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Article

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

Shizu Itaka *1, Shigejiro Yoshida *2, Nobuya Mizoue *2, Tetsuji Ota *2,
Atsushi Takashima *3, Tsuyoshi Kajisa *2 and Koh Yasue *4

ABSTRACT

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

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

INTRODUCTION

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

Previous studies regarding growth of *Cr. japonica* on Yakushima Island have monitored growth since 1973 (Yoshida and Imanaga, 1990; Takashima, 2009), while others have examined growth or dynamics of *Cr. japonica* over a span of 10-20 years (Kimura, 1994; Takyu et al., 2005); however, 10-30 years might not be long enough to understand long-term growth pattern of this species, which can live for over 1000 years. Furthermore, previous research using stem analysis of *Cr. japonica* on Yakushima Island employed only 3 sample trees aged 45-149 years (Hamaoka, 1933), and no previous studies have examined a large enough sample of individuals covering a range of ages that spans hundreds of years. The long-term growth pattern of *Cr. japonica* over the course of several hundred years remains poorly understood.

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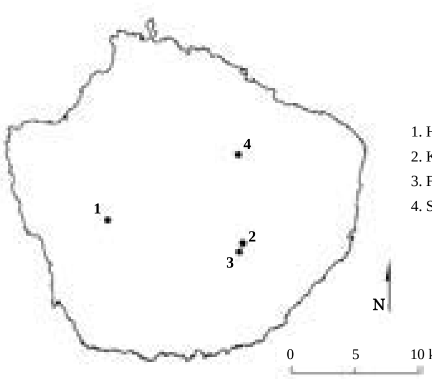
Using variations in tree-ring width, it is possible to extrapolate information regarding growth rate. In fact, recent studies have used tree-ring widths to identify and quantify growth trends (Cherubini et al., 1998; Ota et al., 2007). The time span of monitoring data is limited to only several decades; 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.

MATERIALS AND METHODS

Study area

Yakushima Island is located at 30° 20′ N latitude and 130° 31′ E longitude, approximately 60 km off the southern end of Kyushu, southern Japan and has an area of 504.9 km^2 (Fig. 1). The shape of the island is nearly circular and the boundary length is approximately 130 km. Mt. Miyanoura, located at the center of the island, reaches an altitude of 1936 m and forms the island's highest point. Precipitation levels on Yakushima Island are some of the highest in the world and range from 2400-5000 mm year^{-1} on the coast and 5000-7400 mm year^{-1} within mountainous areas (Takahara and Matsumoto, 2002). This heavy rainfall is caused by ascending air currents under the influence of the warm Pacific current as well as frequent typhoons (Takahara and Matsumoto, 2002). The presence of high precipitation and mild climatic conditions has lead to the development of rich forests, with approximately 90% of the island covered by forest. A difference in elevation of approximately 2000 m exists between the lowlands and the mountain peaks, and within this range can be found sub-tropical and temperate rainforests, mixed conifer-broadleaved forest containing *Cr. japonica*, and evergreen dwarf bamboo grassland surrounding the mountain peaks (Kyushu Regional Forest Office/Yaku-shima Environment Conservation Center, 1996).



1. Hanayama (*HP*)
2. Kohanayama (*KP*)
3. Futaridake-no-komichi (*FP*)
4. Shiratani (*SP*)

Fig. 1 Location of study plots on Yakushima Island.

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

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^{-1})	Mean DBH (cm)	No. (plot^{-1})	Mean DBH (cm)	Mean ring-width (mm)	Range of estimated age (year)
HP	1250	1.0	1974	1992	2003	192	67.5	10	66.3	1.17	206-302
KP	1100	1.0	1973	1988	1998	195	70.6	4	80.6	1.81	186-258
FP	1050	1.0	1973	1991	2002	123	57.5	7	57.6	1.37	170-214
SP	850	0.8	1974	1993	2004	26	75.3	7	61.6	1.83	100-276

DBH: diameter at breast height

(Takashima, 2009).

Sampling and Cross-dating Trees

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).

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

Sampled cores were glued onto wooden mounts and sanded until individual tree-rings were clearly visible. Width of each tree-ring was measured on a TA Unislide Velmex

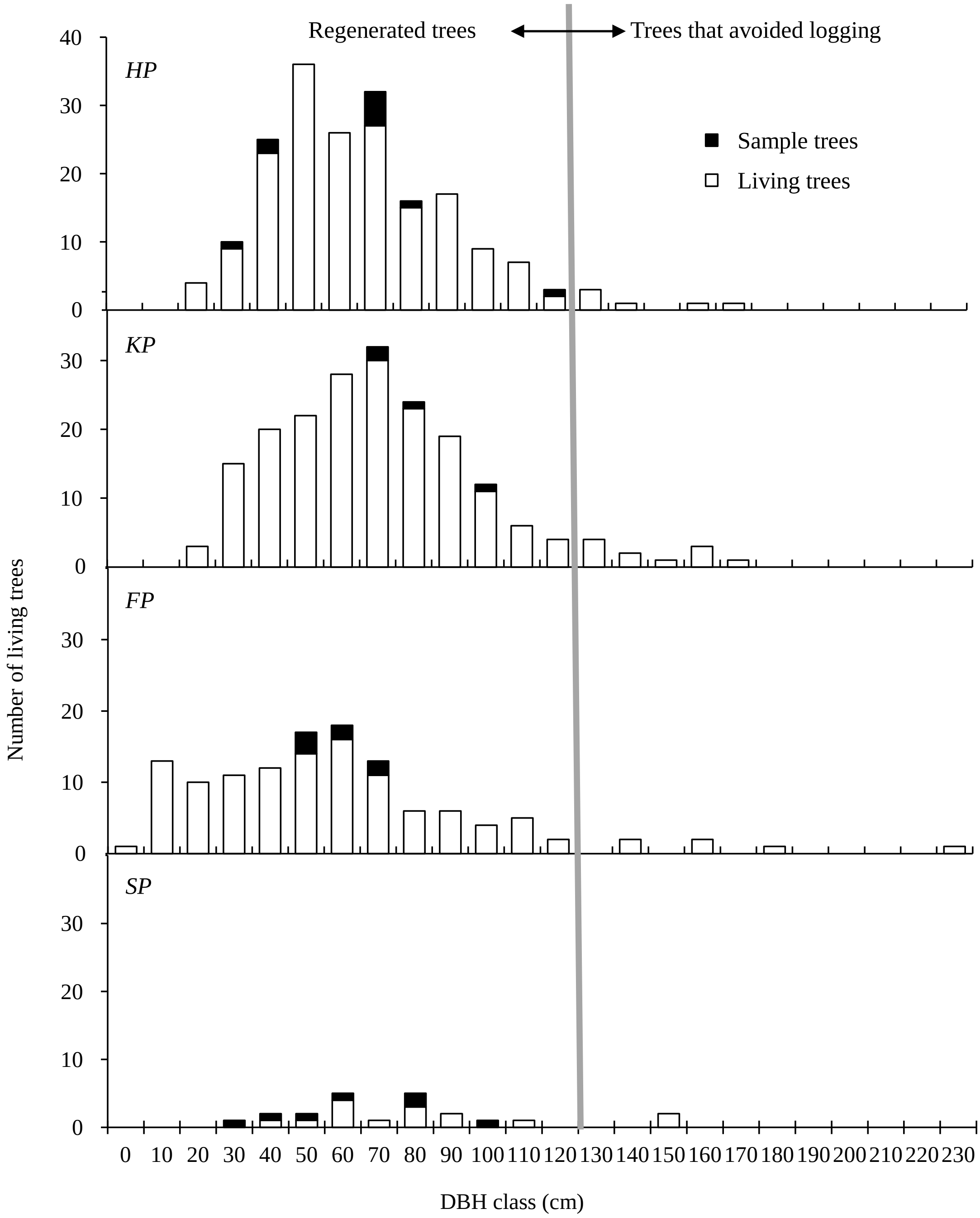


Fig. 2 Diameter distribution of living *Cr. japonica* individuals (3rd measurement interval)

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

Age Estimation

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

1. Measuring arc of inner tree-ring

When sample cores passed close enough to the chronological center that arcs of the inner rings were visible, missing radius lengths were estimated using the equation (Duncan, 1989):

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

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 in order to obtain an estimate of age. When the length of the missing radius appears to be within 50 mm, then the mean absolute error is ±21 years of age (Duncan, 1989). In this study, the mean length of the missing radius was 30.7 mm.

2. Age-diameter model

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

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

Growth-rate Calculation

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

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

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. BAI results were grouped into each age class and diameter class, and Tukey's parametric multiple comparison procedures were applied to test whether there are significant differences in pairs of different classes.

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

RESULTS

Diameter of the coring height of sampled trees was calculated for each year based on tree-ring series (Fig. 3), and age-diameter relationships were inferred from estimated age and tree-ring widths for trees of different age (Fig. 4). For

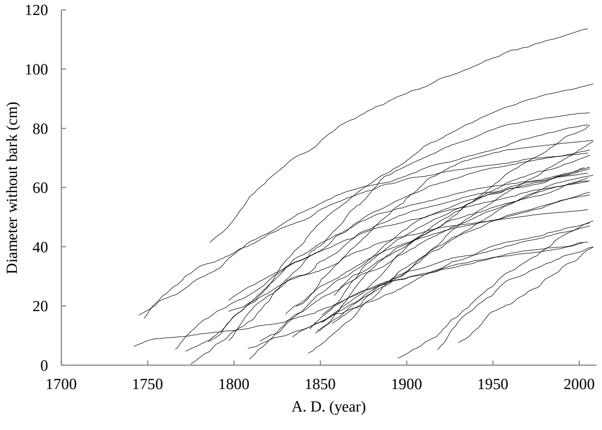


Fig. 3 Tree diameter growth.

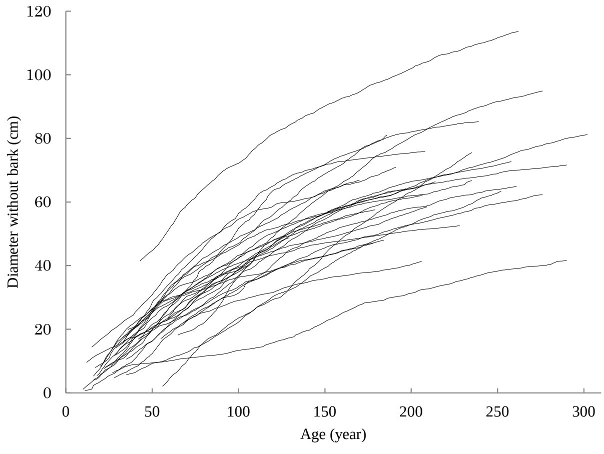


Fig. 4 Age-diameter relationship.

trees sampled in the present study, diameter classes ranged from 30-120 cm, age classes ranged from 100-300 years, and individual diameter growth curves showed high diversity (Figs. 3 and 4). Standard deviation of tree-ring widths and BAI values also showed a wide range (Figs. 5 and 6), which suggested a high degree of variability between individual growth patterns.

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

BAI values of 28 individuals from four study plots were grouped into 10-year age classes as well as 10 cm diameter classes and averaged (Fig. 6). Results of multiple comparisons showed significant differences in BAI growth rate within individuals in age classes below 50 years and diameter classes below 30 cm. In fact, BAI growth rate increased rapidly up until the 50 year age class and the 30 cm diameter class before it reached a ceiling; however, a slow increase in BAI growth rate was observed from the 50 year to the 110 year age class before it gradually decreased (Fig. 6(A)). Furthermore, a slow increase in BAI growth rate from the 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. 6(B)).

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

DISCUSSION

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

According to the results of tree-ring analysis, tree-ring width increased until the 20-50 year age class and the 10 cm diameter class, after which point growth rate gradually decreased (Fig. 5). The decline observed within this age class could be typical of tree-ring width growth patterns, which are wide rings near the pith and narrower rings toward outside (Phipps, 1979). *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.

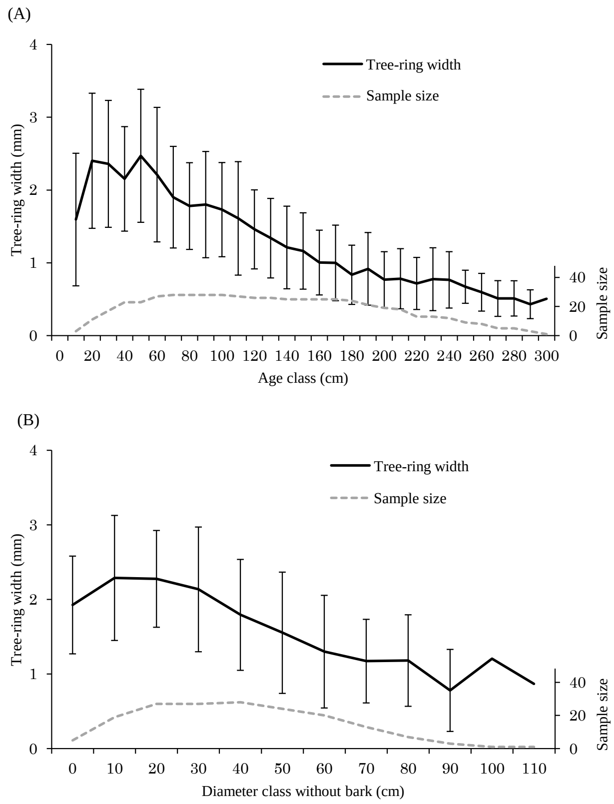


Fig. 5 Growth rate of tree-ring width for each of age (A) and diameter classes (B). The error bar indicates the standard deviation.

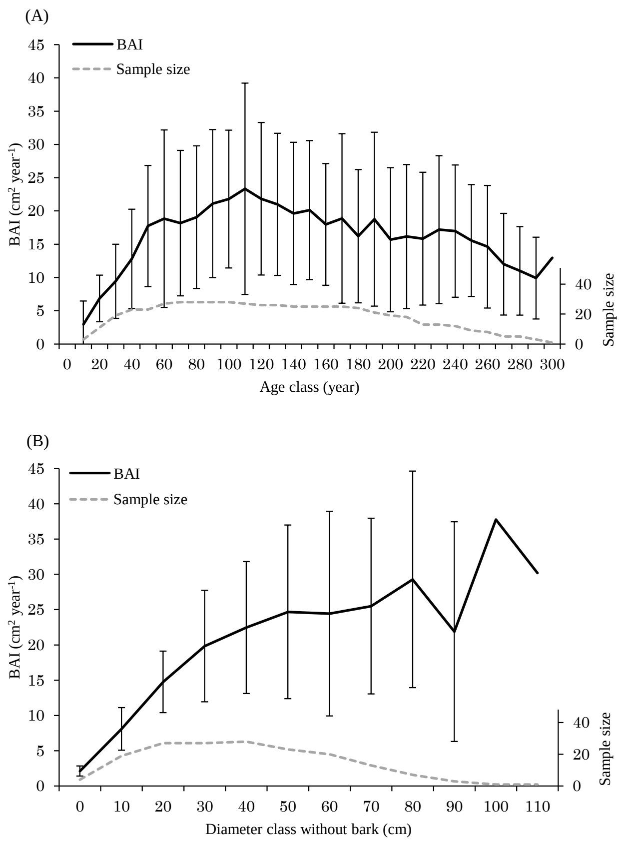


Fig. 6 Growth rate of basal area increment for each of age (A) and diameter classes (B). The error bar indicates the standard deviation.

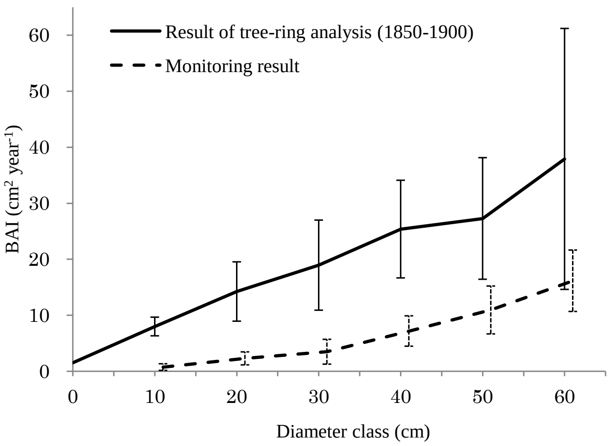


Fig. 7 Growth rate of basal area increment of tree-ring analysis from 1850-1900 and monitoring result during the last 30 years. The error bar indicates the standard deviation.

5(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. 6(A)). Therefore, the observed growth rate peak in age of the natural *Cr. japonica* forest on Yakushima Island was significantly greater than that of artificial *Cr. japonica* forests. However, individual variation in tree growth patterns is a common characteristic of natural forests, because the growing conditions of each individual tree can differ (Kimura, 1994). Wide standard deviations of tree-ring widths and BAI values might also be a characteristic of natural forests (Figs. 5 and 6).

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

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

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

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Article

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 regeneration 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/Yaku-shima 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 km^2 (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; Kakinoki, 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.

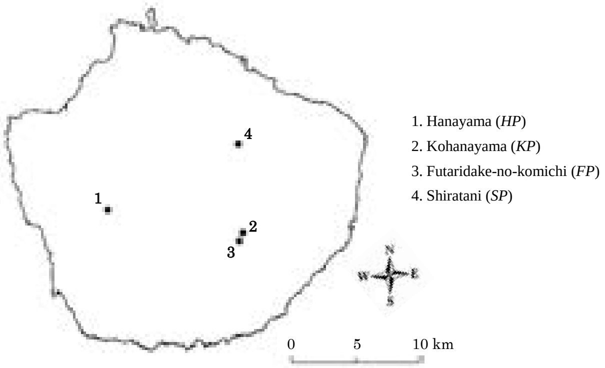

Fig. 1 Location of study plots on Yakushima Island.

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

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^{-1})	Mean DBH (cm)	No ($plot^{-1}$)	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

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-leafed trees were mapped (Takashima, 2009). For *Cr. 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 *Cr. 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):

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

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). In this

Table 2 Sample tree attributes: old-aged sample trees ofthe *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

Tab1e 3 Sample tree attributes: regenerated samp1e tree 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	

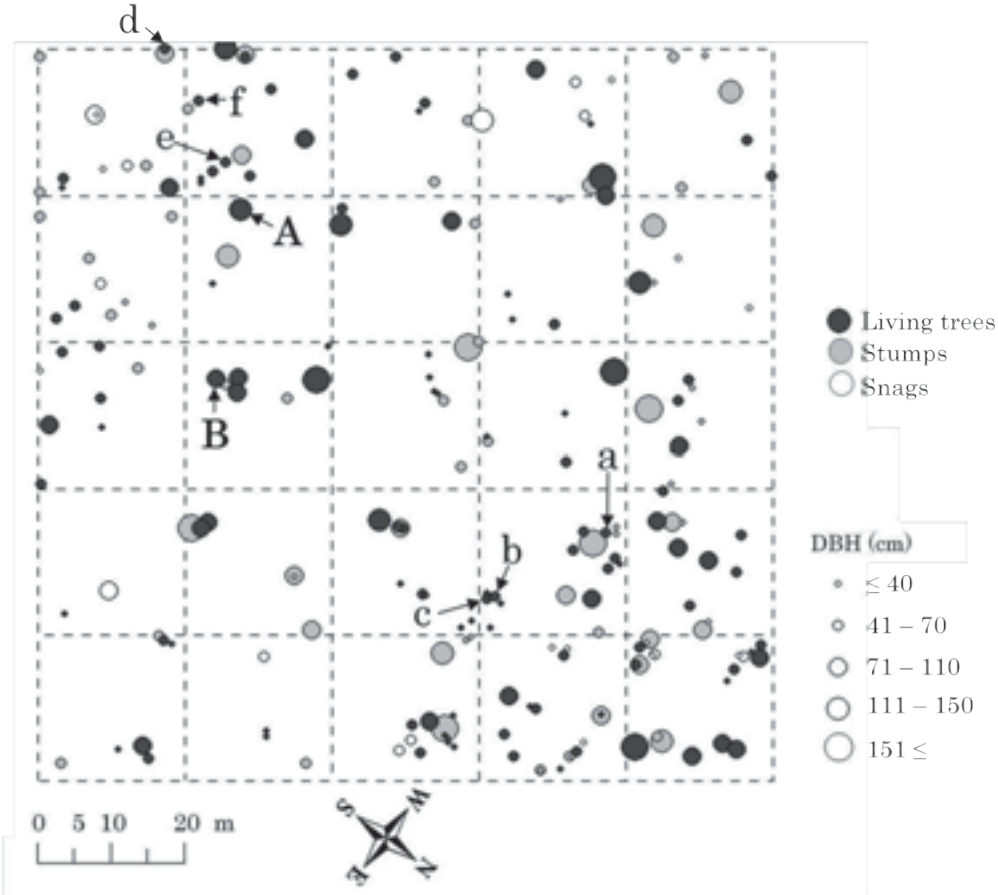

Fig. 2 Location of living trees, stumps and snags in the *FP* study plot.

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:

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

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):

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

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 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 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 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.

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:

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

where PG: prior growth. The R^2 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, 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 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

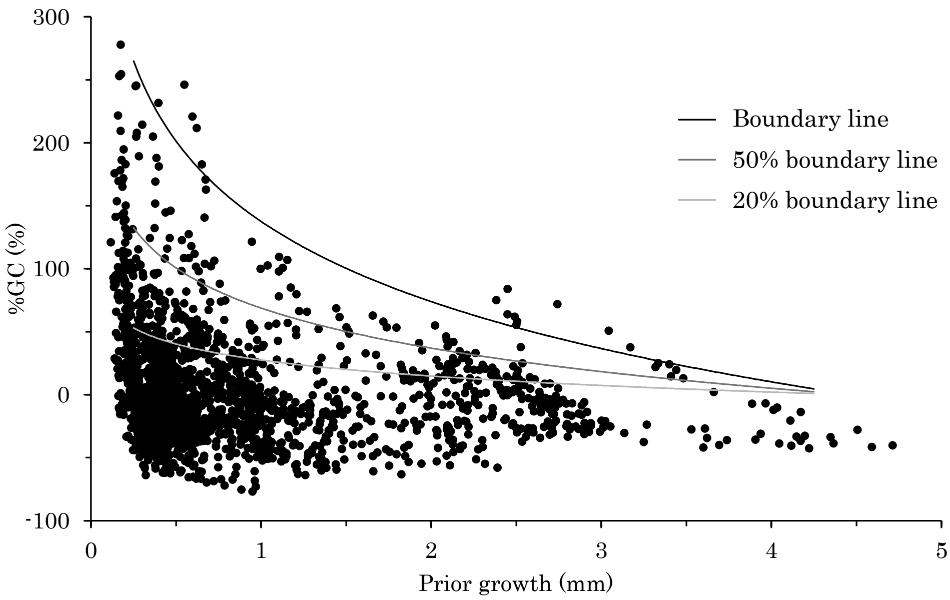

Fig. 3 Boundary line and plot of percent growth change (%GC) values with respect to prior growth for 34 sample trees.

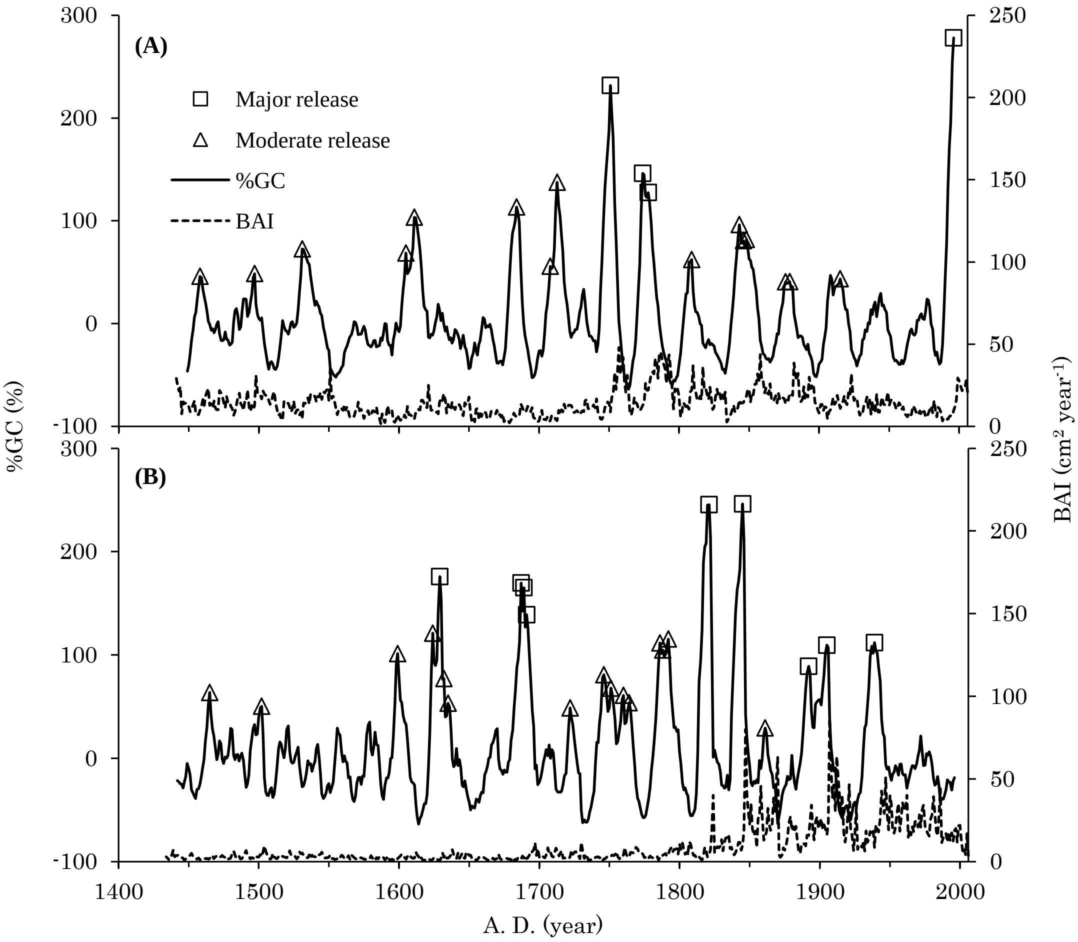

Fig. 4 Percent growth change (%GC) and basal area increment (BAI) for sample trees (A) and (B).

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

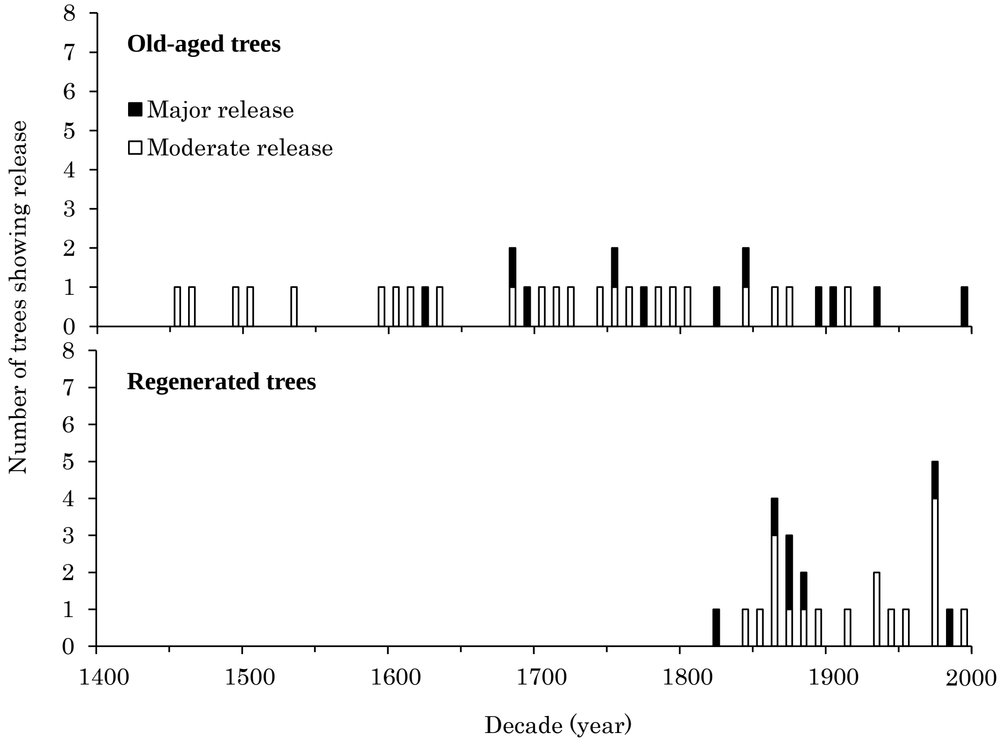

Fig. 5 Decadal distribution of major and moderate releases of two old-aged and six regenerated trees for *FP* study plot.

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.

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Article

A Long-Term Harvest Scheduling Model Involving Two Types of Rotation and Variable Labour Requirements

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ABSTRACT

The objectives of this study were to formulate a long-term harvest scheduling model, involving two types of rotation constrained by the available size of the work force, using 0-1 integer programming and then apply the model to plantation forests in the University of Tokyo Chiba Forest as a case study. The following three silvicultural systems were considered: an 80-year and a 160-year rotation clearcutting system and a non-clearcutting system. The minimum amount of labour required to harvest the minimum area was calculated and then that figure was increased to model its effect on harvesting. Subcompartments better suited to timber production tended to be assigned to clearcutting. There was a tendency for subcompartments with a better site class to be assigned to the shorter rotation and subcompartments with a shorter yarding distance to be assigned to the longer rotation. As the size of the available work force increased, subcompartments less well suited to timber production were also assigned to clearcutting and the harvest volume per person-day and the clear cut area per person-day decreased. The longer rotation was efficient with a smaller work force and the shorter rotation appeared more efficient as the size of the work force increased.

Keywords: long rotation, long-term plan, plantation forest, 0-1 integer programming

INTRODUCTION

Low timber prices have forced forest owners to delay the final cutting of coniferous plantations in Japan. They would like to reduce the number of person-days required for forest management in order to cut costs. Moreover, the population of sika deer (*Cervus nippon* Temminck) has increased in many areas in Japan and this had made forest owners reticent to clearcut the plantation forests because of the additional costs involved in erecting fences to protect seedlings from the deer after clearcutting. Thus, long rotation silvicultural systems have been considered in order to reduce the required number of person-days. The required number of person-days per volume decreases as the rotation is lengthened (Tatsuhara and Doi, 2006). Lengthening rotation immediately, however, leads to unsustainable timber production from plantation forests. Introducing multiple rotations to avoid this is one method to adapt plantation forest management to such social and ecological changes. The term “multiple rotations” means to apply more than one rotation length to plantation forests in a management area.

Harvesting timber needs scheduling in order to sustain both the growing stock and the harvest volume over the time horizon. One of the methodologies used for harvest scheduling is optimization using mathematical programming. Johnson and Scheurman (1977) formulated harvest scheduling models using linear programming and quadratic programming to maximize the discounted net income over the time horizon. There have been many other studies into the optimal long-term planning of harvest scheduling, such as managing plantation forests to match the age class distribution of “normal forests” (Nagumo and Koike, 1981), maximizing yield and income and equalizing them in each working period (Buogiorno and Gilless, 1987) and restricting the harvesting of adjacent stands for environmental protection purposes (Yoshimoto et al., 1994). Næsset (1996) developed a spatial decision support system for long-term planning by combining GIS and linear programming. Most of the studies of harvest scheduling were carried out assuming that the necessary work force was available, although Yamatsu and Ishibashi (2000) used linear programming to consider constraints on the size of the work force in the long-term scheduling of harvesting an area by using age classes to match the age class distribution of a management area with its goal. It is important to learn the size of areas that can be managed with a limited work force and how many workers are necessary to undertake a forest

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management plan. Moreover, it is preferable to schedule harvesting whilst taking into account the variation of income from different silvicultural systems and the number of person-days required for those different silvicultural systems because of variations in site quality and the accessibility of stands for logging. Thus, it is more effective to schedule the harvesting of each subcompartment than to schedule harvest areas based on age classes.

The objectives of this paper were to formulate a long-term harvest scheduling model of clearcutting silvicultural systems with two different rotation lengths with restricted amounts of available labour, then to apply the model to coniferous plantations as a case study. The harvest scheduling model was formulated using 0-1 integer programming. The case study for the model was conducted in the coniferous plantations in the University of Tokyo Chiba Forest (hereafter called Chiba Forest). Harvest volume and required person-days were predicted for each silvicultural system according to the subcompartments' attributes such as site quality, yarding distance and slope angle, determined using GIS. The minimum amount of labour required to harvest the minimum area was calculated and then the amount of labour available in the model was increased from that minimum level. How the subcompartments were subsequently assigned to different silvicultural systems was then analysed.

MATERIALS AND METHODS

Study Area

The study area was composed of 251 subcompartments of sugi (*Cryptomeria japonica* D. Don) plantation and 116 subcompartments of hinoki (*Chamaecyparis obtusa* (Sieb. et Zucc.) Endlicher) plantation in Chiba Forest, located in the southern part of the Boso Peninsula, Japan (35°9'–13' N, 140°6'–10' E). Chiba Forest covers approximately 2,200 ha with about 800 ha being covered by plantation forests. Most of the plantations are sugi and hinoki; sugi and hinoki plantations cover 60% and 30% of the total area of plantation forests, respectively. The age distribution of the plantations has a peak around 50 years old but matured plantations also make up about 40% of the plantation area (Fig. 1). The average stand age is about 70 years and the plantation forest is becoming overmature. Situated at elevations of 50 to 370 m above sea level, Chiba Forest has generally steep slopes and complex topographic features. Thus, it is recommended that cable yarding is used when harvesting from the plantation forests there. With a large sika deer population in Chiba Forest, the damage caused by the deer to seedlings planted there has been a big problem.

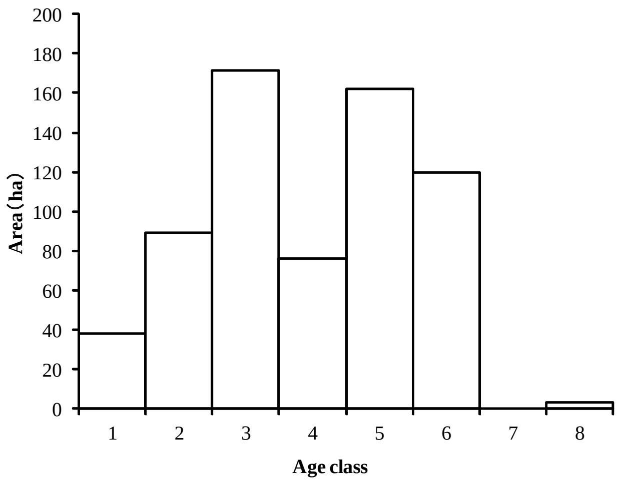

Fig. 1 20-year age class distribution at the beginning of the time horizon
Note: A subcompartment with an age of over 160 years was included in the 8th age class.

Deciding on the Silvicultural Systems to Use

In Chiba Forest, two rotations for the sugi and hinoki plantation forests are used, defined by timber price, age distribution and available work force: 80 years and 160 years. In this study, the following simplified two silvicultural systems were assumed: an 80-year rotation system where there is 30% thinning at 25 and 40 years and 40% thinning at 60 years and the other, a 160-year rotation system with 40% thinning at 30 years and 50% thinning at 90 years. The thinning ratios are based on the number of trees. It was also assumed that every thinning was non-commercial and that the same species was planted the following year after clearcutting. Moreover, non-clearcutting was added as a choice of silvicultural system because not all plantation forests could be clearcut as the required work force was unavailable. Thus, using harvest schedules that maximize total harvest volume from plantation forests over the time horizon, the subcompartments of the plantation forests were assigned to one of three systems: an 80-year rotation system, a 160-year rotation system and a non-clearcutting system.

Obtaining Attributes of the Subcompartments

The attributes of each subcompartment were obtained so that the harvest volume from each subcompartment to be harvested and the number of person-days required to harvest each subcompartment could be calculated. The area being studied was categorized into site classes shown in Table 1 using 10 m by 10 m cells from both topographic and topographically-derived factors using a GIS (Watanabe and Tatsuhara, 2011). The site class of each subcompartment was then determined from the average over cells contained in the subcompartment using a zonal statistics function of the GIS; the site index was determined from the site class as shown in Table 1. Stand age, species and area were obtained from inventory data relating to Chiba Forest and geographical characteristics such as perimeter, slope angle, distance to road, maximum yarding distance and average yarding distance were calculated using GIS data (Table 2). ESRI ArcGIS 9.3.1 was used as the GIS mapping system.

Predicting Yield and Harvest Volume

The yield from each subcompartment was predicted for each silvicultural system using stand density control diagrams for sugi in Southern Kanto and Tokai Region (JAFTA, 1981) and for hinoki in Kanto and Chubu Region (JAFTA, 1982). Height growth curves were used that had been developed from permanent experimental plots in Chiba Forest using the following model:

$$H_s = SI\frac{1 + \exp(a + b\ln)(60 + c) - \ln SI}{1 + \exp(a + b\ln)(t + c) - \ln SI}, \quad (1)$$

where H_s is the average height of dominant and co-dominant trees, SI is the site index, t is the stand age and a, b, and c are parameters whose values are shown in Table 3. The density was calculated, taking thinning and self-thinning into consideration. Harvest volume was calculated, weighting yield by the ratio of the species' average log price. The parameters used for predicting adjusted harvest volume are shown in Table 3.

Calculating Person-days

The total person-days required for each subcompartment was calculated for each silvicultural system. The person-days required for tending activities was calculated from the tending productivity tables relating to the 13th working period of Chiba Forest, as shown in Table 4. Also, the person-days required for setting fences against deer was added to the total person-days required. The person-days for thinning and harvesting were calculated as shown in Table 5, assuming the following logging operation system:

Felling with a chain saw –> cable yarding –> bucking with a chain saw

The actual person-days required for each stand was estimated by multiplying standard person-days by a distance coefficient calculated from the slope and the distance to the nearest road (Zheng et al., 1995; Takahashi et al., 1996).

Problem Formulation

The problem of harvest scheduling was formulated using 0-1 integer programming. Both the length of working periods and the width of age classes were set at 20 years and the length of the time horizon was set at 160 years i.e. eight working periods. It was assumed that all subcompartments were not broken up for harvesting.

Maximize

$$z = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} My_{i,j,t}X_{i,j} \quad (2)$$

subject to

$$\sum_{i=1}^{I} V_{oi} \leq \sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j,8}X_{i,j} \quad (3)$$

$$(1 - a)G \leq \sum_{i=1}^{I}\sum_{j=1}^{J} L_{i,j,t}X_{i,j}(1 + a)G \;\forall t \quad (4)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} M_{yi,j,t-1}X_{i,j} \leq \sum_{i=1}^{I}\sum_{j=1}^{J} My_{i,j,t}X_{i,j} \quad t = 2,3,\cdots,T \quad (5)$$

$$20 \leq \sum_{i=1}^{I}\sum_{j=1}^{J} A_{i,j,t}X_{i,j} \;\forall t \quad (6)$$

$$\sum_{j=1}^{J} X_{i,j} = 1 \quad \forall i \quad (7)$$

$$X_{i,j} \in \{0,1\}$$

where z is the objective function; I is the number of subcompartments (367); J is the number of alternative silvicultural systems (3); t is the number of the working period; T is the total number of working periods (8); $My_{i,j,t}$ is the adjusted harvest volume in the t-th working period when subcompartment i is assigned to silvicultural system j; $V_{0,i}$ is the stand volume of subcompartment i at the beginning of the time horizon; $V_{i,j,8}$ is the volume of subcompartment i at the end of the time horizon; G is the standard amount of labour available; a is the tolerable level of fluctuation in the standard amount of labour available (0.05); $L_{i,j,t}$ are the person-days required when subcompartment i is assigned to silvicultural system j; $x_{i,j}$ is 1 when subcompartment i is assigned to

Table 1 Category of site class and site index used for the simulations

Site class	Sugi		Hinoki	
	Height at 60 years (m)	Site index	Height at 60 years (m)	Site index
1	25 –	26.5	20 –	22
2	22 –25	23.5	16 – 20	18
3	19 – 22	20.5	– 16	14
4	16– 19	17.5	–	–
5	– 16	14.5	–	–

Note: Site class category was determined with reference to Tanaka (1984).

Table 2 Attributes of subcompartments

	Symbol	Unit	Value or equation
Site index	SI	m	
Area	A	ha	
Perimeter	P	m	
Stand age	t	year	
Slope angle	s	degree	
Distance to road	S_{min}	m	
Maximum yarding distance	S_{max}	m	
Average yarding distance	S_{ave}	m	
Average lateral yarding distance	l_y	m	$A/(S_{max}–S_{min})$
Lateral yarding distance		m	60
Number of cable changes	n		l_y/60 rounded down to nearest integer

Table 3 Parameters used to predict adjusted harvest volume

	Symbol	Unit	Value or equation
Planting density	N_0	trees/ha	3500
Density	N_s	trees/ha	Stand density control diagrams *1
Average height	H_s	m	a=11.092, b=−1.903, and c=21.473 for sugi; a=7.587, b=−1.004, and c=4.893 for hinoki *2
Stand volume per ha	V_s	m^3/ha	$(0.082249H_s^{-1.372921}+3681.6H_s^{-2.867826}/N_s)^{-1}$ for sugi; $(0.035147H_s^{-1.080773}+4711.2H_s^{-2.922894}/N_s)^{-1}$ for hinoki
Stand volume	Vs_s	m^3	$V_s A$
Average tree volume	v	m^3	V_s/N_s
Ratio of average log prices	r		1.000 for sugi; 2.059 for hinoki *3
Adjusted harvest volume	My	m^3	$Vs_s\, r$

Note: *1, cited from JAFTA (1981) and JAFTA (1982); *2, a, b, and c, parameters of Eq. (1); *3, the ratio calculated from the average log prices cited from Chiba Prefectural Government (2011).

Table 4 Person-days required for tending plantation forests

Stand age (year)	Operation	Person-days (person-day/ha)	
		Sugi	Hinoki
1	Land preparation	25	
	Transporting seedlings	3	
	Planting	40	
	Setting fences	$0.0236\,P + 0.0593$ *1	
2	Weeding	11	
3	Weeding	11	
4	Weeding	11	–
5	Weeding	11	–
15	Pre-commercial thinning with pruning	20	
20	Pruning	–	37

Note: *1, derived from the records of past operations in Chiba Forest.

Table 5 Equations used to calculate person-days for thinning and harvesting

	Unit	Value or equation	Note
Productivity of felling	m^2/ (crew-day)	$12.295\, v^{0.5} - 0.564$	*1
Productivity of yarding	m^2/ (crew-day)	$S_{ave}^{-0.2896} v^{0.5337} l_y^{-0.04891} 10^{2.611}$	*2
Person-days to install and remove a yarder	person-day	$(0.0763\, S_{max}+2.4)\ (1+0.35+0.7\, n)$	*3
Productivity of non-commercial thinning	m^2/(person- day)	$1/(22.817\, v^{0.2903})$	*4
Number of people in a yarding crew	person	4	*1

Note: v, average tree volume (m^2); S_{ave}, average yarding distance (m); S_{max}, maximum yarding distance (m); ly, average lateral yarding distance (m); n, the number of cable changes.
*1, cited from Umeda et al. (1982); *2, cited from Toyama and Tatsuhara (2007); *3, cited from Sawaguchi (1996); *4, cited Mizuta and Mitobe (2008).

silvicultural system j, otherwise it is 0; $A_{i,j,t}$ is the harvest area in the t-th working period when subcompartment i is assigned to silvicultural system j and the values in parentheses are the values used in this study.

Objective function (Eq. (2)): We were selling two types of timber that had different prices. We maximized the total harvest volume adjusted by the ratio of the species' average log prices across the time horizon as the objective function. The harvest volume was weighted 1.0 for sugi and 2.059 for hinoki.

Constraints for growing stock (Eq. (3)): The quantity of growing stock at the end of the time horizon should be larger than or equal to that at the beginning of the time horizon.

Constraints for labour (Eq. (4)): The number of person-days in each working period was allowed to vary by up to 5% (the tolerable level of fluctuation) to keep the person-days required constant for all working periods.

Constraints for harvest volume (Eq. (5)): The adjusted harvest volume in each working period should be larger than or equal to that in its previous working period so that the harvest volume does not change drastically across the working periods.

Constraints for harvest area (Eq. (6)): Chiba Forest intends to clearcut about 1 ha of plantation forests every year. Thus, the minimum area harvested was set at 20 ha during each 20 year working period.

Constraints for the number of silvicultural system to be assigned (Eq. (7)): The summation of $x_{i,j}$ over i should be 1 so that each subcompartment could be assigned only one silvicultural system.

Solving the Problem

The number of variables was 1,101 (= 367 subcompartments × three alternative silvicultural systems) and the number of constraints was 401. The model was solved using IBM ILOG CPLEX Optimization Studio V12.3 on a personal computer equipped with 64 bit Windows 7, Intel Core i3-2120 3.3 GHz processor and 8.0 GB RAM. First, the minimum amount of labour required to satisfy the constraints for clearcutting a harvest area of at least 20 ha in each working period was obtained by solving the equations by changing the standard amount of labour available. Then, the standard amount of labour available was increased from the minimum number. The distribution of site classes and species in the subcompartments assigned to each of the silvicultural systems was obtained for each size of work force; the geographical characteristics of the subcompartments, as shown above, were averaged for each size of work force. The solutions were imported into GIS to map the layouts of subcompartments assigned to each of the silvicultural systems.

RESULTS

The minimum amount of labour required was 350 person-days/year. The standard amount of labour available was set initially at 400 person-days/year and then increased by 200 person-days/year. Iterations were stopped at 1,200 person-days/year because no feasible solution was obtained in that case. Figure 2 shows the layouts of subcompartments assigned to the three silvicultural systems. As the standard amount of labour available increased, the total harvest volume over the time horizon increased but the total harvest volume per person-day decreased after a peak at 400 person-days/year (Fig. 3). As the standard amount of labour available increased, the total area harvested over the time horizon increased but the total area harvested per person-day decreased (Fig. 4).

At the minimum labour levels, 80-year rotation and 160-year rotation were assigned to 17 and 40 subcompartments, respectively. Only 15% of the subcompartments were assigned to clearcutting and 85% were assigned to non-clearcutting across the time horizon (Table 6). The subcompartments assigned to clearcutting tended to have a larger area, a gentler slope, a shorter distance to the road, a shorter yarding distance, a shorter average yarding distance, a longer lateral yarding distance and a larger number of cable changes (Table 7). The subcompartments assigned to an 80-year rotation were concentrated on hinoki plantations and better site classes; those assigned to a 160-year rotation did not tend to favour a particular species with a particular site class and had a smaller area, a shorter distance to the road and a shorter average yarding distance when compared to the subcompartments assigned to an 80-year rotation.

As the standard amount of labour available increased, both the 80-year rotation and the 160-year rotation were assigned to increasing numbers of subcompartments; this was particularly true of the 80-year rotation whilst sugi plantations and lower site class plantations were assigned more often (Table 6). Subcompartments assigned to a 160-year rotation tended to have larger areas than subcompartments assigned to an 80-year rotation but a similar distance to road, maximum yarding distance and average yarding distance when compared to subcompartments assigned to an 80-year rotation. When the standard amount of labour available was relatively small, such as 400 and 600 person-days/year, the attributes of subcompartments assigned to clearcutting tended to be similar to those in the case of the minimum amount of labour. As the standard amount of labour available increased, the relationships between subcompartments assigned to clearcutting and subcompartments assigned to non-clearcutting of area, slope angle, average lateral yarding distance, and the number of cable changes reversed (Table 7).

DISCUSSION

Labour constraints have been considered in medium-term and short-term plans so that the labour available was assigned equally to each year (Nagumo et al., 1993; Zheng et al., 1995). In this study, we incorporated labour constraints into long-term plans to assign subcompartments to the three silvicultural systems and eight working periods for clearcutting and optimized adjusted harvest volume over the time horizon with equal labour requirements in each working period. An 80-year rotation yields more harvest volume over the time horizon than a 160-year rotation, although the latter rotation requires a smaller number of person-days

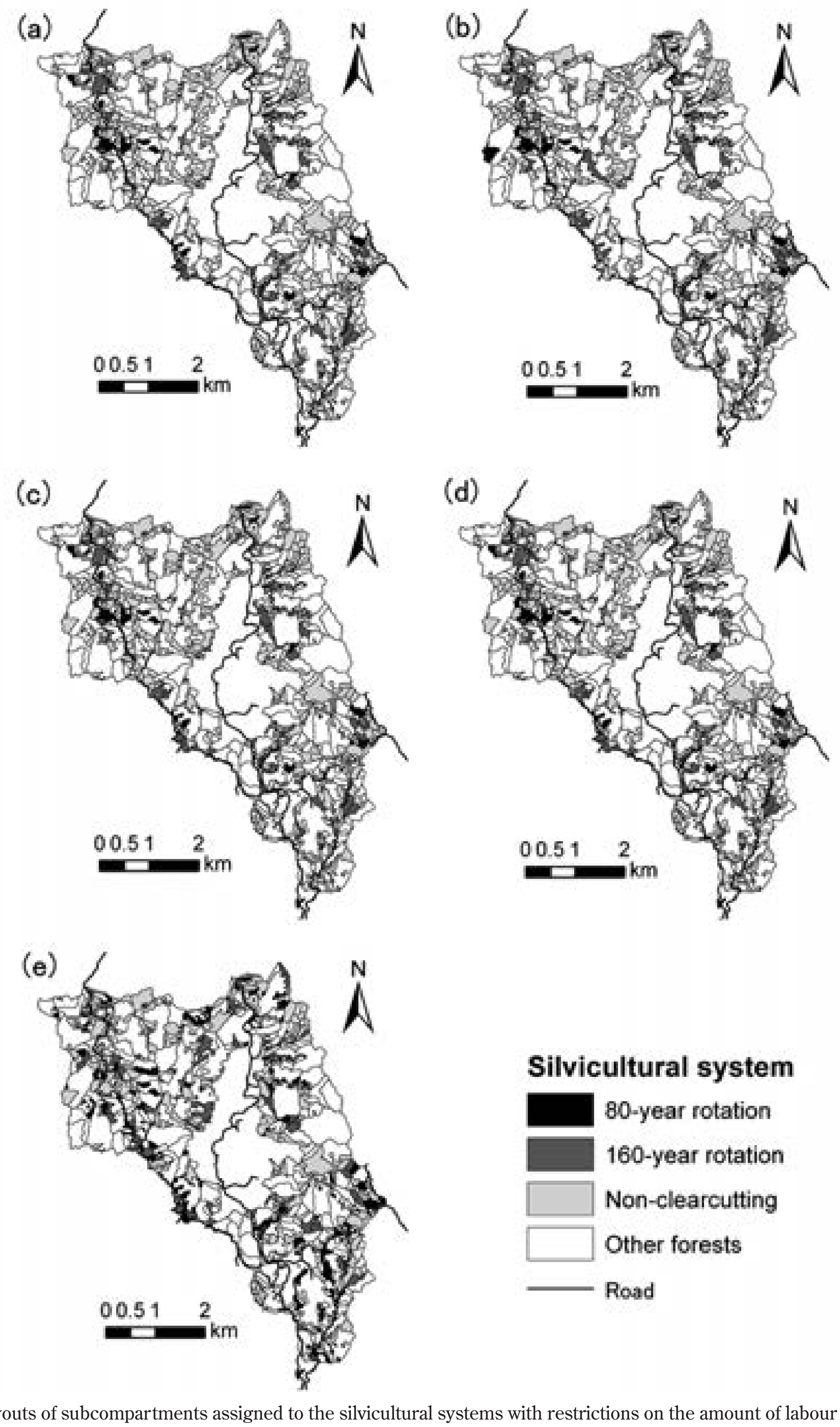

Fig. 2 Layouts of subcompartments assigned to the silvicultural systems with restrictions on the amount of labour available (a) 350 person-days/year; (b) 400 person-days/year; (c) 600 person-days/year; (d) 800 person-day/year; and (e) 1,000 person-days/year.

per volume than the 80-year rotation. Because maximizing harvest volume by restricting work force was a trade-off, the subcompartments were assigned to the different silvicultural systems. In this case, there were few subcompartments over 120 years old at the beginning of the time horizon (Fig. 1). There were not enough overmature subcompartments that could be assigned to a 160-year rotation. Thus, some subcompartments were assigned to a 80-year rotation despite the limited size of work force, even though a 160-year rotation required a smaller number of person-days per volume than an 80-year rotation. Most subcompartments assigned to an 80-year rotation had to be harvested in the first and second working periods.

The subcompartments assigned to clearcutting tended to have a better site class and be hinoki plantations rather than sugi plantations. Stands with a better site class yield more timber and are more profitable. Hinoki is more profitable than sugi because of the timber price, though it grows more slowly

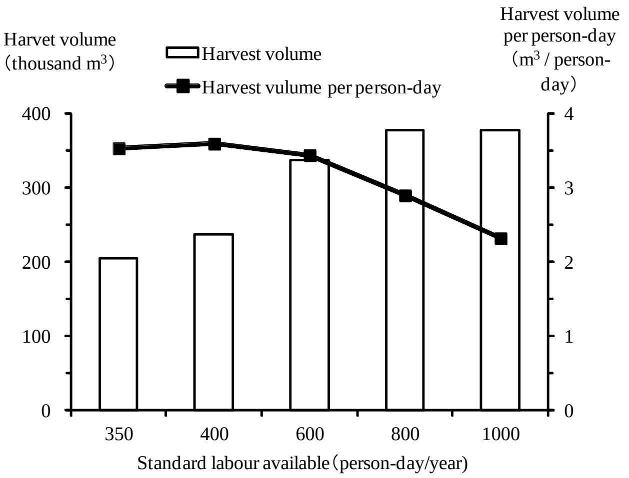

Fig. 3 Change of the total adjusted harvest volume over the time horizon using the standard amount of labour available

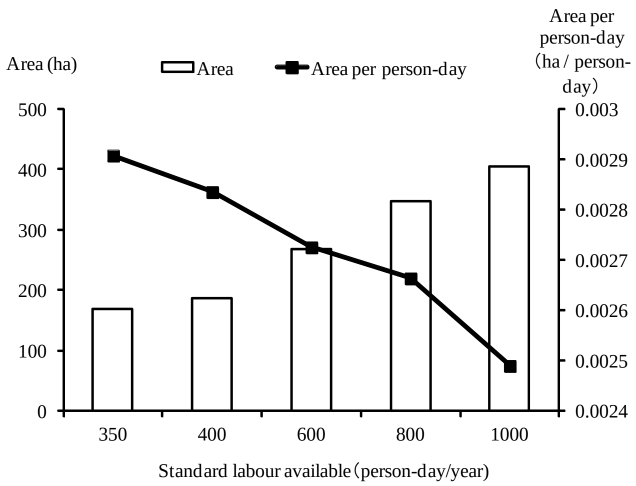

Fig. 4 Change of the total area of subcompartments assigned to clearcutting over the time horizon using the standard amount of labour available

than sugi does. The subcompartments assigned to clearcutting tended to be better suited, geographically, for timber production i.e. have a larger area, a gentler slope, a shorter maximum yarding distance and a shorter average yarding distance. A gentler slope gives better productivity when tending the plantation; a shorter maximum yarding distance and a shorter average yarding distance give better productivity when logging. Larger stand areas also give better productivity when logging because more timber can be harvested at once. Subcompartments with these attributes require less person-days to manage. In contrast, the subcompartments assigned to clearcutting tended to need more cable changes, which results in poorer productivity. However, the decrease in productivity as a result of an increase in the number of cable changes would be smaller than the increase in productivity as a result of an increase in area. In general, subcompartments which were better suited for timber production were assigned to clearcutting.

When comparing the subcompartments assigned to an 80-year rotation and a 160-year rotation, the subcompartments assigned to an 80-year rotation tended to have better site class but a longer distance to road, a greater maximum yarding distance and a greater average yarding distance. Site class took priority over yarding distance when choosing between the two types of rotation. This is consistent with the analysis by Tatsuhara and Dobashi (2006) that concluded that site class was more important than yarding distance for timber production.

When subcompartments assigned to clearcutting had labour available at levels of 800 and 1,000 person-days/year, it can be seen that, with these increased levels of labour, the total harvest volume increased but the total harvest volume per person-day decreased. This happened because a greater number of subcompartments, less suited to clearcutting, were assigned to clearcutting and a greater number were assigned to an 80-year rotation which is less profitable than a 160-year rotation in terms of harvest volume per person-day. The clearcut area per person-day decreased as the standard amount of labour available increased. This meant that the average productivity in the clearcutting silvicultural systems decreased as the standard amount of labour available increased. These results suggested that it was better to concentrate on clearcutting subcompartments that had good conditions with a small work force than to try to clearcut a greater number of subcompartments with a larger work force. Toyama et al. (2012) showed that good conditions such as shorter skidding distances and larger stand areas were preferable to gain a positive soil expectation value from sugi plantation management for timber production in Japan. From the viewpoints of both work force size and finance, it would be preferable to choose and focus on profitable stands for clearcutting than to clearcut large areas.

When the available labour was small, 160-year rotation was the method most often assigned. As the amount of labour available increased, so did the number of subcompartments assigned to an 80-year rotation. Tatsuhara and Doi (2006) showed that the yield per person-day increased as the rotation period increased. In other words, person-days per yield decreased as the rotation period lengthened from 80 years to

Table 6 Distribution of site classes and species in subcompartments assigned to the different silvicultural systems

Available labour (person-day/year)	Silvicultural system	Species	Site class					Total
			1	2	3	4	5	
350	80-year rotation	Sugi	2	1	0	0	0	3
		Hinoki	9	5	0	–	–	14
	160-year rotation	Sugi	8	5	6	0	1	20
		Hinoki	8	9	3	–	–	20
	Non-clearcutting	Sugi	81	56	78	1	12	228
		Hinoki	27	43	12	–	–	82
400	80-year rotation	Sugi	3	0	0	0	0	3
		Hinoki	12	5	0	–	–	17
	160-year rotation	Sugi	7	5	6	0	0	18
		Hinoki	11	9	4	–	–	24
	Non-clearcutting	Sugi	81	57	78	1	13	230
		Hinoki	21	43	11	–	–	75
600	80-year rotation	Sugi	15	1	0	0	0	16
		Hinoki	20	6	0	–	–	26
	160-year rotation	Sugi	8	6	7	0	0	21
		Hinoki	14	19	3	–	–	36
	Non-clearcutting	Sugi	68	55	77	1	13	214
		Hinoki	10	32	12	–	–	54
800	80-year rotation	Sugi	19	8	9	0	1	37
		Hinoki	23	15	3	–	–	41
	160-year rotation	Sugi	13	13	18	1	4	49
		Hinoki	7	13	4	–	–	24
	Non-clearcutting	Sugi	59	41	57	0	8	165
		Hinoki	14	29	8	–	–	51
1,000	80-year rotation	Sugi	42	20	26	1	3	92
		Hinoki	22	19	7	–	–	48
	160-year rotation	Sugi	10	18	28	0	2	58
		Hinoki	2	11	3	–	–	16
	Non-clearcutting	Sugi	39	24	30	0	8	101
		Hinoki	20	27	5	–	–	52
Total number of subcompartments		Sugi	91	62	84	1	13	251
		Hinoki	44	57	15	–	–	116

160 years. As we mentioned above, 160-year rotation requires a smaller number of person-days per volume than the 80-year rotation. Thus, many subcompartments were assigned to a 160-year rotation with a smaller work force and more subcompartments were assigned to an 80-year rotation as the work force size increased.

This study dealt with long-term planning. The person-days required for tending and harvesting plantation forests in Figs. 4 and 5 may change in the future, due to technological changes and new labour-saving devices. This study showed that the amount of labour available affected the optimal solution of long-term planning. Decreasing the required person-days has the same effect on the optimal solution as increasing the amount of labour available.

CONCLUSIONS

In this study, we used 0-1 integer programming to simulate the scheduling of the harvesting of subcompartments using two types of rotation and with various restrictions on the size of the available work force. Subcompartments which were better suited to timber production tended to be assigned to clearcutting. There was a tendency for those subcompartments with a better site class to be assigned a shorter rotation and subcompartments with a shorter yarding distance to be assigned a longer rotation. As the amount of available labour increased, subcompartments less well suited to timber production were also assigned to be clearcut; the harvest volume per person-day and the clearcut area per person-day decreased. Longer rotation was efficient with a smaller work force whereas shorter rotation was assigned more often as the size of the work force increased. We

Table 7 Average geographical characteristics of subcompartments assigned to the different silvicultural systems

Available labour (person-day/year)	Silvicultural system	Area (ha)	Perimeter (m)	Slope (degrees)	Distance to road (m)	Maximum yarding distance (m)	Average yarding distance (m)	Average lateral yarding distance (m)	Number of cable changes
350	80-year rotation	2.45	855	25.4	89	267	169	130	1.71
	160-year rotation	2.13	735	24.4	81	230	147	221	2.20
	Non-clearcutting	1.72	611	29.4	275	429	351	118	1.45
	Total	1.80	636	28.6	245	400	320	130	1.65
400	80-year rotation	2.25	744	26.3	145	334	234	113	1.45
	160-year rotation	2.31	779	24.3	64	225	137	215	2.07
	Non-clearcutting	1.70	609	29.4	276	428	351	119	1.48
	Total	1.80	636	28.6	245	400	320	130	1.65
600	80-year rotation	1.64	588	25.1	157	305	226	102	1.19
	160-year rotation	2.28	791	26.9	129	288	205	208	2.25
	Non-clearcutting	1.72	610	29.6	283	438	360	117	1.45
	Total	1.80	636	28.6	245	400	320	130	1.65
800	80-year rotation	1.39	555	26.9	174	316	241	96	1.08
	160-year rotation	1.78	610	28.4	191	337	261	157	1.53
	Non-clearcutting	1.96	674	29.4	289	451	369	132	1.72
	Total	1.80	636	28.6	245	400	320	130	1.65
1,000	80-year rotation	1.00	465	28.5	221	348	282	83	0.90
	160-year rotation	1.71	621	29.7	194	344	269	109	1.32
	Non-clearcutting	2.58	800	28.3	292	474	380	182	2.24
	Total	1.80	636	28.6	245	400	320	130	1.65

have calculated the size of work force required for a given management plan and the area which can be clearcut using a known size of work force. GIS was essential in creating the simulation, helping to identify the difference between the stands in terms of site quality, accessibility and other geographical properties. The combination of GIS and mathematical programming would be effective to help with forest management planning.

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Short Communication

A Method for Estimating the Stand Density in an Even-aged Pure Stand Using Hemispherical Photography

Akio Inoue [*1] and Kazukiyo Yamamoto [*2]

ABSTRACT

We propose a method for estimating the stand density in an even-aged pure stand on a flat slope by hemispherical photography. This method is an application of the method for estimating the stand density proposed by Suzuki, i.e., distance method, and the method for estimating canopy-gap size using two photographs taken at two different heights. First, we assume a homogeneous tree height within an even-aged pure stand on a flat slope, and the straight and vertical axes of all stems. At a sample point selected from the stand randomly, two hemispherical photographs are taken with the vertically mounted camera equipped with a fish-eye lens at two different heights. Next, the radial distances between the center of the hemispherical image and the tip position of tree having the third-largest elevation angle (third-smallest zenith angle) are measured on each photograph taken at the two different heights. By substituting the measured radial distances into the relationship between radial distance and zenith angle of the fish-eye lens used, the elevation angles between camera and tip of the third-nearest tree can be obtained. Using these values of elevation angle, the distance from the photographic sample point to the third-nearest tree can be geometrically computed, and then the stand density can be estimated by substituting the computed distance into the equation of Suzuki's distance method.

Keywords: distance method, forest measurement, even-aged pure forest, hemispherical photograph

INTRODUCTION

The hemispherical photography has been widely used to estimate the canopy characteristics such as leaf area index as well as the potential direct and diffuse light through discrete canopy openings (e.g., Hale and Edwards, 2002; Inoue et al., 2004b; Yamamoto et al., 2010). The hemispherical photography has the advantage of providing a permanent record of the canopy openings, light environment and stand condition. As a permanent record, the photographs can be studied using existing analytical methodology and would serve for future studies as method are further developed and refined (Rich, 1990). An inexpensive high-resolution digital camera that can equip with an exclusive fish-eye lens has recently become available, and it enables us to reduce the cost, time and labor for film processing and image scanning (Inoue et al., 2004b). The digital technique also has the advantage that the images can be viewed immediately in the field, and retaken if necessary (Hale and Edwards, 2002).

Despite of the many advantages, so far the application of hemispherical photography to the estimation of common stand attributes, i.e., stand density, mean tree height, mean diameter at breast height, total basal area and stand volume, has been superficial (cf., Clark, 2009). Such application can replace the field work for the measurement of attributes by the estimation from image analysis of hemispherical photographs. The photographs can be taken and analyzed by a single observer, and therefore the use of photography would be less labor-intensive than the traditional field work. In addition, the photographs can be reanalyzed by the other researchers as well as the observer that took them as many times as needed.

In this study, we proposed a method for estimating the stand density, or the number of trees per unit area, in an even-aged pure stand on a flat slope using hemispherical photography. Suzuki (1965) proposed a method for estimating the stand density by measuring the average distance between a randomly selected sample point and the third-nearest tree from the point (hereafter called "distance method"). Yamamoto (2000) also devised a method for estimating the canopy-gap size from two photographs taken with a vertically mounted camera at different heights, and successfully

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estimated the canopy-gap sizes in the *Cryptomeria japonica* D. Don plantations. The method presented here is an application of these two methods to the hemispherical photography. The objective of this paper is to propose a theory and methodology; and thus the accuracy and precision of the proposed method in the field are the beyond the scope of this study.

METHODOLOGY

To estimate the stand density rapidly and easily, Essed (1957) proposed a distance method and Suzuki (1965) modified this distance method as follows: Now suppose that a tree is randomly distributed over a stand. Lets x_3 be the distance from a randomly selected sample point in a stand to the third-nearest tree. Denoting the average of x_3 measured at some sample points in the stand as X_3, the stand density, i.e., number of trees per hectare, ρ can be estimated by the following equation:

$$\rho = \left(\frac{100}{X_3}\right)^2 \left(\frac{15}{16}\right)^2 \fallingdotseq \frac{8789}{X_3^2}. \quad (1)$$

To obtain the value of X_3, the hemispherical photographs are used in the method presented here. The common fish-eye lens used in hemispherical photography is designed to be a simple polar projection (e.g., Frazer et al., 2001; Inoue et al., 2004a). In this projection formula, the relationship between radial distance (the distance between the center of hemispherical image and a given point on the photograph) r and zenith angle θ is given by

$$\theta = kr \quad (2)$$

where k is a constant, which varies with the radius of hemispherical image R, i.e., $k=\pi/2R$. Eq. 2 can be rewritten in terms of the elevation angle α as follows:

$$\alpha = \frac{\pi}{2} - kr. \quad (3)$$

For this method, we assume a homogeneous tree height within an even-aged pure stand on a flat slope, and the straight and vertical axes of all stems. This assumption has been used in the vertical angle count sampling developed by Hirata (1955). At a sample point selected from the stand randomly, two hemispherical photographs are taken with the vertically mounted camera equipped with a fish-eye lens at two different heights, h_1 and h_2. Under this condition, the third-nearest tree from the sample point has the third-largest elevation angle (or the third-smallest zenith angle) between camera and tree tip. The elevation angle can be estimated from the radial distance at the position of the tip on the hemispherical photograph. For this reason, the radial distances between the center of hemispherical image and the tip of tree having the third-largest elevation angle, r_1 and r_2, are measured on two photographs taken at the heights of h_1 and h_2, respectively. In this step, the same tree having the third-largest elevation angle should be selected from each of the two photographs taken at a sample point. Substituting the measured radial distances, r_1 and r_2, into Eq. 3 enables us to obtain the elevation angles between camera and tip of the third-nearest tree, α_1 and α_2, respectively. Denoting the tree height as h, the following equations hold geometrically (see Fig. 1)

$$h - h_1 = x_3 \tan \alpha_1, \quad (4)$$

and

$$h - h_2 = x_3 \tan \alpha_2. \quad (5)$$

Eliminating h from Eqs. (4) and (5), we have

$$x_3 = \frac{h_2 - h_1}{\tan \alpha_2 - \tan \alpha_1}. \quad (6)$$

By analyzing hemispherical photographs taken at several sample points, we obtain the estimate of the average distance from the sample point to the third-nearest tree, X_3. The substitution of X_3 estimated using hemispherical photographs into Eq. (1) allows us to estimate the stand density, ρ, in the stand.

CONCLUSIONS

In this paper, we presented a method for estimating the stand density in an even-aged pure stand on a flat slope. This method would provide a simple and rapid mean for evaluating the stand density in even-aged pure stands. The accuracy and precision will be heavily dependent upon whether the tree tip can be recognized on the hemispherical photographs. Hence, although it may be inappropriate to apply to estimate the stand density in very dense stands, it might be useful in estimating stand density in scarce stands or deciduous ones such as larch spp. In a later study, the accuracy, precision and working efficiency of the proposed method should be verified.

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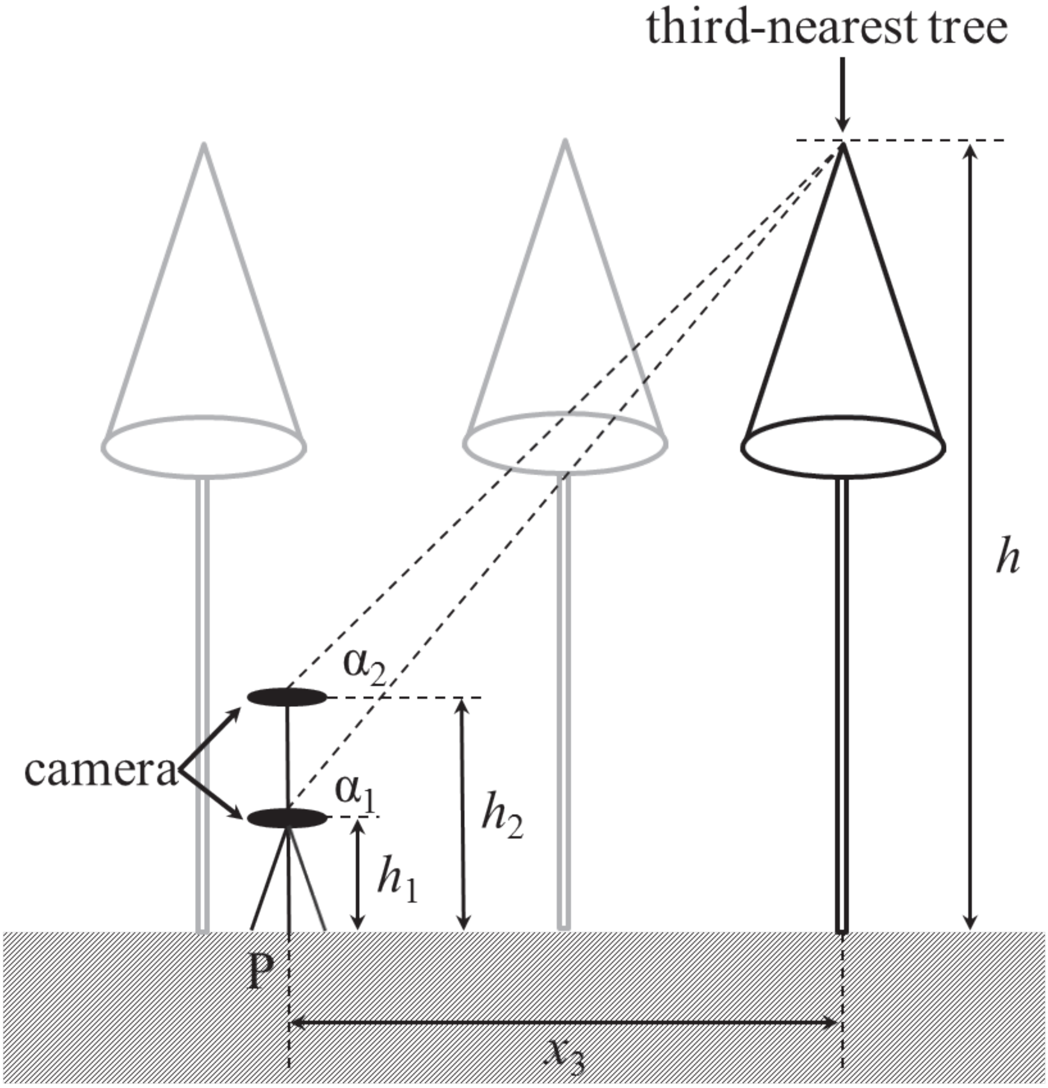

Fig. 1 Schematic diagram for estimating the distance from the sample point to the third-nearest tree
P: sample point, h: tree height, x_3: distance from the sample point to the third-nearest tree, h_1 and h_2: camera height, α_1 and α_2: elevation angles between camera and tip of the third-nearest tree

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