Dendroecological Analysis of Long-term Forest Dynamics of Old-growth Cryptomeria japonica Forest on Yakushima Island

伊高, 静
Department of Forest and Forest Products Sciences, Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University

https://doi.org/10.15017/26651

出版情報：九州大学, 2012, 博士（農学）, 課程博士
バージョン：
権利関係：

Dendroecological Analysis of Long-term Forest Dynamics of Old-growth *Cryptomeria japonica* Forest on Yakushima Island

Shizu Itaka

2013

Contents

Chapters

1. General introduction

1.1. Objectives

Japanese built up their culture in rich forest resources over several ten thousands of years (Yasuda, 1980). *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), and the old-growth *Cr. japonica* forests on Yakushima Island had been affected by logging activities. Currently the forest on the island consists of 200–300 year-old *Cr. Japonica* that regenerated after logging activities and 400 to over 1000 year-old trees that have survived logging activities. (Kyushu Regional Forest Office/Yaku-shima Environment Conservation Centre, 1996; Yoshida and Imanaga, 1990). The *Cr. japonica* forest on Yakushima Island is a valuable site enables estimation of long-term growth dynamics and effects of human disturbance. However, growth dynamics and the effects of human disturbances on the growth of *Cr. japonica* on Yakushima Island have not been studied. Conservation of a forest such as this requires an understanding of the growth dynamics and the effects of human disturbances on the growth of *Cr. japonica*, because it may help researchers elucidate past forest structure and provide useful information for the long-term forest management strategy for old-growth *Cr. japonica* forest on Yakushima Island.

Tree-ring analysis provides unique data source as they cover a wide range of time. Tree-ring information is generally used for reconstruction of past environments (Fritts, 1976), tree growth (Cherubini *et al.*, 1998; Ota *et al.*, 2007) and disturbance (Lorimer and Frelich, 1989), or dating historical materials (Mitsutani, 1987). To estimate long-term patterns in forest growth, continuous census is generally carried out. However, the time span of monitoring data is limited to only several decades. There are some researches about dynamics and disturbance history of 300-400 year old-growth forest (Abrams *et al.*, 1999; Ota *et al.*, 2007; Ziegler, 2004). Using variations in tree-ring width, it is possible to extrapolate information regarding growth dynamics and evaluating the disturbance history.

This thesis attempted to clarify the long-term growth dynamics and the effects of human disturbances on the growth of *Cr. japonica* based on dendroecological analysis. And also growth from diameter censuses and tree-ring data were compared to know error range, because census will be a very important tool to know further growth dynamics.

1.2. Methods of This Study

To understand long-term growth pattern of *Cr. japonica* on Yakushima Island over the last several hundred years, dendroecological analysis was employed (Chapter 2). 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. Therefore, *Cr. japonica* samples that regenerated subsequent to the inaugural year of logging which ranged in age from about 200-300 years were used to develop an understanding of growth patterns. Annual basal area increment (BAI) was calculated from tree-ring series. Because 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).

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. To reveal past logging activity, its effects of human disturbances on the growth of *Cr. japonica* and the germination year of regenerated *Cr. japonica* through gap formations, dendroecological approaches were used (Chapter 3). 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).

To estimate long-term patterns in forest growth, generally obtain from continuous diameter census or tree-rings measurements. However, relatively little research has focused on comparing inventories and tree-ring data (Biondi, 1999; Clark et al., 2007). Biondi (1999) reported that tree-ring data was closely matched with repeated forest inventories. We focused on 30 years diameter census and tree-ring chronologies of *Cr. japonica* to compare growth from diameter censuses and tree-ring data to know error range in order to consider about the role of old-growth forest census (Chapter 4).

1.3. Yakushima Island

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 km^2. 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).

1.4. *Cryptomeria japonica* Forest on Yakushima Island

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). *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). 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; Kakinoki, 1954; 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). The logging is prohibited since 1982 for over 800 year old *Cr. japonica* and since 2002 for the all natural *Cr. japonica* in Yakushima Island (Kanetani and Yoshimaru, 2007; Kumamoto Regional Forest Office, 1982; Sato and Teraoka, 2012).

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* 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 has been carried out mainly in plantations (Kyushu Regional Forest Office/Yaku-shima Environment Conservation Centre, 1996).

1.5. Study Area

During 1973-1974, five permanent plots were established by the Kumamoto Regional Forest Office, named the Hanayama plot (*HP*), Kohanayama plot (*KP*), Futaridake-no-komichi plot (*FP*), Shiratani plot (*SP*) and Tenmon-no-mori plot (*TP*) (Fig. 1-1). 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 1-1). 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 1-1), 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).

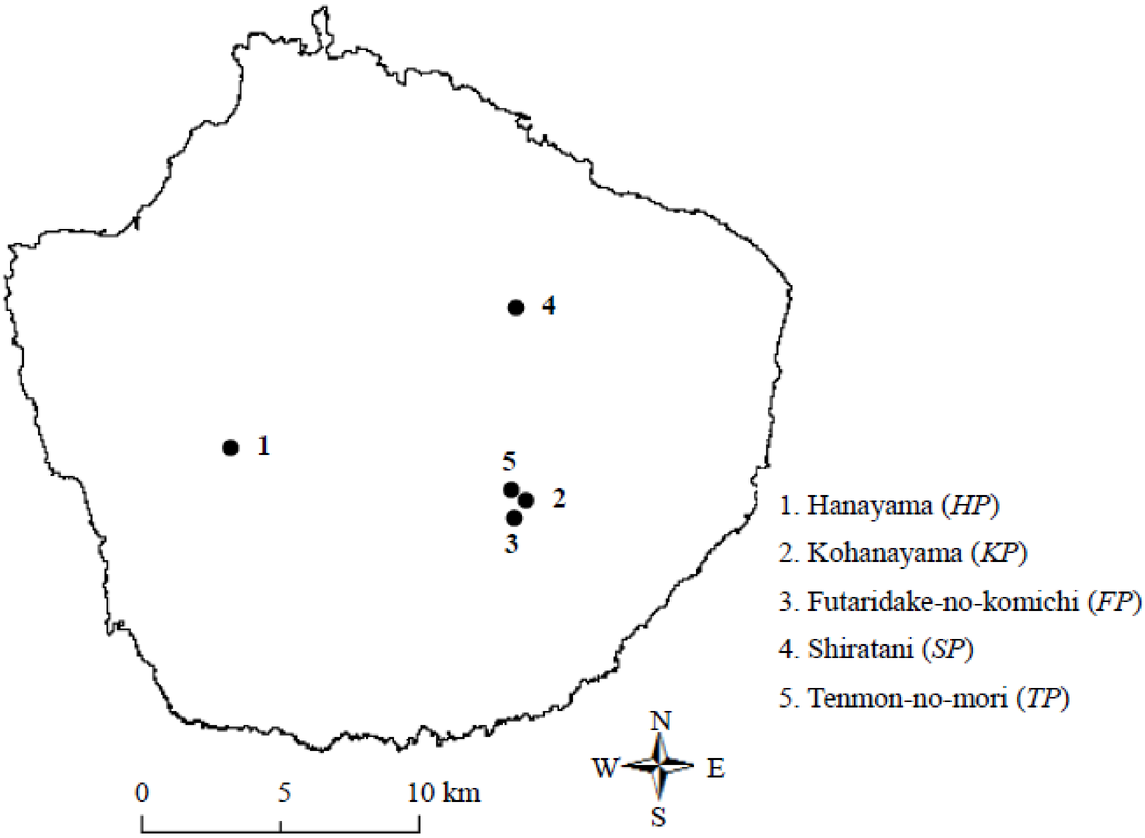
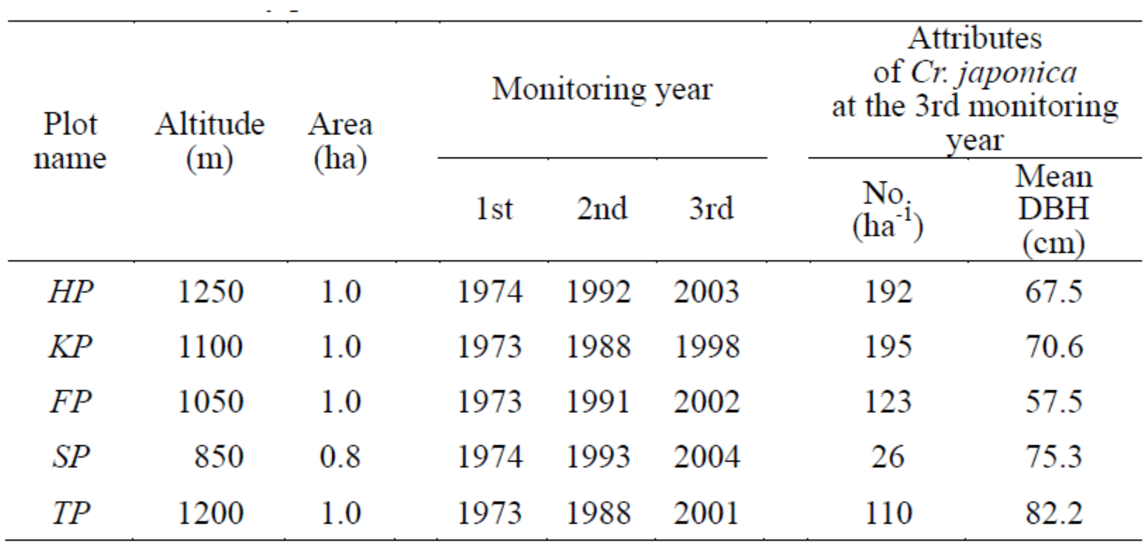


Fig. 1-1 Location of study plots on Yakushima Island.

Table 1-1 Study plot attributes



Plot name	Altitude (m)	Area (ha)	Monitoring year			Attributes of *Cr. japonica* at the 3rd monitoring year	
			1st	2nd	3rd	No. (ha^{-1})	Mean DBH (cm)
HP	1250	1.0	1974	1992	2003	192	67.5
KP	1100	1.0	1973	1988	1998	195	70.6
FP	1050	1.0	1973	1991	2002	123	57.5
SP	850	0.8	1974	1993	2004	26	75.3
TP	1200	1.0	1973	1988	2001	110	82.2

All plots, however, contained almost the same number of *Cr. japonica* stumps, and the forest structure of these plots may have been similar prior to large-scale logging activities (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 1-1).

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

2.1. Introduction

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 *Cr. japonica* on Yakushima Island over the last several hundred years. Regenerated *Cr. 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 *Cr. japonica* forest on Yakushima Island could be obtained. In the present study, sample cores were collected from *Cr. 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.

2.2. Material and Methods

2.2.1. 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 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.

Four plots, *HP, KP, FP* and *SP* were used as study sites in this study (Fig. 1-1 and Table 1-1). Within study plots, DBH distributions obtained from the second measurement interval were normal for *Cr. 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. 2-1).

Cores were taken from 68 trees, but only 28 trees were analyzed as certain cores were broken or too short for age estimation (Table 2-1). 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.

2.2.2. Age Estimation

Sample cores often lacked pith, the chronological center of a tree. 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):

$$r = L^2 / 8h + h / 2 \qquad (1)$$

where r: length of the missing radius, L: length of arc, h: height of an arc. Estimated lengths of missing radius was 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

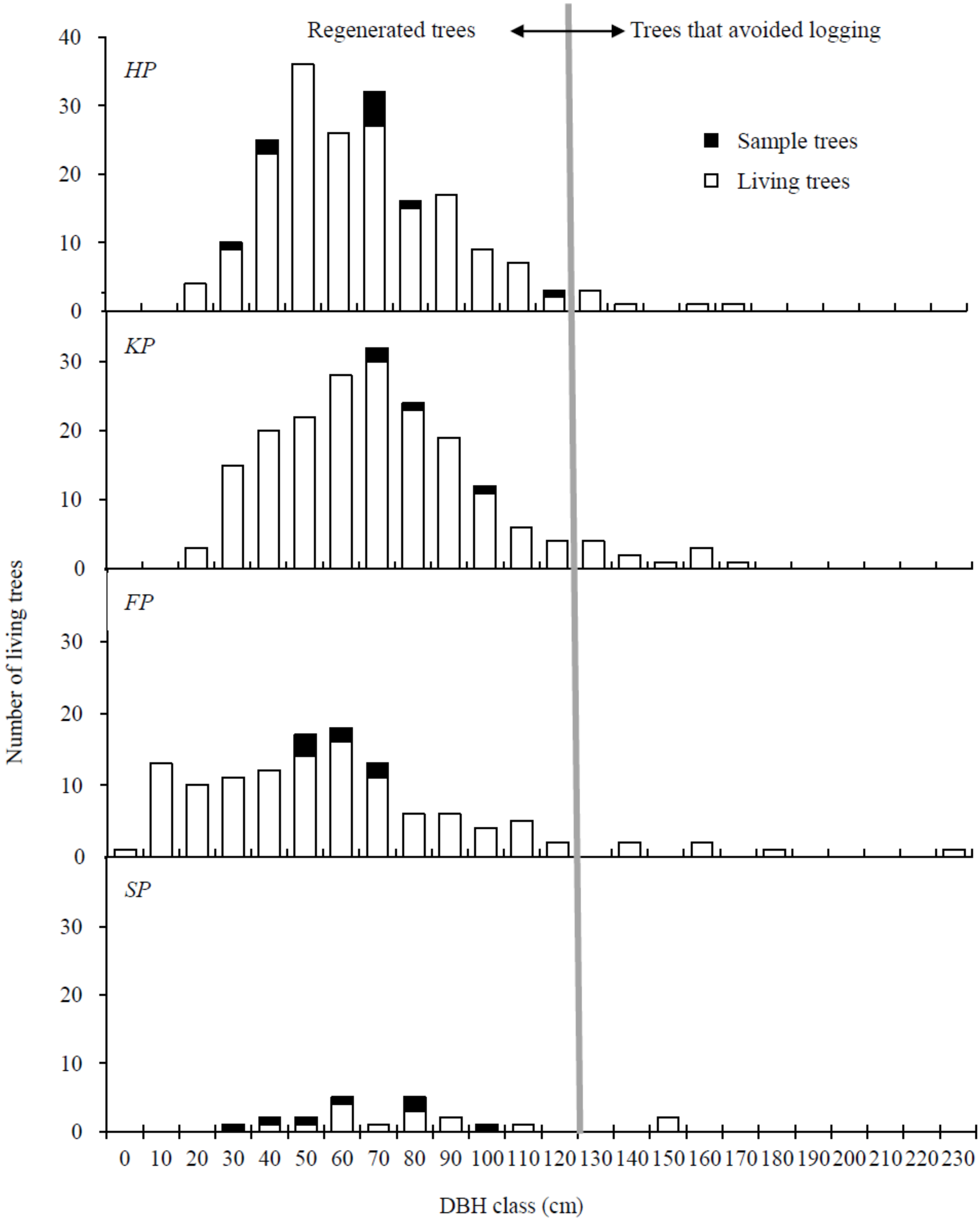


Fig. 2-1 Diameter distribution of living *Cr. japonica* individuals (3rd measurement interval).

Table 2-1 Sample tree attributes

	No. (plot^{-1})	Mean DBH (cm)	Mean ring-width (mm)	Range of estimated age (year)
HP	10	66.3	1.17	206-302
KP	4	80.6	1.81	186-258
FP	7	57.6	1.37	170-214
SP	7	61.6	1.83	100-276

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%.

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).

2.2.3. 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:

$$\mathrm{BAI} = \pi\ (D_t\ /\ 2)^2 - \pi\ (D_{t\text{-}1}\ /\ 2)^2 \qquad (2)$$

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.

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 of 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.

2.3. Results

Diameter of the coring height of sampled trees was calculated for each year based on tree-ring series (Fig. 2-2), and age-diameter relationships were inferred from estimated age and tree-ring widths for trees of different age (Fig. 2-3). 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 (Fig. 2-3). Standard deviation of tree-ring widths and BAI values also showed a wide range (Figs. 2-4 and 2-5), 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. 2-4). Tree-ring growth rates

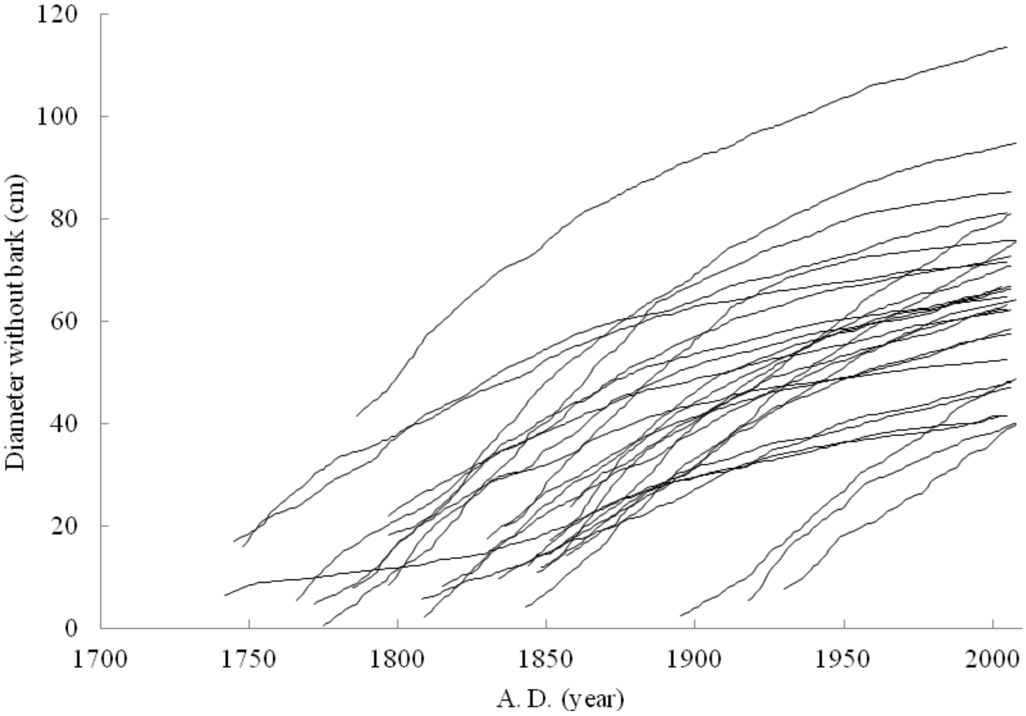


Fig. 2-2 Tree diameter growth.

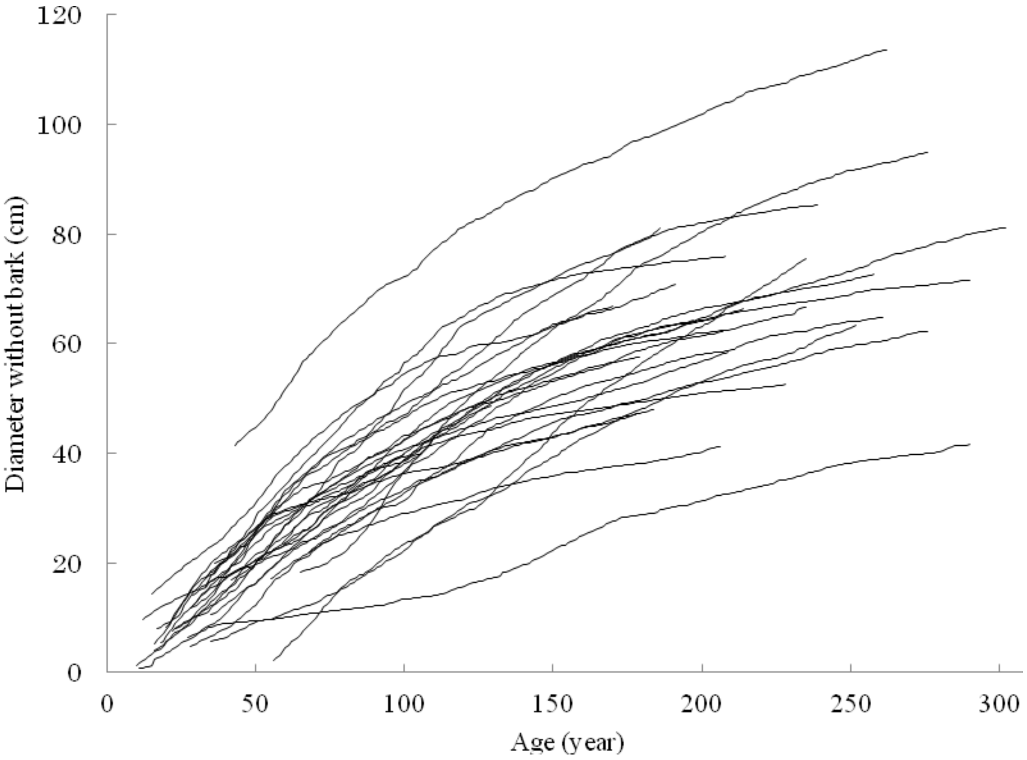


Fig. 2-3 Age-diameter relationship.

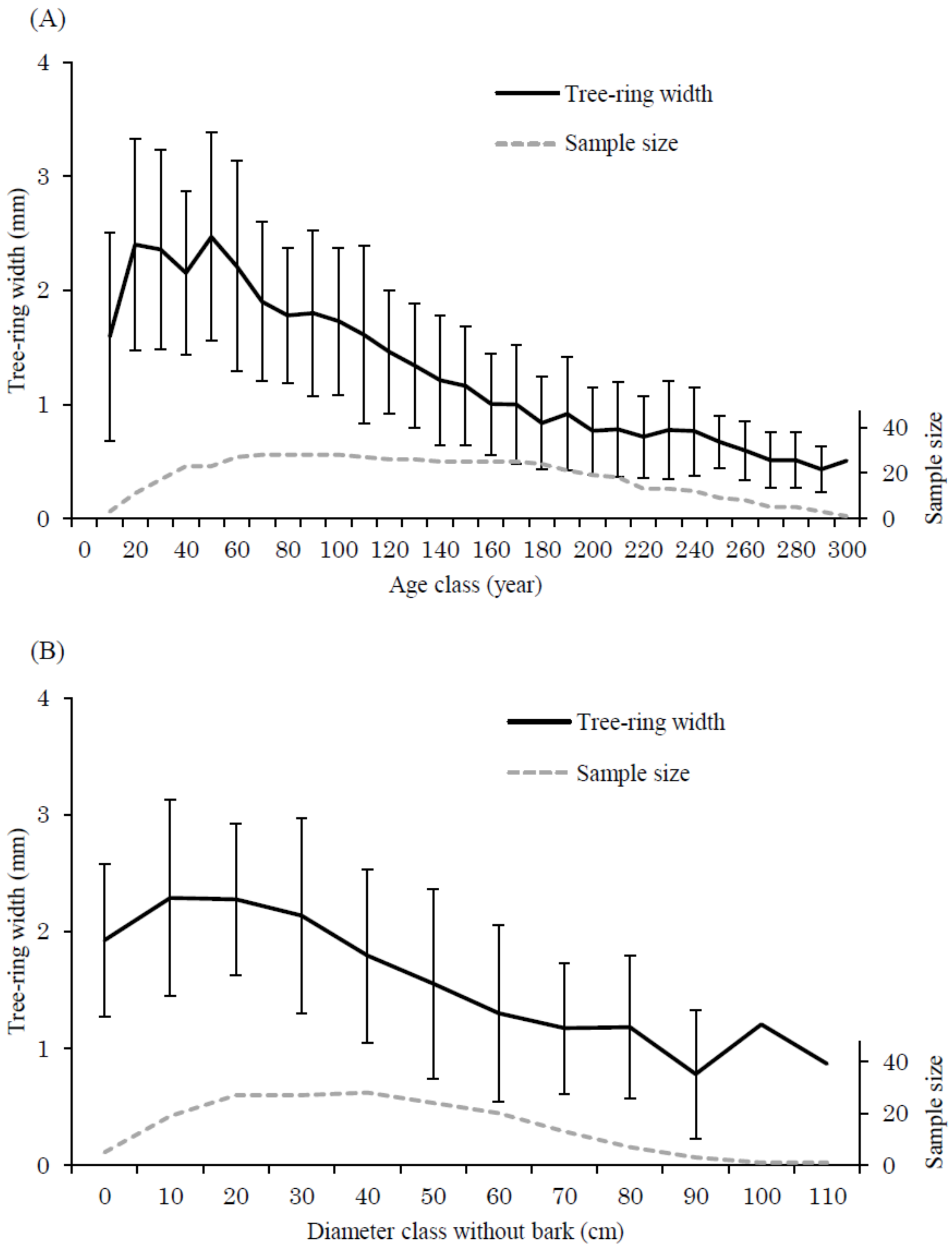


Fig. 2-4 Growth rate of tree-ring width for each of age (A) and diameter classes (B). The error bar indicates the standard deviation.

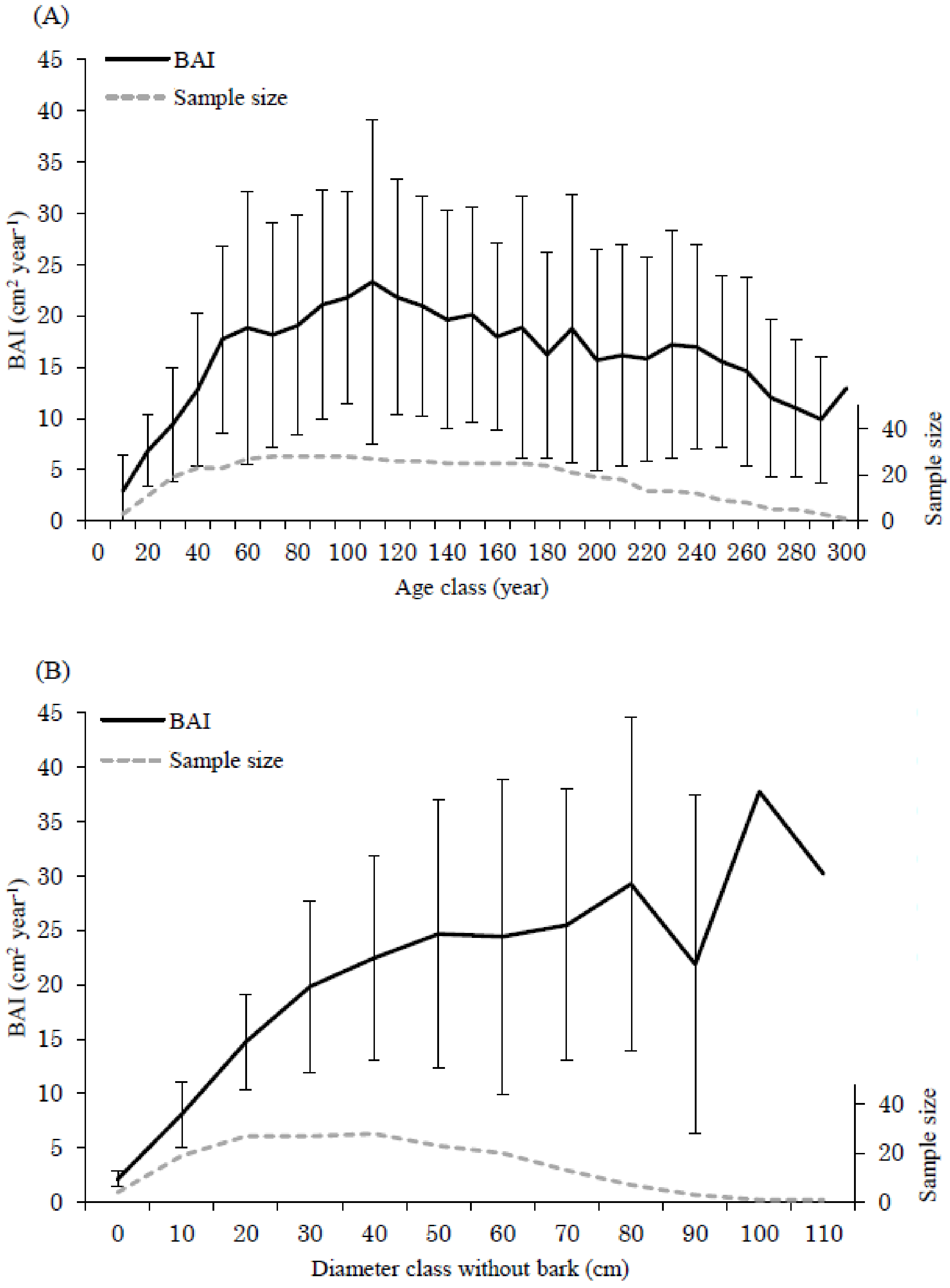


Fig. 2-5 Growth rate of basal area increment for each of age (A) and diameter classes (B). The error bar indicates the standard deviation.

increased and peaked within the 20-50 year age class and the 10 cm diameter class, after which growth rate decreased gradually (Fig. 2-4). Mean of tree-ring width was greater than 1 mm in individuals below the 160 year age class (Fig. 2-4(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. 2-5). 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. 2-5(A)). Furthermore, a slow increase in BAI growth rate from the 30 cm diameter 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. 2-5(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. 2-6).

2.4. Discussion

The present study attempted to clarify the long-term growth patterns of *Cr. japonica* on Yakushima Island over last several hundred years using tree-ring analysis.

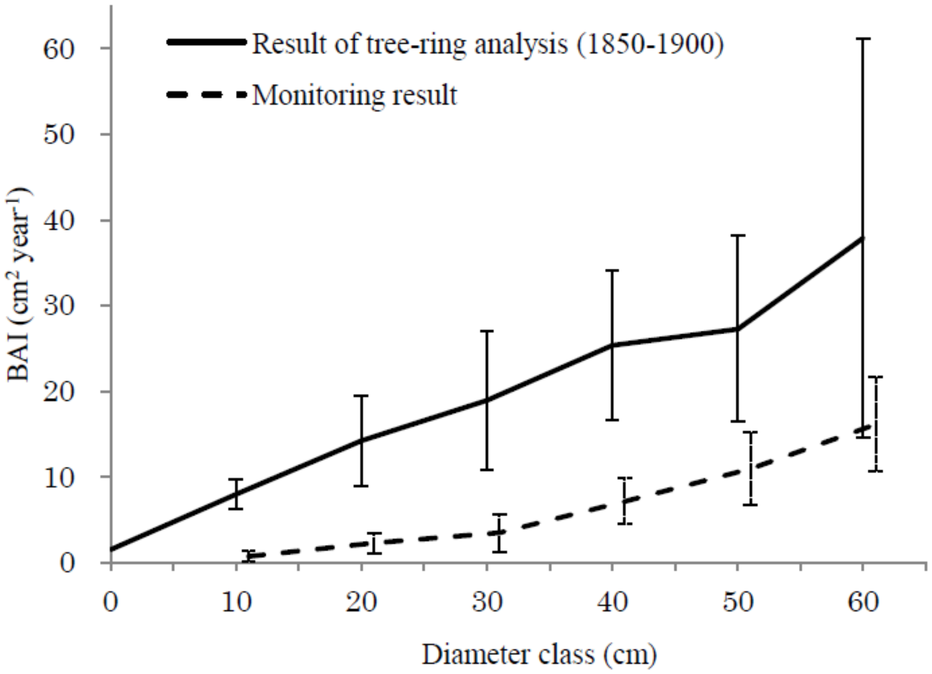


Fig. 2-6 Growth rate of basal area increment of tree-ring analysis from 1850-1900 and monitoring result during the last 30 years. The error bar indicates the standard deviation.

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. 2-4). 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). *Cr. 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. 2-4(A)).

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. 2-5(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. 2-4 and 2-5).

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. 2-5(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 60cm consistently had significant differences comparing to mean BAI growth rate of tree-ring analysis from 1850-1900 (Fig. 2-6). 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.

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

3.1. Introduction

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. For this study we focused on detecting releases in the *FP* study plot. The *FP* area has been designated as recreation forest since 1971.

3.2. Material and Methods

3.2.1. Sampling and Cross-dating Trees

Four plots, *HP, KP, FP* and *SP* were used as study site in this study (Fig. 1-1 and Table 1-1). The methods of taking sample cores, measuring tree-ring width and evaluating error of measurements were the same as "2.2.1. Sampling and Cross-dating Trees". 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 3-1 and 3-2). 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 (Table 3-3).

3.2.2. Standing Tree Monitoring and Mapping

Diameter and species name of all living trees with DBH ≥ 4 cm have been recorded three different times since 1973 or 1974 within each study plot (Table 1-1). Elevations were measured on a 20 m grid at corners of the sub-blocks and positions of all softwood and dominant broad-leafed trees were mapped (Takashima, 2009). For *Cr. japonica* trees in the *FP* study plot

Table 3-1 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 3-2 Sample tree attributes: regenerated 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)	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	-

Table 3-3 Sample tree attributes

	No. (plot^{-1})	Mean DBH (cm)	Mean ring-width (mm)
HP	13	77.7	1.18
KP	5	97.9	1.55
FP	9	66.5	1.19
SP	7	62.0	1.83

regeneration types were also recorded; trees regenerated from the ground, logs or stumps. Within the *FP* study plot *Cr. japonica* snags and stumps (DBH $\geq$ 10 cm) were mapped and their DBH were recorded in 2005 (Takashima, 2009). Fig. 3-1 shows positions of living trees, snags and stumps in the *FP* study plot.

3.2.3. Age Estimation

The method of age estimation was same as “2.2.2. Age Estimation, 1. Measuring arc of inner tree-ring”. In this 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.

3.2.4. Growth-rate Calculation

BAI was calculated using the same formation as “2.2.3. Growth-rate Calculation”.

3.2.5. 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):

$$\%GC = (M_2 - M_1) / M_1 \times 100 \qquad (3)$$

where M_1: preceding 10-yr mean, M_2: subsequent 10-yr mean. A 10-yr span

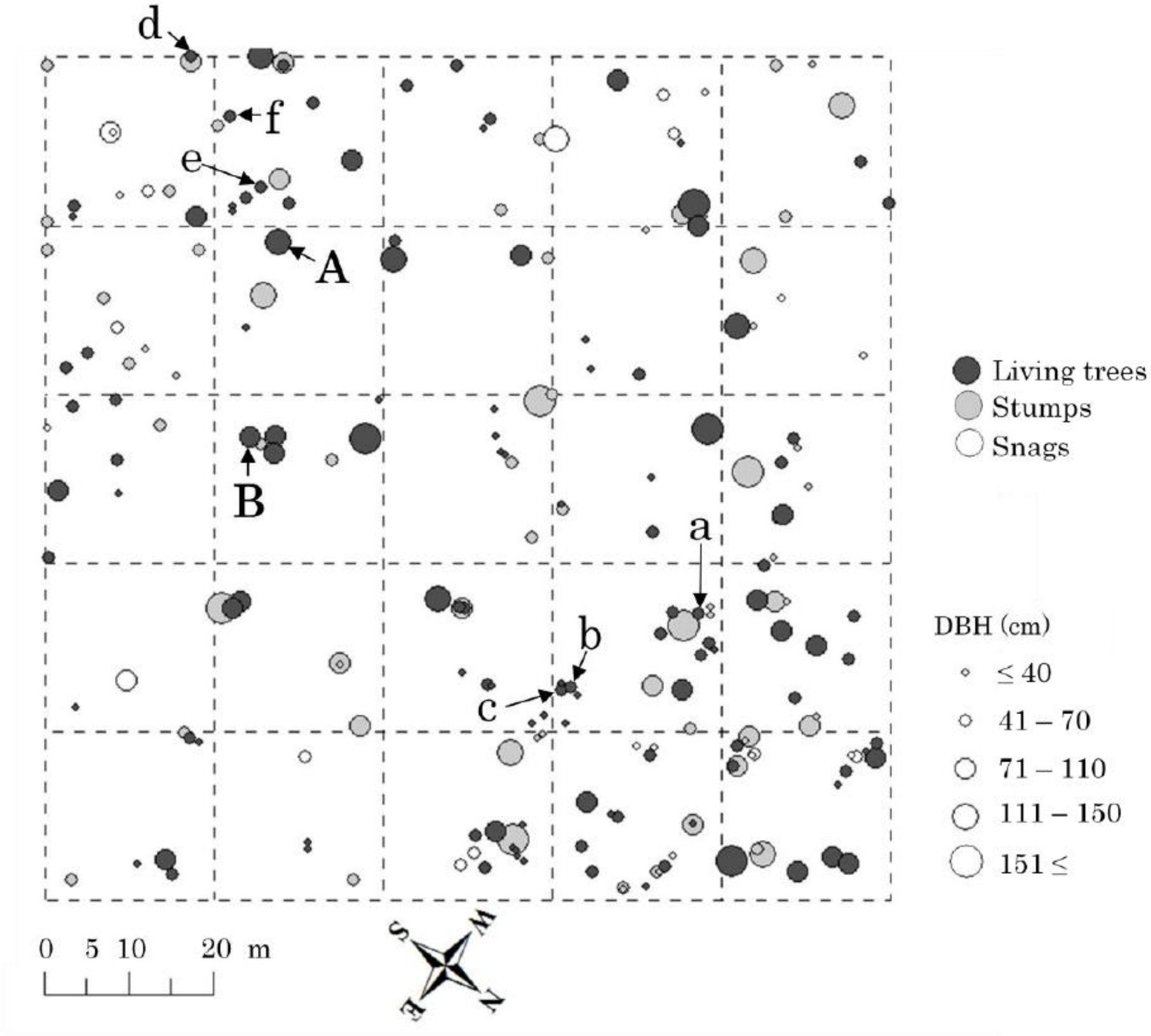


Fig. 3-1 Location of living trees, stumps and snags in the *FP* study plot. A and B: old-aged trees. a-f: regenerated trees.

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 line (Splechtna *et al.*, 2005).

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 3-3). 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 R^2 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.

3.3. Results

3.3.1.Boundary Line

The best fitted equation as the boundary line was:

$$\%GC = -91.88 \ln (PG) + 137.56 \qquad (4)$$

where PG: prior growth. The R^2 value of above equation was 0.96 (Fig. 3-2(A)). All calculated %GC ranged from –77.7 to 277.9% for prior growth from 0.12 to 4.71 mm (Fig. 3-2(B)). Fig. 3-2(B) also includes the lines indicating 50% and 20% of the boundary line, which are thresholds used to define major and moderate releases, respectively.

3.3.2. Disturbance History

Fig. 3-3 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, 1691, 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 3-2 shows the estimated age from regenerated living trees and

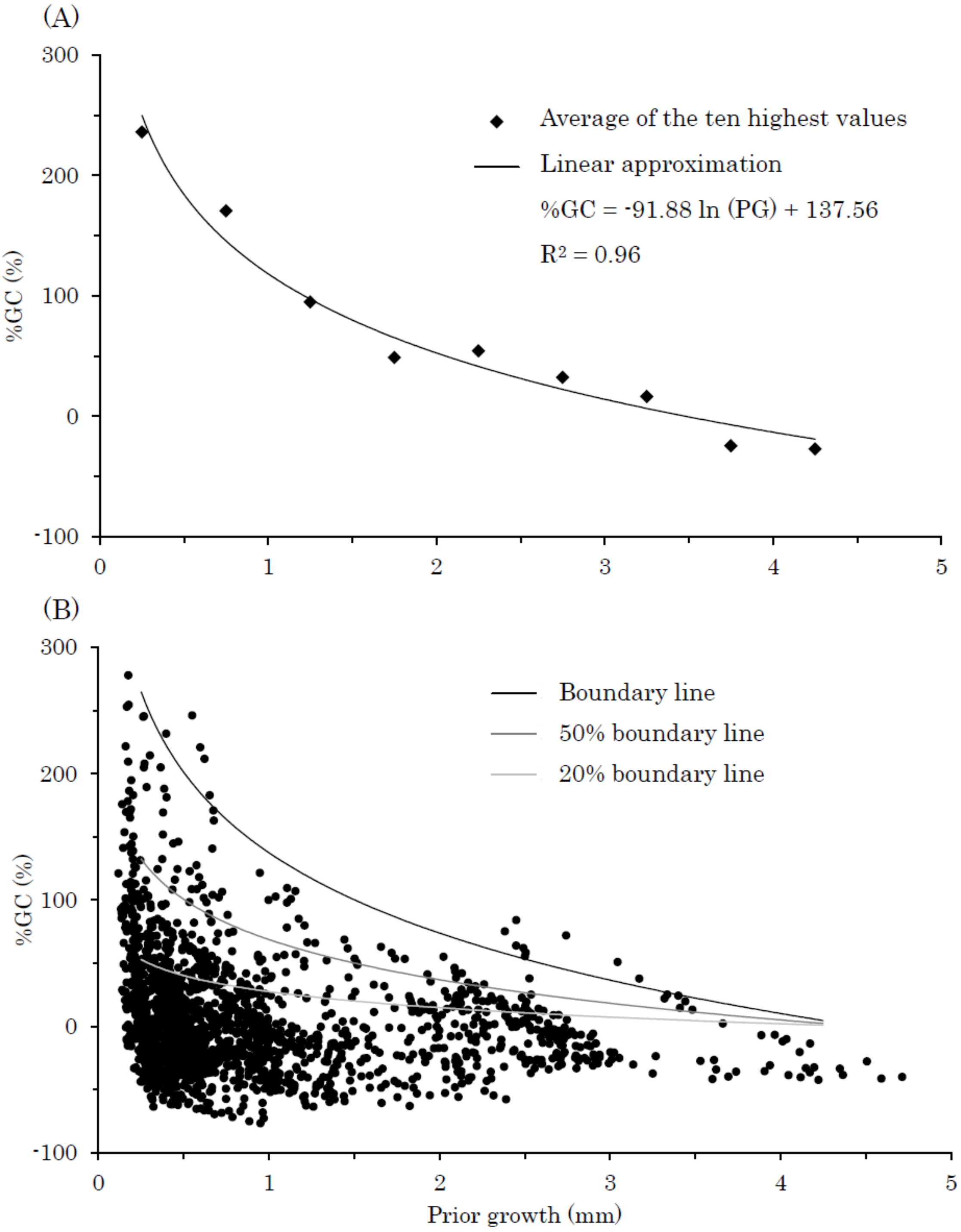


Fig. 3-2 Linear approximation of averaged value of ten highest growth change for every growth class (A). Boundary line and plot of percent growth change (%GC) values with respect to prior growth for 34 sample trees (B).

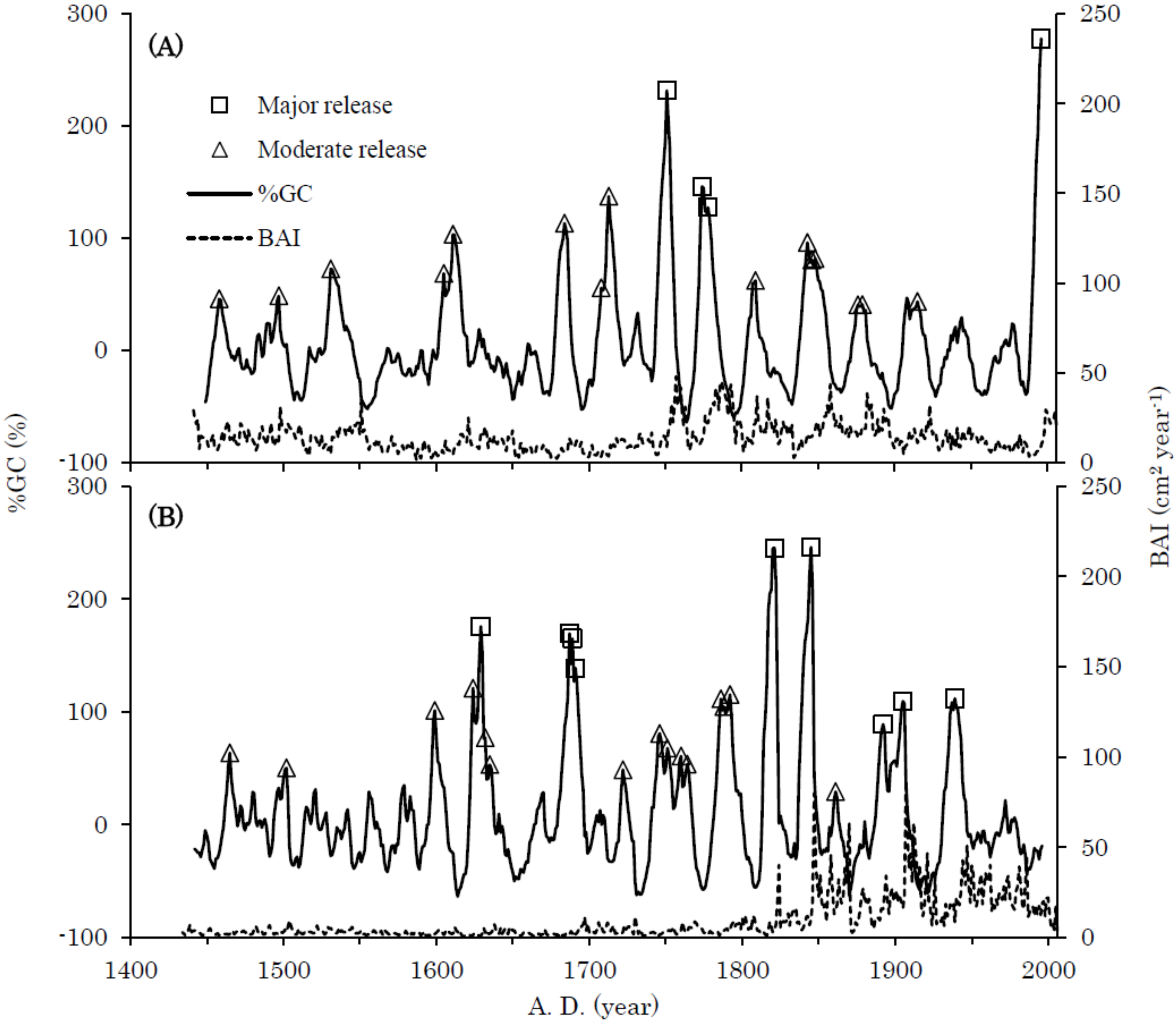


Fig. 3-3 Percent growth change (%GC) and basal area increment (BAI) for sample trees (A) and (B).

regeneration types. Even though they were located in two different areas (Fig. 3-1), 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. 3-4 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.

3.4. 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. 3-3). Both trees showed a relatively high BAI value for about 150 years after these releases (Fig. 3-3). 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

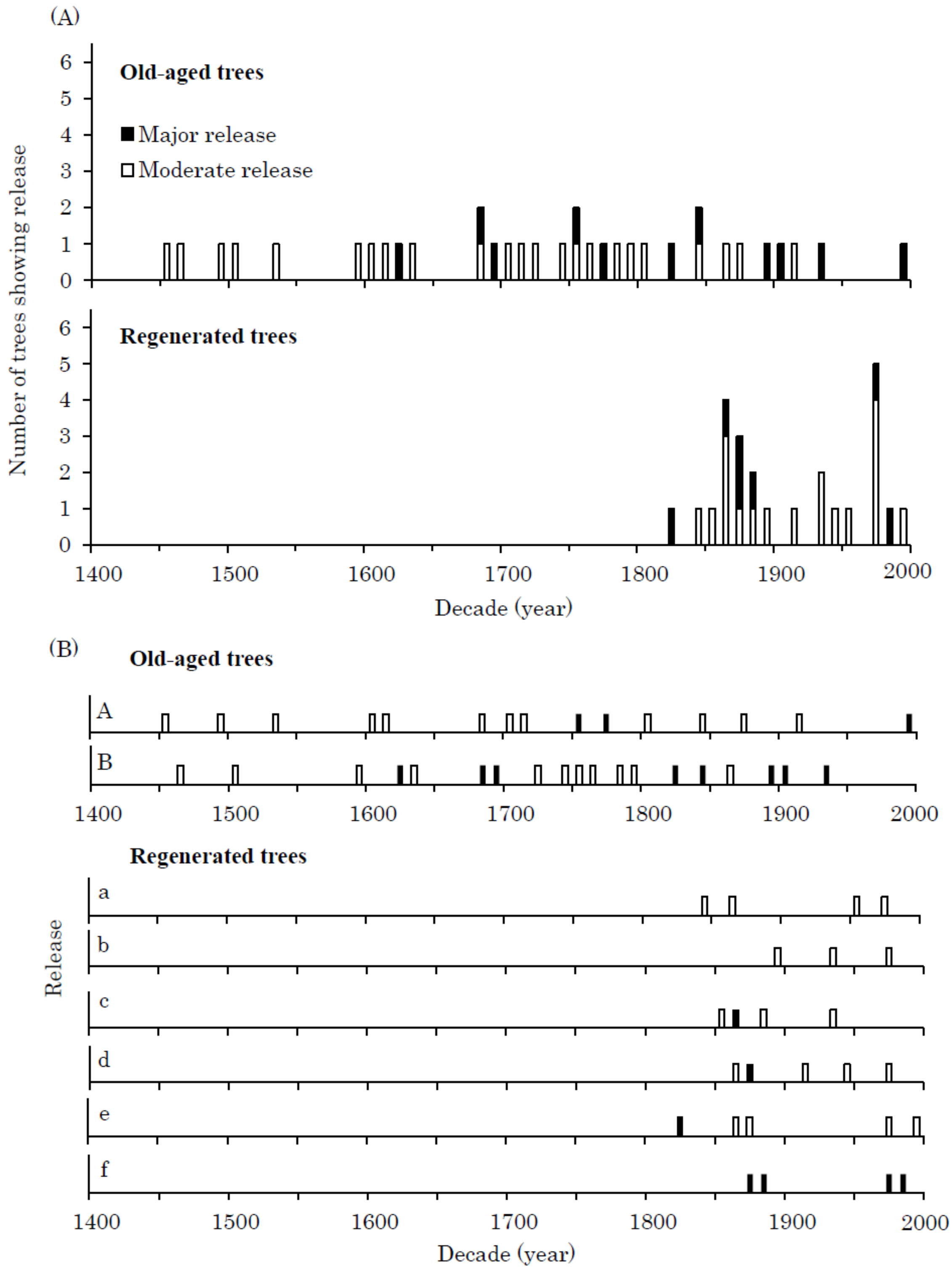


Fig. 3-4 Decadal distribution of major and moderate releases of two old-aged and six regenerated trees for *FP* study plot. Total number of release (A), and release for each sample trees (B).

logs (Table 3-2). 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 3-2 and Fig. 3-1). 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. 3-3 and 3-4). Major releases of regenerated trees for the 1970's and 1980's were also detected (Fig. 3-4). 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 happen at least last 600 years, judging from the number of tree-ring for the sample trees (Table 3-1) and the existence of many large trees and stumps (Fig. 3-1). 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. This suggests disturbances since 1970's might have been smaller scale than previous logging activity 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* and small scale disturbance associated with individual tree level might be inadequate to stimulate 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.

4. Comparing 30-years Diameter Censuses and Tree-ring Chronologies on Old-growth *Cryptomeria japonica* from Yakushima Island, Japan

4.1. Introduction

Conservation of the old-growth forest requires an understanding of long-term growth in *Cr. japonica*, because identification of long-term patterns in forest growth is needed to understand forest dynamics, with direct implications in forest management and silviculture (Biondi, 1999). However, growth of natural forest is not well known, because forest structure of natural forest is complex and its growth process is various. Continuous diameter census or tree-rings measurements are required to estimate long-term patterns in forest growth.

The most common method of growth estimation is measuring tree diameters repeatedly and calculating diameter change (Clark *et al.*, 2007). This approach has the advantages that diameters can be measured rapidly (Clark *et al.*, 2007), it is possible to collect data in protection area without damaging trees, and it is easy to get information about surrounding actual situation, but not possible to get past information before starting census. However there are several disadvantages to diameter measurements. The diameter measurements have substantial error (Barker *et al.*, 2002; Kitahara *et al.*, 2009), and negative growth could be observed (Clark *et al.*, 2007) although positive growth should occur each year. Annual growth rates are often unknown, because intervals between measurements can be long (Clark *et al.*, 2007). Especially it is difficult to measure big *Cr. japonica* trees because of irregular shape, covering thick moos of tree surface, and poor footing caused by many big stumps and logs on forest floor. Thus, it is concerned that as the diameters are bigger, measurements may be less accurate.

In comparison, advantage of tree-ring measurement is that tree-ring data provide an accurate representation of year-to-year growth patterns (Biondi, 1999), and negative growth can’t be observed. Tree-ring information also represents past growth back to the year of germination of the tree. However, there are some disadvantages. Tree-ring data might include false or missing rings. As one or two sample cores are taken generally from one tree, the actual tree circumference is not known (Clark *et al.*, 2007). Sample cores shrink after taking from trees and are not be able to be taken from protected areas or places where trees do not produce identifiable annual rings.

Relatively little research has focused on comparing inventories and dendrochronological records (Biondi, 1999; Clark *et al.*, 2007). Biondi (1999) reported that tree-ring data was closely matched with repeated forest inventories. We focused on 30 years diameter census and tree-ring chronologies on old-growth *Cr. japonica* forest from Yakushima Island, which consists of few hundred year old trees. The objective of this study was to compare growth from diameter censuses and tree-ring data to know error range in order to consider about the role of census for natural old-growth *Cr. japonica* forest on Yakushima Island.

4.2. Material and Methods

4.2.1. Diameter Census

DBH of all living trees with DBH ≥ 4 cm were recorded three different times since 1973 in the five plots (Table 1-1). DBH measurement was conducted using caliper in 0.5 cm round based up to 90 cm or 100 cm caliper size. Two measurements from different directions at right angles to each other were obtained for each tree, and the measurement values were averaged. Diameter tape was used for each tree that was not able to be measured using caliper, in 0.5 cm round based. Pole was used for each tree that was standing on poor footing caused by many big stumps and logs on forest floor, in 5 cm round based. At the breast height we placed number plates and measured DBH every census at same place. Furthermore, the rest lengths of the nails, which attached the number plates to the stems (Fig. 4-1), were randomly selected and measured in 0.1 cm round based during at third measurement for 224 trees in study plots of *HP*, *FP* and *SP* (Fig. 1-1 and Table 1-1).

4.2.2. Sampling and Cross-dating Trees

Tree-ring width of sample cores from 49 individuals from study plots *HP*, *KP*, *FP* and *SP*, were measured (Fig. 1-1 and Table 1-1). The methods of taking sample cores, measuring tree-ring width and evaluating error of measurements were the same as “2.2.1. Sampling and Cross-dating Trees”. In *TP* study plot (Fig. 1-1 and Table 1-1), 12 sample cores from 11 individuals were taken in 2012. To know percentage of shrink, cores were inserted into straw and the size of core (without bark) was marked on the straw immediately after the taking cores and the length were measured. After air dried, length of cores were measured and percentage of shrink is calculated. The results from tree-ring measurement were increased by average shrink percentage 1.5%, which were added to the result of tree-ring measurement.

4.2.3. Analysis

The period between the first and second measurements of diameter census

Fig. 4-1 Driving a nail in to the stem (Yoshida, 2007).

is termed as ‘first period’, between the second and third measurements as ‘second period’, and between the first and third measurements as ‘all period’. The first period and second period were termed 10-19 years and all period was termed 28-30 years. For first, second and all periods, diameter growth per 10 years (without bark) was calculated from the census records. The percentage of bark thickness was estimated using the relationship between diameter and bark thickness of disc from stem analysis (Togo, 1981). We calculated the diameter growth of 49 individuals, which were identical to trees whose sample cores were taken from 4 study plots (*HP*, *KP*, *FP* and *SP*) (Table 4-1). For the same period, diameter growth per 10 years was calculated from the sum of tree-ring widths. Diameter growth per 10 years from 14 individuals, for which rest lengths of the nails were measured and also sample cores were taken, was calculated.

Paired *t* test was applied to test the null hypothesis of no difference between diameter census/nail measurement and tree-ring measurement. For the continuous variables, we calculated average difference (AD), average percentage difference (APD), standard deviation (SD) of the differences, which are commonly used measures of random measurement error (Kitahara *et al.*, 2009). For the calculation tree-ring measurements were defined as true value. AD defined as the average of the diameter census/nail measurement minus the tree-ring measurement, and APD defined as the average of the absolute difference divided by the tree-ring measurement. Diameter growth per 10 years from diameter census, tree-ring measurement and rest lengths of the nails were grouped into each diameter class, and AD, APD and SD for each diameter class were also calculated.

From the all data of rest length of nail, percentage that nails have fallen away from the stem and nails have been pushed out of the stem, were

Table 4-1 Sample tree attributes at the 3rd monitoring year

Plot name	Attributes of sample tree for diameter census vs. tree-ring measurement			Attributes of sample tree for nail measurement vs. tree-ring measurement		
	No. (plot^{-1})	Mean DBH (cm)	Mean ring-width (mm)	No. (plot^{-1})	Mean DBH (cm)	Mean ring-width (mm)
HP	17	75.6	0.70	6	61.8	0.75
KP	9	81.1	0.72	-	-	-
FP	15	65.1	0.79	7	67.5	0.80
SP	8	63.9	0.15	1	64.5	0.88
TP	11	80.0	-	-	-	-

calculated.

4.3. Results

4.3.1. Diameter Census vs. Tree-ring Measurement

Fig. 4-2 shows scatter plot of diameter growth (cm 10^{-1} years) from diameter census and tree-ring measurement. Linear approximation and determination coefficient were; for 1st period y = 0.24 x + 1.85, R^2 = 0.01, for 2nd period y = 1.12 x – 1.51, R^2 = 0.06 and for all period y = 0.47 x + 0.73, R^2 = 0.04. Negative growths were observed at diameter census for every period, and there was great variability between diameter census and tree-ring measurement (Fig. 4-2). The results of paired *t* test showed no significant differences in diameter census and tree-ring measurement. Table 4-2 shows the deviations of diameter census from tree-ring measurement. The AD, APD and SD were high, but the values of all period were lower than 1st and 2nd period. Table 4-3 shows the deviations of diameter census from tree-ring measurement for DBH class. About the half of AD of all DBH class were negative differences. The APD and SD were higher for DBH $\geq$ 70 cm. Fig. 4-3 shows diameter growth (cm 10^{-1} years) from diameter census and tree-ring measurement for each of DBH class. The result of tree-ring measurement showed constant growth for every diameter class for every period, but the result of diameter census showed negative growth and large range of difference especially for diameter class of 80 and 110 cm.

4.3.2. Nail Measurement vs. Tree-ring Measurement

Fig. 4-4 shows scatter plot of diameter growth (cm 10^{-1} years) from nail measurement and tree-ring measurement. Linear approximation was y = 1.00 x + 0.68 (R^2 = 0.25). There was great variability between nail

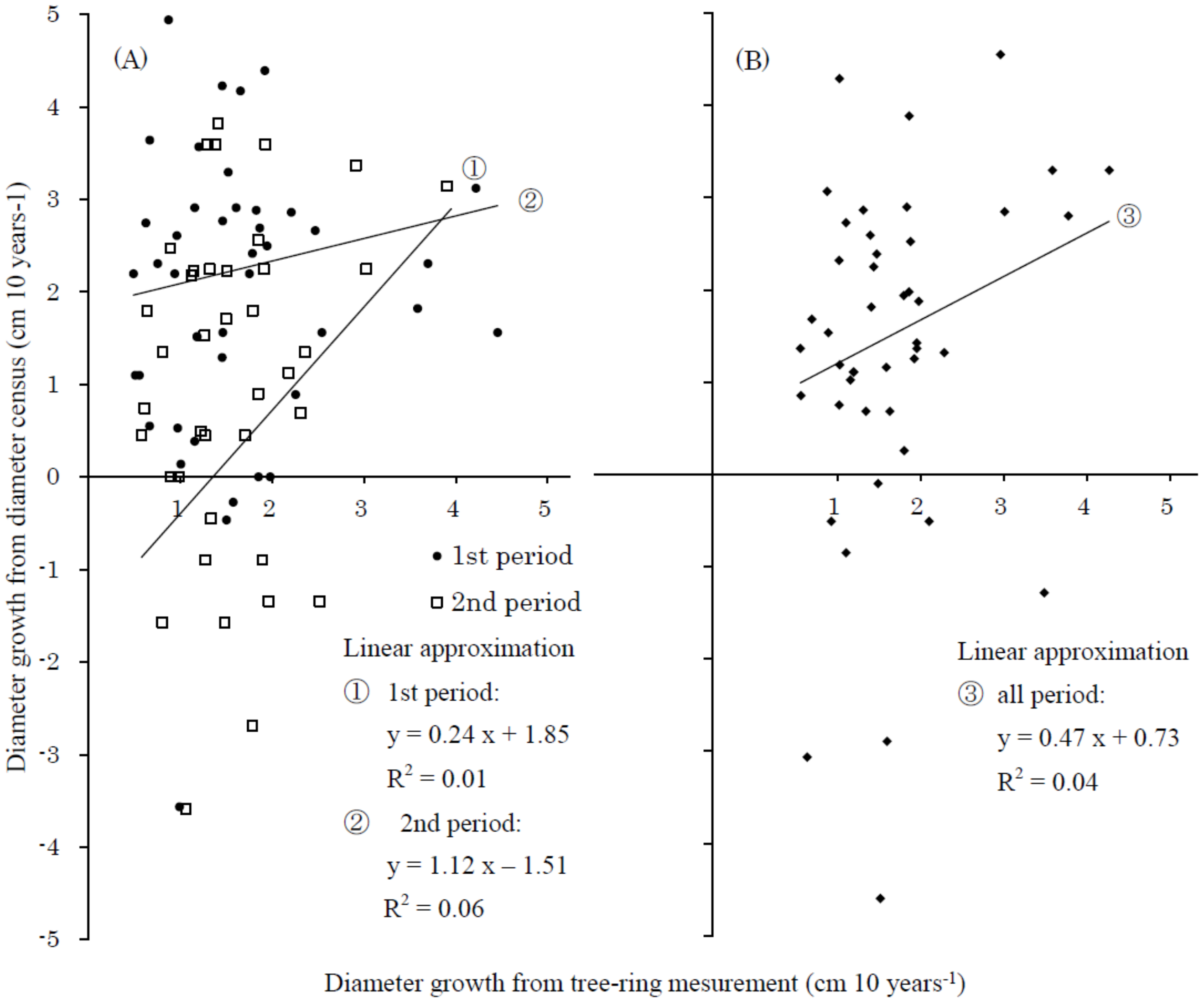
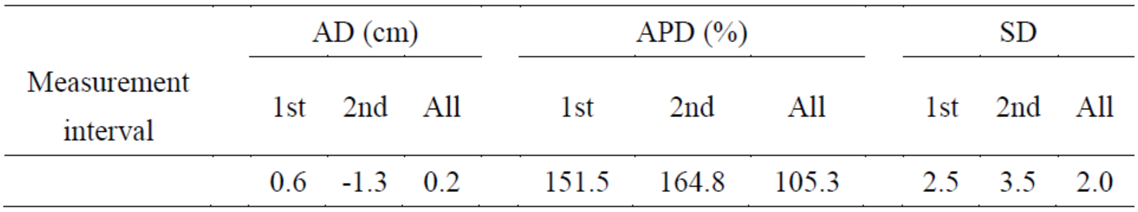


Fig. 4-2 Scatter plot of diameter growth (cm 10^{-1} years) from diameter census and tree-ring measurement, (A) for 1st and 2nd period and (B) for all period.

Table 4-2 Deviation of diameter census from tree-ring measurement (n = 49)



Measurement interval	AD (cm)			APD (%)			SD		
	1st	2nd	All	1st	2nd	All	1st	2nd	All
	0.6	-1.3	0.2	151.5	164.8	105.3	2.5	3.5	2.0

Table 4-3 Deviation of diameter census from tree-ring measurement for each DBH class

		AD (cm)			APD (%)			SD		
Measurement interval		1st	2nd	All	1st	2nd	All	1st	2nd	All
DBH class	*n*									
30	2	0.3	-2.0	-0.6	104.8	128.8	27.1	1.9	1.5	0.6
40	4	0.1	-0.4	-0.1	134.3	96.4	43.2	2.1	2.1	0.7
50	6	-0.3	0.4	0.0	45.2	62.5	33.9	1.0	1.2	0.8
60	7	1.7	-0.4	0.9	140.3	48.4	82.0	1.3	0.6	0.8
70	11	1.1	-1.5	0.1	179.8	175.11	129.4	3.4	2.4	1.7
80	7	0.2	-4.9	-1.8	121.8	352.1	99.4	1.9	5.8	2.0
90	5	-0.3	0.1	-0.1	276.8	95.5	158.9	3.7	2.3	2.5
100	4	1.7	0.3	1.1	185.6	91.7	130.5	2.9	1.2	2.1
110	1	1.7	-12.6	-3.7	347.5	1419.5	579.0	-	-	-
120	2	-1.0	1.7	-0.6	58.8	86.47	30.4	1.3	-	-

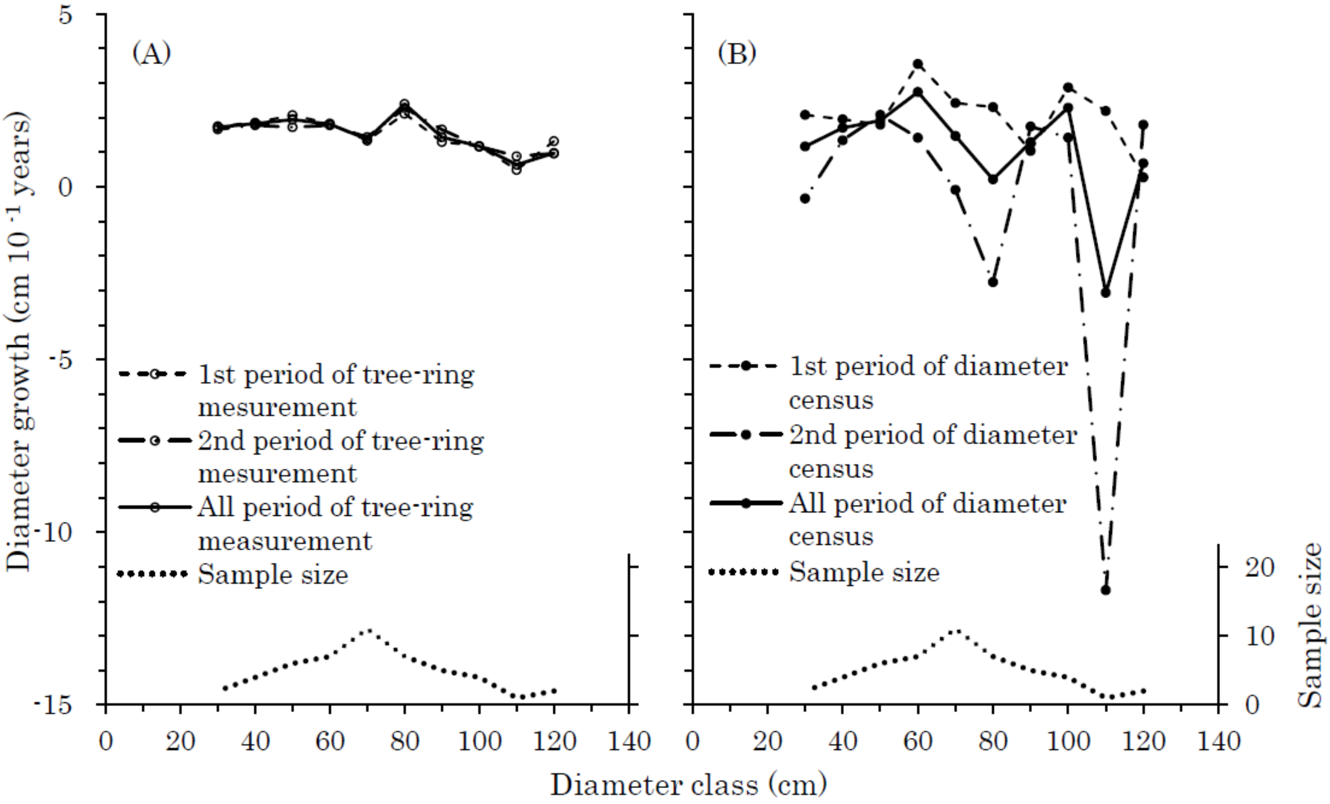


Fig. 4-3 Diameter growth (cm 10^{-1} years) from tree-ring measurement (A) and diameter census (B) for each of DBH class.

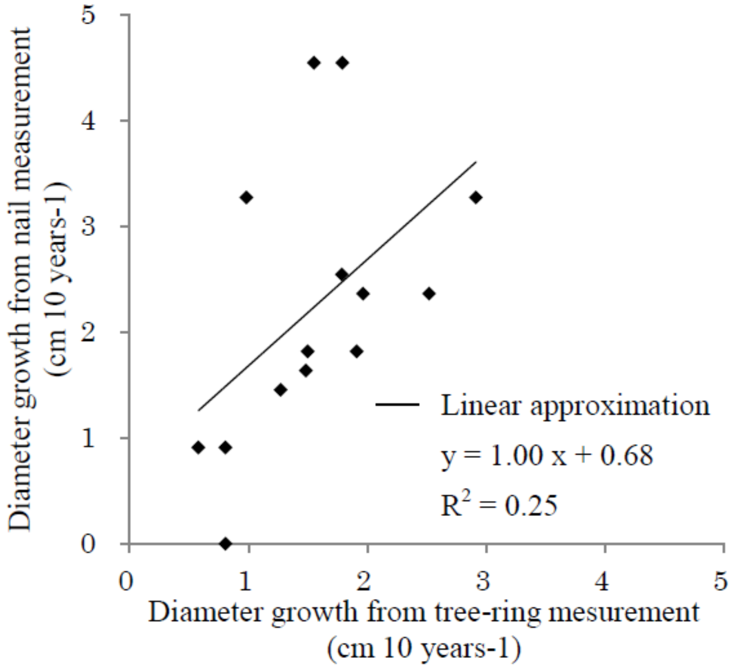


Fig. 4-4 Scatter plot of diameter growth (cm 10^{-1} years) from nail measurement and tree-ring measurement.

measurement and tree-ring measurement, but the variability is smaller than between the result of diameter census and tree-ring measurement (Figs. 4-2 and 4-4). The results of paired *t* test showed no significant differences in nail measurement and tree-ring measurement. Table 4-4 shows the deviations of nail measurement from tree-ring measurement. The AD, APD and SD were much lower than between diameter census and tree-ring measurement (Tables 4-4 and 4-5). Table 4-5 and Fig. 4-5 shows diameter growth (cm 10^{-1} years) from nail measurement and tree-ring measurement for each of diameter class. The tree-ring measurement was consistently lower than nail measurement for all diameter classes.

From the all data of rest length of nail from 224 trees, percentage of that nails have fallen away from the stem was 6.7%, and nails have been pushed out of the stem, was 2.2%.

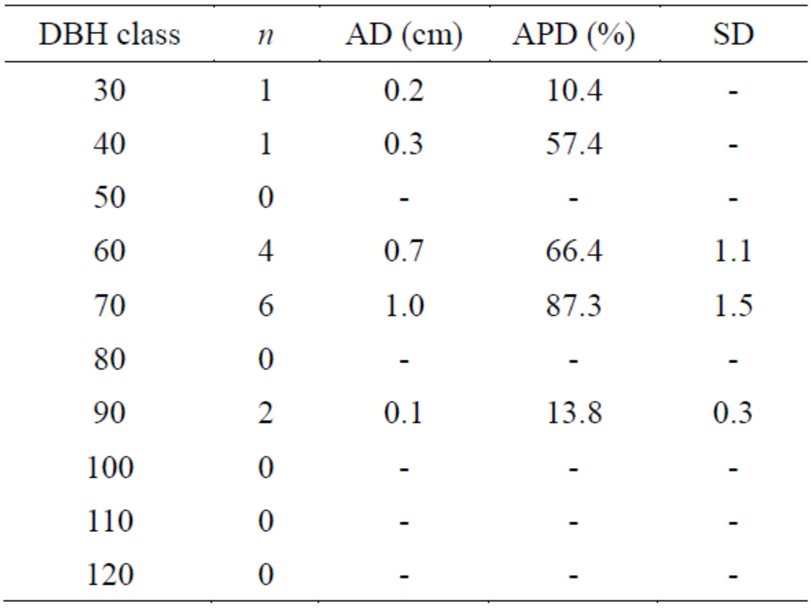
4.4. Discussion

The present study attempted to clarify error of growth from 30-years diameter censuses and tree-ring measurement of *Cr. japonica* on Yakushima Island. At diameter census, negative growth was observed, and there was great variability between diameter census and tree-ring measurement (Fig. 4-2). The reason of the variability and high APD and SD of the differences especially for DBH $\geq$ 70 cm might be resulting from the measurement errors using diameter tape; differences in tape tension and divergences in tape placement from the plane perpendicular to the tree axis (Elzinga *et al.*, 2005) (Table 4-3). Another possible reason for error is the placement of the tape above or below the specified breast height (Elzinga *et al.*, 2005), but it might be not a main reason because we measured DBH for diameter census at same position, where number plate was placed. Specific possible reasons

Table 4-4 Deviation of nail measurement from tree-ring measurement (*n* = 14)

AD (cm)	APD (%)	SD
0.7	63.2	1.1

Table 4-5 Deviation of nail measurement from tree-ring measurement for each DBH class



DBH class	*n*	AD (cm)	APD (%)	SD
30	1	0.2	10.4	-
40	1	0.3	57.4	-
50	0	-	-	-
60	4	0.7	66.4	1.1
70	6	1.0	87.3	1.5
80	0	-	-	-
90	2	0.1	13.8	0.3
100	0	-	-	-
110	0	-	-	-
120	0	-	-	-

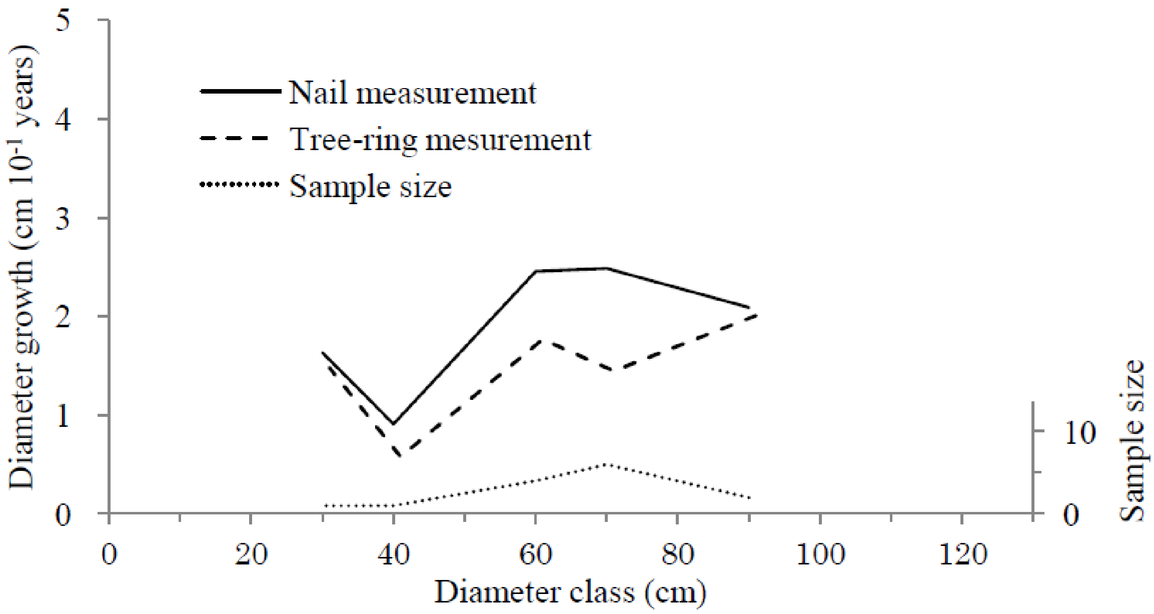


Fig. 4-5 Diameter growth (cm 10^{-1} years) from nail measurement and tree-ring measurement for each of diameter class.

for error of *Cr. japonica* on Yakushima Island might be thick moos covering the surface of stem and poor footing caused by many big stumps and logs on forest floor; these might make difficult to measure correctly. In some cases, it was impossible to use diameter tape, and pole was used for each tree 5 cm round based. The error using pole might be much bigger than using diameter tape. Also typical character for *Cr. japonica* with big diameter on Yakushima Island is irregular shape. As the sample core for tree-ring measurement was taken from just one or two directions, thus the actual tree circumference is not known (Clark *et al.*, 2007).

Between the nail measurement and tree-ring measurement, there was great variability but it is not as much as between diameter census and tree-ring measurement (Figs. 4-2 and 4-4). The deviations of nail measurement from tree-ring measurement showed lower APD and SD of the differences than between diameter census and tree-ring measurement (Tables 4-2, 4-3, 4-4 and 4-5). However there were significantly positive differences, indicating that the tree-ring measurement is consistently underestimated (Table 4-5 and Fig. 4-5). This under estimation might be caused by swelling by wound tissue, which can be observed after pinning (Kuroda, 1986).

Biondi (1999) reported that tree-ring data was closely matched with repeated forest inventories. However the deviations of diameter census from tree-ring measurement for AD, APD and SD were very high (Tables 4-2 and 4-3). This high deviation might be caused from error of diameter census because of bad condition mentioned before, and also of tree-ring measurement, which used only one or two cores from irregular shape of stem. Existence of false or missing rings might not be one major reason for error, because we evaluated tree-ring data using COFECHA program (Holmes, 1983).

In the study plots, census was conducted with 10-19 years intervals. However, this study indicated that longer monitoring period would be necessary especially for large trees with DBH ≥ 70 cm, because the deviations were much lower for all period, which was 28-30 years intervals (Tables 4-2 and 4-3). The data from nail measurement might be used as reference for correction of data from diameter census. Currently, all old-growth *Cr. japonica* forests are in the protected area on Yakushima Island. The diameter census will be a very important tool to know further growth dynamics because taking core from natural *Cr. japonica* tree from those forests will be difficult. Knowing the results from this study is important to understand growth and dynamics towards natural old-growth *Cr. japonica* forests using census data.

5. General Discussion

This thesis attempted to clarify the long-term growth dynamics and the effects of human disturbances on the growth of *Cr. japonica* on Yakushima Island based on dendroecological analysis. The growth pattern and germination year of regenerated *Cr. japonica* on Yakushima Island that regenerated subsequent to the inaugural year of past logging activity were revealed. I also tried to pinpoint the time of disturbance over last several hundred years and effects of disturbances on the growth of old *Cr. japonica* that escaped logging. Additionally, growth from diameter censuses and tree-ring data were compared to know error range.

The long-term growth patterns of *Cr. japonica* on Yakushima Island over last several hundred years was revealed using dendroecological analysis in Chapter 2. Tree-ring widths of samples were measured and annual basal area increment (BAI) was calculated from tree-ring series. Tree-ring series indicated diversity among individual diameter growth curves. The 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. Generally, growth rate (m^3 year^{-1}) culmination of artificial *Cr. japonica* forests occurs after approximately 15-40 years (Otomo, 1983). However, the BAI 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 trees maintained high growth rates. 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. Mean of tree-ring width was greater than 1 mm below the 160 year age class, although *Cr. 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). The growth rate was higher 100-150 years ago than the last 30 years. These results clarified 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.

The time and the scale of disturbances and the effects of logging on growth of old-aged *Cr. japonica* were revealed using dendroecological analysis in Chapter 3. The result suggested that systematic large scale logging activities of *Cr. japonica* occurred as part of the historical record. In our study site, logging activity might have 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 500-600 years old, while the growth rate of trees normally declines as a tree ages (Gower *et al.*, 1996). However, 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. The gap formation may be important for regeneration of *Cr. japonica*. The small scale disturbance associated with individual tree level might be inadequate to stimulate regeneration of *Cr.*

japonica, because there were some releases since 1970, but based on monitoring results since 1973 in study sites, only a few *Cr. japonica* have been recruited (Takashima, 2009). Low levels of disturbances also occurred before 1630 and these releases were likely to be caused by logging but might have been small scale, because Ushijima *et al.*, 2006 suggested some logging activities before 1642 based on the tree-ring analysis of stumps. These results suggest past logging activities are important to encourage growth and regeneration of *Cr. japonica*.

In Chapter 4, growth from 30-years diameter censuses and tree-ring data of *Cr. japonica* on Yakushima Island was compared. At diameter census, negative growth was observed, and there was great variability between diameter census and tree-ring measurement. The high APD and SD of the differences for DBH ≥ 70 cm might be resulting from the measurement errors using diameter tape; differences in tape tension and divergences in tape placement from the plane perpendicular to the tree axis (Elzinga *et al.*, 2005). Specific possible reasons for error of *Cr. japonica* on Yakushima Island might be thick moos covering the surface of stem and poor footing caused by many big stumps and logs on forest floor; these might make difficult to measure correctly. In some cases, it was impossible to use diameter tape and pole was used for each tree in 5 cm round based. The error using pole might be much bigger than using diameter tape. Also typical character for *Cr. japonica* with big diameter on Yakushima Island is irregular shape. As the sample core for tree-ring measurement was taken from just one or two, thus the actual tree circumference is not known (Clark *et al.*, 2007). In the study plots, census was conducted 10-19 years intervals. However, this study obtained that longer monitoring period would be necessary especially for large trees with DBH ≥ 70 cm.

In conclusion, this thesis revealed that growth rate of *Cr. japonica* on Yakushima Island showed relatively late culmination compared to artificial *Cr. japonica* forests, and the systematic large scale logging activities encouraged growth rates in older trees about 500-600 years old and regeneration of *Cr. japonica*. Hence, large scale of disturbances as past logging activity might be very important to encourage growth and germination of *Cr. japonica*. This paper also suggested the need for larger interval of diameter census for large trees with DBH ≥ 70 cm, than currently adopted one because of large measurement error for large trees. Currently, logging of natural *Cr. japonica* in Yakushima Island is basically not allowed. The diameter census will be a very important tool to know further growth dynamics because taking core of living natural *Cr. japonica* tree from those forests will be difficult. There are *Cr. japonica* plantations in the buffer area of protection area and in the production area in Yakushima Island, where selective loggings are carried out. Knowing the results from this study will be useful for forming a long-term forest management strategy in these buffer and production area of *Cr. japonica* forests. Further research should focus on tree-ring analysis of stumps and fallen logs to understand growth pattern of more ancient *Cr. japonica* trees and exact time point of logging.

References

Abrams, M. D., Copenheaver, C. A., Terazawa, K., Umeki, K., Takiya, M., Akashi,N. (1999) A 370-year dendroecological history of an old-growth Abies-Acer-Quercus forest in Hokkaido, northern Japan. Can. J. For. Res. 29: 1891-1899

Barker, J. R., Bollman, M., Ringold, P. L., Sackinger, J., Cline, S. P. (2002) Evaluation of metric precision for a riparian forest survey. Environ. Monit. Assess. **75**: 51-72

Biondi, F. (1999) Comparing tree-ring chronologies and repeated timber inventories as forest monitoring tools. Ecol. Appl. **9**: 216-227

Black, B. A. and Abrams, M. D. (2003) Use of boundary-line growth patterns as a basis for dendroecological release criteria. Ecol. Appl. **13**:1733-1749

Bonnicksen, T. and Stone, E. (1980) The giant sequoia-mixed conifer forest community characterized through pattern analysis as a mosaic of aggregations. For. Ecol. Manage. **3**: 307-328

Cherubini, 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

Clark, J. S., Wolosin, M., Dietze, M., Ibáñez,I., LaDeau, S., Welsh, M., Kloeppel, B. (2007) Tree growth inference and prediction from diameter censuses and ring widths. Ecol. Appl. **17**: 1942-1953

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

Elzinga, C., Shearer, R.C., Elzinga, G. (2005) Observer variation in tree diameter measurements. West. J. Appl. Forestry **20**: 134-137

Fritts, H. C. (1976) Tree rings and climate. Academic Press, London. 567pp

Gower, S., McMurtrie, R. E. and Murty, D. (1996) Aboveground net primary production decline with stand age: potential causes. Trends. Ecol. Evol. **11**: 378-382

Hamaoka, T. (1933) Regeneration of *Cryptomeria japonica* in natural forest of Yakushima Island* (in Japanese). J. Jpn. For. Soc. **15**: 150-162

Holmes, R. L. (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. **43**: 69-78

Imada, M. (1986) Fundamental planning and its experimental forest of the group selection system of sugi (*Cryptomeria japonica* D. Don) in Yakusima. J. Jpn. For. Soc. **68**: 35-40 (in Japanese)

Ishii, H., Takashima, A., Makita, N. and Yoshida, S. (2010) Vertical stratification and effects of crown damage on maximum tree height in mixed conifer-broadleaf forests of Yakushima Island, southern Japan. Plant Ecol. **211**: 27-36

Japan Meteorological Agency (2013) Climate statistics. http://www.data.jma.go.jp/obd/stats/etrn/index.php (Accessed on 02 February, 2013)

Kagoshima prefecture (2012) Annual report on the environment. http://www.pref.kagoshima.jp/kurashi-kankyo/kankyo/sougou/hakusho/index.html (Accessed on 12 February, 2013)

Kakinoki, T. (1954) A study of *Cryptomeria japonica* on Yakushima Island (in Japanese). Forestry Office of Kagoshima, Kagoshima, 20-44

Kanetani, S. and Yoshimaru, H. (2007) Nature and history of Yakushima Island (in Japanese). In: KANETANI, S. and YOSHIMARU, H. (eds) Yakushima no mori no sugata [Aspect of forest in Yakushima*] (in Japanese). Bun ich Co., Ltd., Tokyo, 11-25

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)

Kitahara, F., Mizoue, N., Yoshida, S. (2009) Evaluation of data quality in Japanese National Forest Inventory. Environ.Monit.Assess. 159:331-340

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

Kuroda, K. (1986) Wound effects on cytodifferentiation in the secondary xylem of woody plants. Wood research: bulletin of the wood research institute Kyoto University. **72**: 67-118

Kyushu Regional Forest Office (2013) Yakushima shinrin seitaikei hogo chiiki [Forest Ecosystem Protected Area in Yakushima*] (in Japanese). http://www.kyusyu.kokuyurin.go.jp/hogorin/seitaikei/yakushima/yakushima-02-syosai.html (Accessed on 15 February, 2013)

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

Leak, W. B. (1987) Comparison of standard and actual tree-growth trends for deciduous and coniferous species in New Hampshire. Can. J. For. Res.

17: 1297-1300

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

Lorimer, C. G. and Frelich, L. E. (1989) A methodology for estimating canopy disturbance frequency and intensity in dense temperate forests. Can. J. For. Res. **19**: 651-663

Maeda, T. (1983) Natural distribution (in Japanese). In: National Forestry Extension Association in Japan (eds) Sugi no subete [All about the Japanese cedar*] (in Japanese). National Forestry Extension Association in Japan, Tokyo, 8-27

Mitsutani, T. (1987) Establishment and application of dendrochronology in Japan I. Characteristics of ring patterns in modern hinoki (Chamaecyparis obtuse S. et Z.) trees. J. Wood Sci. 33:165-174 (in Japanese with English summary)

Miyawaki, A. (1980) Vegetation of Japan volume 1 Yakushima (in Japanese). Shibundo, Tokyo, 376pp

Nishizono, T., Sawata, S. and Awaya, Y. (2006) Structure and growth in an old-growth sugi (*Cryptomeria japonica*) forest in Akita prefecture, northeastern Japan. J. Jpn. For. Soc. **88**: 8-14 (in Japanese with English summary)

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

Nowacki, G. J. and Abrams, M. D. (1997) Radial-growth averaging criteria for reconstructing disturbance histories from presettlement-origin oaks. Ecol. Monogr. **67**: 225-249.

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

Sato, M. and Teraoka, Y. (2012) The current situation and historical change of Yaku-sugi debris production. Res. Bull. Kagoshima Univ. for. 39: 1-7 (in Japanese with English summary)

Shimokawa, E. and Jitousono, T. (1984) Residence time of soil on slopes and Yaku-sugi (*Cryptomeria japonica*) in the Yaku-shima Wilderness Area, Yaku-shima island. In: Conservation reports of the Yaku-shima wilderness area, Kyushu, Japan. Nature conservation bureau, Environment Agency, Japan. 83-100 (in Japanese with English summary)

Splechtna, B. E., Gratzer, G. and Black, B. A. (2005) Disturbance history of a European old-growth mixed species forest – A spatial dendro-ecological analysis. J. Veg. Sci. **16**: 511-522

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**: 223-241

Tagawa, H. (1994) Sekai no sizen isan Yakushima [World heritage site Yakushima*] (in Japanese). NHK books, Tokyo. 187 pp

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, 108pp

Takyu, 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) Yakusugi tennensei rinbun no rinbun kouzou ni tsuite [Forest structure of natural *Cryptomeria japonica* forest on Yaku-shima Island*] (in Japanese). Bachelors Thesis, Kagoshima University, 45pp

Ushijima, S., Takashima, A., Yoshida, S., Murakami, T., Mizoue, N. and Kimura, K. (2006) Dendrochronological analysis of the stumps in *Cryptomeria japonica* forests on Yakushima Island. Kyushu J. For. Res. **59**: 150-153 (in Japanese with English summary)

Yasuda, Y. (1980) Kankyo koukogaku kotohajime [Introduction to Environmental Archaeology*] (in Japanese). NHK books, Tokyo, 270pp

Yoshida, S. (2007) Method of continuous research on natural *Cryptomeria japonica* forest (in Japanese). In: KANETANI, S. and YOSHIMARU, H. (eds) Yakushima no mori no sugata [Aspect of forest in Yakushima*] (in Japanese). Bun ich Co., Ltd., Tokyo, 55-61

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)

Ziegler, S. S. (2004) Composition, structure, and disturbance history of old-growth and second-growth forests in Adirondack Park, New York. Phys. Geogr. **25**: 152-169

* The English titles are tentative translations from the original Japanese titles.

Summary

Old-growth *Cryptomeria japonica* forest on Yakushima Island, Japan may have been affected by large-scale logging activities that began approximately 350 years ago and continued over 300 years. The forest on the island currently consists of 200–300 year-old *Cr. Japonica* that regenerated after logging activities and 400 to over 1000 year-old trees that have survived logging activities. Thus the *Cr. japonica* forest on Yakushima Island is a valuable site that enables estimation of long-term growth pattern and effects of human disturbance. The objectives of this thesis were; 1) to reveal long-term growth patterns of *Cr. japonica* on Yakushima Island over the last several hundred years and the scale and the effects on growth of *Cr. japonica* on Yakushima Island of past disturbances based on dendroecologial approach, 2) to reveal error range of growth estimation from diameter censuses in comparison with tree-ring data in old-growth *Cr. japonica* forest.

In Chapter 1, growth condition and previous studies on *Cr. japonica* forest on Yakushima Island were summarized.

In Chapter 2, long-term growth patterns in regenerated *Cr. japonica* on Yakushima Island, which ranged in age from about 200-300 years, were examined. Tree-ring widths of samples were measured and annual basal area increment (BAI) was calculated from tree-ring series. Tree-ring series indicated diversity among individual diameter growth curves. BAI increased with age until approximately 110 years and the 50 cm diameter class and decreased gradually; this period of increase is longer than that observed in *Cr. japonica* in an artificial forest. Comparison of these results with census results suggested that growth rates were higher 100-150 years

ago than they were during the last 30 years.

In Chapter 3, tree-ring analysis was employed to understand the scale and pinpoint the time of past disturbances. To detect release events caused by human or natural disturbances, annual BAI and growth change from tree-ring width were calculated. Sample trees showed release events from 1600 to 1900s, and showed high BAI values for 150 years after releases. The estimated germination timing of regenerated trees subsequent to the inaugural year of logging is consistent with release events followed by high BAI values of old-aged trees. The evidence on all regenerated samples germinating 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 from 1600 to 1900s encouraged the growth rate of approximately 500-600 years old trees, and also large scale of disturbance was important for regeneration of *Cr. japonica*.

In Chapter 4, growth of 30-years diameter censuses, which have been conducted three different times, and tree-ring data of *Cr. japonica* on Yakushima Island were compared. The results showed variability and large range of errors in diameter measurement for trees with diameter at breast height (DBH) ≥70 cm, which might be resulting from measuring error using diameter tape, etc.. Specific possible reasons for error of old-growth *Cr. japonica* on Yakushima Island might be thick moos covering the surface of stem and poor footing caused by many big stumps and logs on forest floor; it might make difficult to measure correctly. In the permanent study plots, census was conducted 10-19 years intervals. However, this study indicated that longer monitoring interval would be necessary especially for trees with DBH ≥ 70 cm.

In Chapter 5, the obtained results were totally discussed. This thesis revealed long-term growth dynamics and effects of human disturbance on growth of *Cr. japonica* on Yakushima Island. The *Cr. japonica* forest in the study plot was affected by large scale of logging activities and the logging affected growth and germination. In this paper, also diameter censuses and tree-ring data of *Cr. japonica* on Yakushima Island were compared. Diameter census for big tree had large measurement error; it might have been caused by specific reasons in Yakushima Island. Further research should focus on using tree-ring analysis of stumps and fallen logs to understand growth pattern of more ancient *Cr. japonica* trees and exact time point of logging.

Summary (in Japanese)

屋久島の老齢スギ天然林では，約 350 年前に大規模伐採が始まり，伐採は約 300 年続いたといわれている。現在，屋久島におけるスギ林では，伐採後に更新した樹齢 200-300 年のスギと，伐採を免れた樹齢 400 年から 1000 年を超えるスギが混在している。つまり，屋久島のスギ林は，人為活動の影響を含めた長期成長パターンを解明することができる非常に貴重な研究サイトである。そこで本研究では，1）屋久島のスギにおける，数百年に及ぶ長期成長パターンと，過去の伐採が成長に及ぼす影響を，年輪生態学的手法を用いて解明すること，2）屋久島での継続調査における直径計測結果と年輪解析データを比較・検討し，老齢な天然林での大径木調査の測定誤差を明らかにすることを目的とした。

第 1 章では，屋久島におけるスギの成育概況と，既存の研究について概説した。

第 2 章では，更新木である樹齢 200-300 年の年輪幅を計測し，年間断面積成長量を算出した。年輪幅より算出した直径成長曲線は，それぞれの供試木間で大きなばらつきを示したが，おおむね断面積成長量は，樹齢と共に樹齢階 110 年と直径階 50 cm までは増加，それ以降は下降する傾向を示し，スギ人工林と比較するとかなり緩慢な成長を示した。これらの結果と継続調査結果を比較して，過去 30 年間よりも 100-150 年前の成長量の方が大きいことを明らかにした。

第 3 章では，年輪解析を用いて過去の撹乱時期やその規模を解明した。人為もしくは自然介入による撹乱を抽出するため，年間断面積成長量と年輪幅成長量変化の割合を算出した。その

結果，1600-1900年代にかけての大規模な撹乱が存在し，供試木は撹乱後 150 年間，高い断面積成長量を示した。また，スギ更新木の発生時期は，高い断面積成長量を伴う撹乱の後であった。さらに，それら更新木は，切り株や伐倒木の上に更新していることからも，この様な撹乱は人為撹乱であると推測された。以上より，1600-1900年代の間に大規模伐採が行われ，それによっておよそ樹齢500-600年という老木の成長が促され，スギ更新にも重要な役割を果たしたことを明らかにした。

第4章では，屋久島におけるスギの過去30年に及ぶ継続調査における 3 回の直径計測結果と，年輪解析による年輪幅データを比較した。結果にはばらつきがみられ，特に胸高直径 70 cm以上で誤差が大きかった。これは，直径テープ等による計測の際に生じた誤差，大径木を覆う厚い苔の存在，更に林内の大きな切り株や伐倒木による足場の悪さといった，屋久島並びに老齢天然林特有の要因が，正確な計測を困難にしていると考えられた。屋久島におけるスギ天然林の固定試験地においては，10-19年おきに直径計測が行われているが，以上より，特に胸高直径70cm以上の大径な個体に関しては，それ以上の間隔での計測が望ましいことが示唆された。

第5章では，研究結果について総合考察を行った。本研究より，長期成長動態や，人為介入が屋久島のスギの成長に及ぼす影響について明らかになった。大規模伐採が，スギの成長と更新を促したことが判明した。また，直径計測と年輪データを比較した結果，大径木の直径計測には，大きな誤差が生じることが判明し，それは屋久島特有の要因が影響していると推測された。今後更に過去に遡った成長パターンを解明して，伐採年を確定するためには，切り株や伐倒木の年輪を解析していく必要性がある。

Acknowledgements

Permission of taking sample cores 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.

I would like to thank chief examiner Prof. Dr. Yoshida, associate examiner Dr. Mizoue and Dr. Gyokusen, for assisting my study and writing of this doctoral thesis. I also would like to thank Dr. Kajisa and Dr. Ota, who belong to Laboratory of Forest Management, for many comments on this paper. I appreciate the detailed data about preceding research and comments received from Dr. Takashima from University of the Ryukyus. I have greatly benefited from Dr. Yasue from Shinshu University, for teaching the method of tree-ring analysis. Furthermore, I would like to thank Mr. Yamada, Mr. Ushijima, Mr. Kawasoe and Ms. Koishi for preceding researches and the members of the Institute for Forest Management Laboratory for many advices and serving tee.

Additionally, I want to thank my husband, my 2-year old daughter and a baby in my body for understanding my work and sacrifice of some family-weekends.

February 2013. Shizu Itaka

*This study was supported by the "Evaluation and Prediction of Effects on Forest Ecosystems in Southwestern Japan Caused by Air Pollution" project administered by the Environment Ministry of Japan and headed by S.

Kanetani, as well as the Global COE Program (Ministry of Education, Culture, Sports, Science and Technology, Japan; Center of excellence for Asian conservation ecology as a basis of human-nature mutualism).