recorded in 2005 (Takashima, 2009). Fig. 2 shows positions of living trees, snags and stumps in the FP study plot.

#### Age Estimation

Sample cores often lacked pith, the chronological center of a tree. Missing parts of tree-ring radius were estimated using an arc of inner tree-rings. When sample cores passed close enough to the chronological center so that arcs of the inner rings were visible, missing radii lengths were estimated using the equation (Duncan, 1989):

\[
r = L^2 / 8h + k / 2
\]

where \( r \) : length of the missing radius, \( L \) : length of arc, \( h \) : height of an arc. Estimated lengths of missing radii were divided by the average tree-ring width of the innermost 20 rings 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).

### Table 1 Study plot attributes

| Plot name | Altitude (m) | Area (ha) | Monitoring year | Attributes of Cr. japonica at the 3rd monitoring year | Attributes of sample tree |
|-----------|--------------|-----------|----------------|------------------------------------------------------|---------------------------|
|           |              |           | 1st | 2nd | 3rd | No (ha) | Mean DBH (cm) | No (plot) | Mean DBH (cm) | Mean ring-width (mm) |
| HP        | 1250         | 1.0       | 1974 | 1992 | 2003 | 192      | 67.5          | 13         | 77.7          | 1.18               |
| KP        | 1100         | 1.0       | 1973 | 1988 | 1998 | 195      | 70.6          | 5          | 97.9          | 1.55               |
| FP        | 1050         | 1.0       | 1973 | 1991 | 2002 | 123      | 57.5          | 9          | 66.5          | 1.19               |
| SP        | 850          | 0.8       | 1974 | 1993 | 2004 | 26       | 75.3          | 7          | 62.0          | 1.83               |

DBH: diameter at breast height

### Table 2 Sample tree attributes: old-aged sample trees of the FP study plot

| Sample tree ID | DBH (cm) | Tree height (m) | Number of tree-ring | Mean tree-ring width (mm) | Estimated age (year) |
|----------------|----------|-----------------|---------------------|---------------------------|----------------------|
| A              | 111.0    | 24.3            | 567                 | 0.57                      | -                    |
| B              | 83.8     | 26.1            | 574                 | 0.59                      | 626                  |

### Table 3 Sample tree attributes: regenerated sample tree of the FP study plot

| Sample tree ID | DBH (cm) | Tree height (m) | Number of tree-ring | Mean tree-ring width (mm) | Estimated germination year | Regeneration types |
|----------------|----------|-----------------|---------------------|---------------------------|---------------------------|--------------------|
| a              | 58.5     | 29.0            | 177                 | 1.17                      | 209                       | 1796 | Stump |
| b              | 48.0     | 20.8            | 173                 | 1.13                      | 184                       | 1821 | Log   |
| c              | 54.0     | 19.6            | 164                 | 1.64                      | 179                       | 1826 | Log   |
| d              | 47.0     | 21.4            | 150                 | 1.11                      | 178                       | 1827 | Stump |
| e              | 66.5     | 30.3            | 192                 | 1.53                      | 214                       | 1791 | Log   |
| f              | 67.0     | 24.7            | 156                 | 1.69                      | 170                       | 1835 | Log   |

| Mean          | 56.8     | 24.3            | 169                 | 1.38                      | 189                       | 1816  |
study, we estimated age of 7 sample cores from FP study plot. The mean length of the missing radii was 28.27 mm. One old-aged sample tree had a core which was too short, thus we did not calculate the age to avoid a large margin of error.

Cores were not taken at ground level; rather, most were taken at 1.2 m above ground level. The exact age of sampled trees was estimated based on stem analysis of *Cr. japonica* on Yakushima Island. The age to reach the coring height was estimated using the relationship between height and tree-ring number of disc from stem analysis (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:

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

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. However, if the measured diameter was shorter than twice sample core length, we calculated the diameter as an additional value of length of the core and estimated missing radius.

Release Analysis

Release analysis using tree-ring width is a useful approach for evaluating the disturbance history of a stand with complex age structure (Lorimer and Frelich, 1989). For the analysis, the percentage growth change (%GC), which was the percentage difference between preceding and subsequent 10-yr means of tree-ring width, was calculated using the formula below (Nowacki and Abrams, 1997):

\[
%GC = \frac{M_2 - M_1}{M_1} \times 100
\]

where \(M_1\): preceding 10-yr mean, \(M_2\): subsequent 10-yr mean. A 10-yr span for radial-growth averaging was used to detect sustained growth increases in percentage to discount the influence of climate and other short-term growth perturbations (Leak, 1987). %GC of eight *Cr. japonica* sample trees in FP study plot were calculated to detect growth increases caused by gap formations from human or natural disturbance.

To obtain release criteria, the boundary line method was used (Black and Abrams, 2003) because this method solved the dendroecological problems of ring width decreasing caused by aging and narrow ring width showing extremely large %GC. This method uses two steps: (1) empirical estimation of the maximum growth change based on prior growth, and (2) scaling of the releases relative to the boundary.
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In the first step the boundary line method is determined based on the relationship between %GC and prior growth values, which was mean growth over the prior 10 years. For calculating the species-specific boundary line, a large data set of tree ring measurements was needed. Therefore, we supplemented tree-ring data from the FP study site with data from another three permanent study plots on Yakushima Island; total number of individuals used was 34 (Table 1). We divided the data set into nine prior growth classes (class width 0.5 mm), averaged the ten highest growth change values for every growth class, and fit linear, power, logarithmic and exponential curves and selected the function that yielded the highest R² value. In the second step, all the releases were evaluated relative to the boundary line. We identified potential releases according to a procedure developed by Black and Abrams (2003) as follows: only %GC values greater than 10% were retained. A time series graph of %GC shows increases at points of potential release, and only the maximum %GC for each ascent was used so that each peak would be considered only once as a potential release. Only these potential releases were then evaluated relative to the boundary line. We identified any %GC peak more than 20% of the boundary line at the given prior growth rate as moderate release and any peak exceeding 50% of the value of the boundary line as a major release.

RESULTS

Boundary Line

All calculated %GC ranged from –77.7 to 277.9% for prior growth from 0.12 to 4.71 mm (Fig. 3). The best fitted equation as the boundary line was:

%GC = –91.88 ln (PG) + 137.56

where PG: prior growth. The R² value of above equation was 0.958 (Fig. 3). Fig. 3 also includes the lines indicating 50% and 20% of the boundary line, which are thresholds used to define major and moderate releases, respectively.

Disturbance History

Fig. 4 shows the distribution of release for sample trees (A) and (B). Sample tree (A) showed major releases in 1751, 1774, 1778 and 1996, and sample tree (B) showed them in 1629, 1687, 1689, 1821, 1845, 1892, 1905 and 1939. The BAI value of sample tree (A) increased from the middle of 1700s to the beginning of 1900s. The BAI of sample tree (B) increased from the beginning of 1800s to the end of 1900s. These increases of BAI value occurred after the frequent major releases from the middle of 1700s for sample tree (A) and from the beginning of 1800s for sample tree (B).

Table 3 shows the estimated age from regenerated living trees and regeneration types. Even though they were located in two different areas (Fig. 2), regeneration years were within the relatively narrow range between the years 1791 and 1835. This timing was consistent with a major release followed by high BAI values for both sample trees (A) and (B).

Fig. 5 shows the number of sample trees showing moderate and major releases within each of 10-year class for old-aged and regenerated trees. Old-aged trees showed major and moderate releases from the 1450’s to 1990’s. Regenerated trees showed major and moderate releases from the 1820’s to 1990’s.

DISCUSSION

The present study attempted to pinpoint the time of disturbance of Cr. japonica on Yakushima Island over last several hundred years using tree-ring analysis. Old-aged sample trees (A) and (B) showed increasing growth although they were approximately 500 to 600 years old, while the
growth rate of trees normally declines as a tree ages (Gower et al., 1996). The sample tree (A) showed major release from the middle of 1700s and the sample tree (B) showed major release from the beginning of 1800s (Fig. 4). Both trees showed a relatively high BAI value for about 150 years after these releases (Fig. 4). In old growth natural Cr. japonica forest in Akita, the growth of 160–200 years old Cr. japonica increased after thinning (Nishizono et al., 2006). This study clarified that much older Cr. japonica trees on Yakushima Island also increased their growth rates after disturbances.

Estimated germination years of regenerated trees were between 1791 and 1835, which were after the major release of old-aged sample trees followed by long-lasting high BAI values, and all of them regenerated on stumps or logs (Table 3). Hence, these regenerated trees might have grown up in improved light and better conditions of competition on neighboring trees because of logging activity. Even though the regenerated sample trees were located in two separate places, germination year of sample trees centered on a short period of time (Table 3 and Fig. 2). This result shows there was logging activity in the same time point in both these areas of the study site.

A major release of the old-aged sample tree (A) was detected during the 1990’s, but sample tree (B) did not show release for the 1990’s (Figs. 4 and 5). Major releases of regenerated trees for the 1970’s and 1980’s were also detected (Fig. 5). These releases might have been caused by natural disturbance, because the FP study plot has been strictly protected since 1971. The major natural disturbance in Yakushima Island might be land slide and typhoon. Shimokawa and Jitousono (1984) reported that land slide may happen every 1000 years in steep or drainage basin in Yakushima Island. In FP study plot on gentle slope, however, land slide might not happened at least last 600 years, judging from the number of tree-ring for the sample trees (Table 2) and the existence of many large trees and stumps (Fig. 2). Yakushima Island is susceptible to typhoons, which may cause the canopy gaps in the study plot. The weather station of Yakushima recorded wind velocities exceeding 55 m s$^{-1}$ eight times from 1938 to 2012 (Japan Meteorological Agency, 2013), meaning powerful typhoons hit about every 10 years in Yakushima Island. However, Takashima (2009) reported that only a few Cr. japonica have been recruited in permanent study plots including FP study plot based on monitoring results since 1973. In these plots, some losses of apical parts of the crowns were observed (Ishii et al., 2010), while whole crown damaged or uprooted trees are rarely observed, especially in larger trees. Only one big Cr. japonica with a DBH of 250 cm in KP study plot was felled by the typhoon (No. 19) in 1997, but no recruitment of Cr. japonica was observed (Takashima, 2009). This suggests disturbances since 1970’s might have been smaller scale than previous logging activity.

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**Fig. 4** Percent growth change (%GC) and basal area increment (BAI) for sample trees (A) and (B).
and happened at the individual tree level. In addition, such small scale natural disturbance may also occur all the time even before 1970’s and during the large scale logging activity.

There are historical descriptions showing the earliest logging occurred in 1563 and the starting year of systematic logging activity was 1642. In the FP study site some moderate releases were detected since 1450’s, but no major releases occurred until 1629. Based on the tree-ring analysis of stumps, there may have been some logging activities before 1642 (Ushijima et al., 2006), and so these moderate releases before 1642 may have been caused by logging as well as natural disturbances. However, these logging activities might have been smaller scale than later systematic logging activities, because only moderate releases occurred.

In conclusion, this study emphasized that systematic large scale logging activities of Cr. japonica occurred as part of the historical record. In our study site, logging activity started about 1630 and large scale logging activity occurred from the middle of 1700s. Large scale logging activity encouraged growth rates in older trees about 500 to 600 years old; gap formation may be important for regeneration of Cr. japonica. Low levels of disturbances also occurred before 1630 and these releases were likely to be caused by logging but might have been small scale. These results suggest past logging activities are important to encourage growth and regeneration of Cr. japonica.

Currently, logging of Cr. japonica is basically not allowed in the core area in FEPA. However, selective loggings are carried out for Cr. japonica plantations in the buffer area in FEPA and in the production area outside FEPA. Our findings suggest that group selection system is more appropriate rather than single-tree selection in order to encourage natural regeneration and growth of remaining trees in such areas. Interestingly, Imada (1986) had already proposed the group selection system with 240 year rotation for production area of Cr. japonica forest on Yakushima Island, and this system has been experimentally implemented. Thus, it could be very valuable to evaluate such an experimental practice to further confirm the effects of loggings.

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