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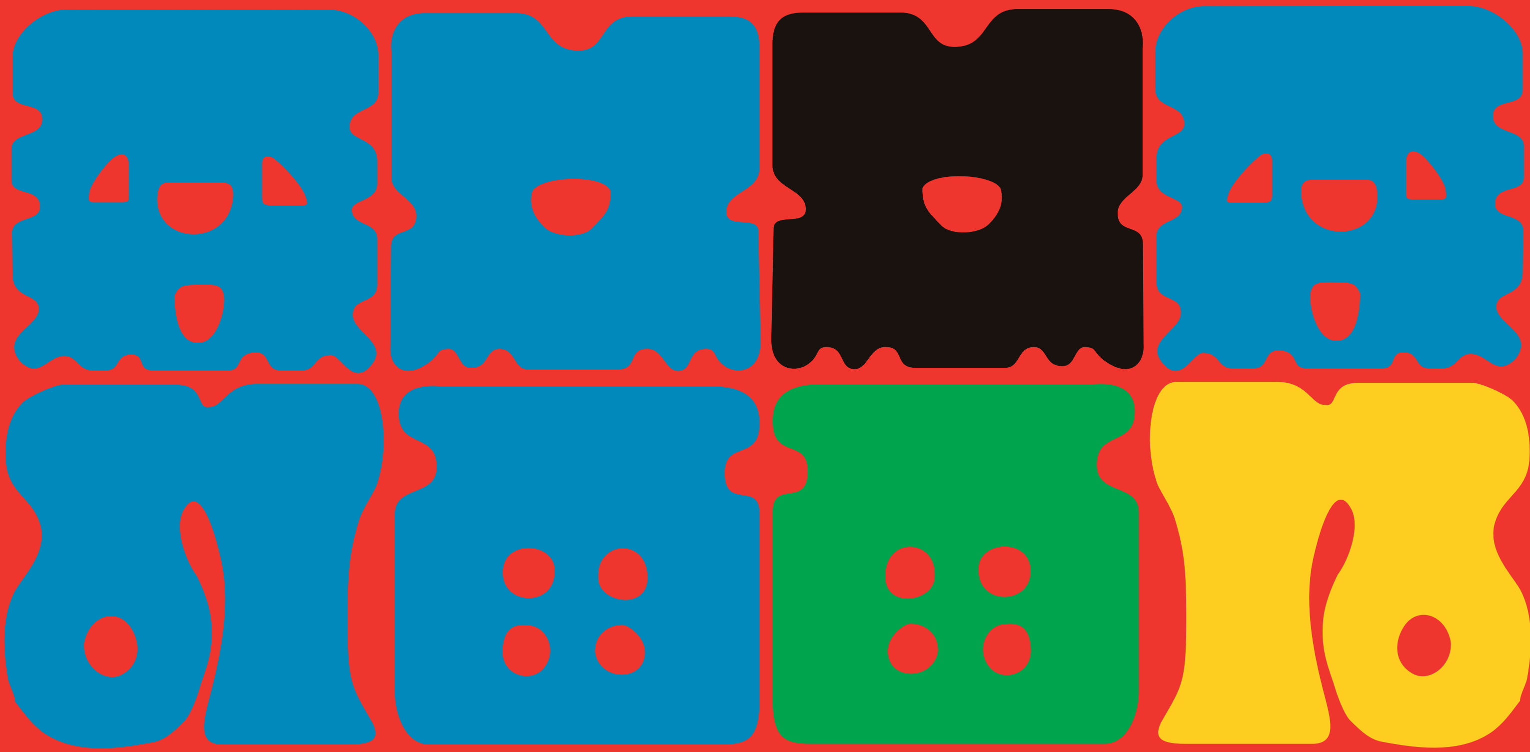
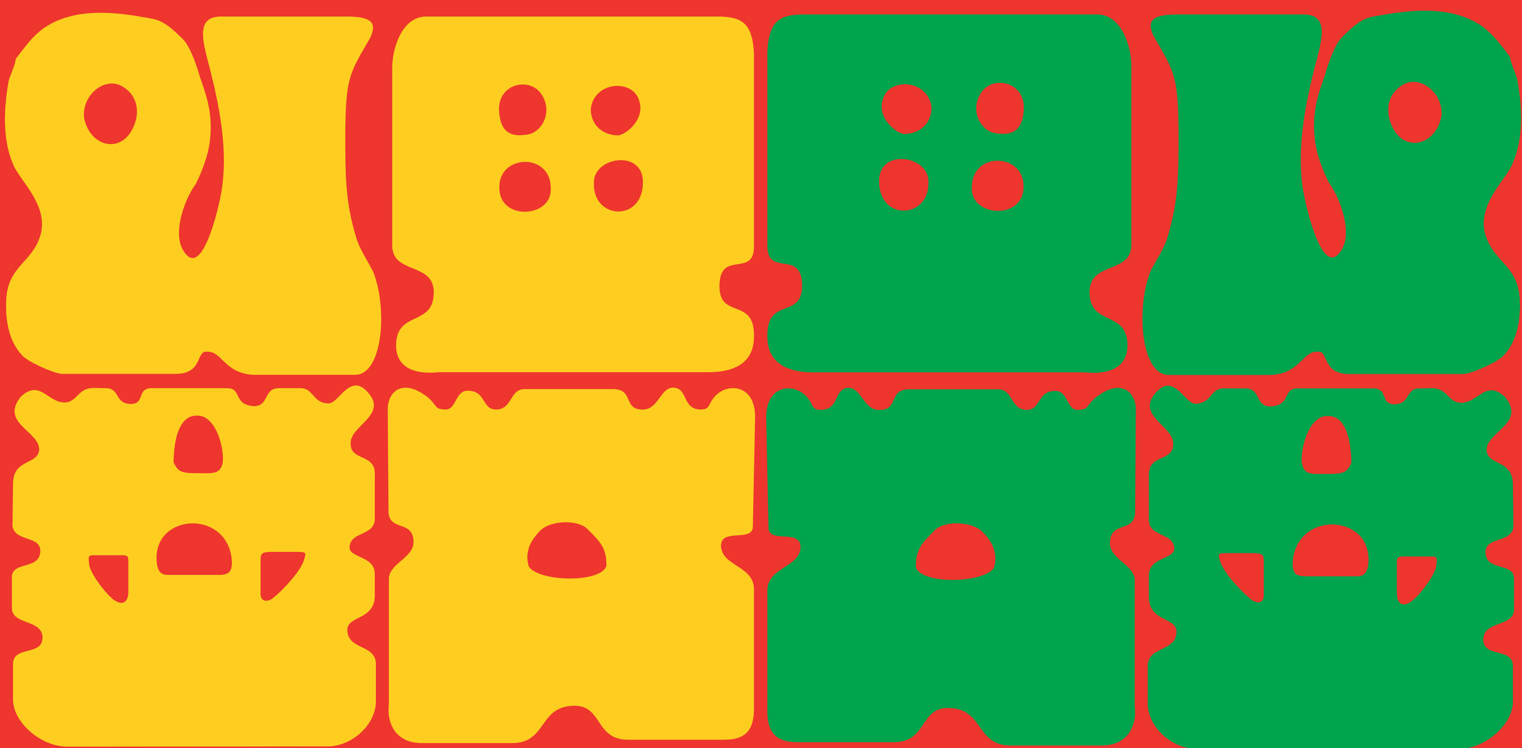


JOURNAL OF FOREST PLANNING



Japan Society of Forest Planning

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Aims and Scope

Journal of Forest Planning is a peer-reviewed periodical that publishes articles, reviews, and short communications. It covers all aspects of forest management, modeling, and assessment such as forest inventory, growth and yield modeling, remote sensing and geospatial information technologies for forest management, forest management planning, forest zoning, evaluation of ecosystem services, managerial economics, and silvicultural systems. Manuscripts regarding forest policy, forest economics, forest environmental education, landscape management, climate change mitigation and adaptation strategies, and drone applications for forest management are welcome. The Journal aims to provide a forum for international communication among forest researchers and forestry practitioners who are interested in the above-mentioned fields.

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Dr. Masashi Konoshima
Journal of Forest Planning
Faculty of Agriculture, University of the Ryukyus
1 Senbaru, Nishihara Cho, Okinawa, 903-0213, JAPAN
Tel: +81-98-895-8775, FAX: +81-98-895-8775
E-mail: jsfp_e@forestplanning.jp

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Article

Cross-sectional Area Increment of the Lower Trunk in Aged Sugi (*Cryptomeria japonica*) Trees: A Heightening Trend

Takashi Kunisaki [1] and Shigejiro Yoshida [2, *]

ABSTRACT

The vertical distribution of the cross-sectional area increment of the lower trunk in aged Sugi (*Cryptomeria japonica*) trees was analyzed using annual ring data from disks. We collected data from three approximately 90-year-old mature plantations under different density management and three old-growth stands of 160 years or more. Of the nine sample trees in the thinning experiment plots, only three had significantly higher cross-sectional area increments at a relative height of 0.2 × tree height (0.2*h*) than the mean cross-sectional area increment. This result did not strongly support the hypothesis that several trees in mature stands that are thinned regularly may show a heightening trend in the cross-sectional area increment of the lower trunk. In contrast, the cross-sectional area increment at 0.2*h* was significantly higher than the mean cross-sectional area increment for all three sample trees in the old-growth stands. A generalized linear mixed model with the presence or absence of a heightening trend in the cross-sectional area increment of the lower trunk as a response variable was used for 20 sample trees. The results showed that the model with the ratio of height to diameter at breast height (H/D ratio) and relative spacing index (Sr) as fixed effects was optimal. The probability of trees showing a heightening trend in the cross-sectional area increment of the lower trunk increased with a lower H/D ratio and a higher Sr at the most recent values. We estimated that if stand density is maintained at an Sr≥19%, where the forest canopy is sparse, a heightening trend of cross-sectional area increment at the lower part of the trunk occurs in trees with a H/D ratio of ≤71.

keywords: cross-sectional area, *Cryptomeria japonica*, lower trunk increment, mature trees, stem analysis

INTRODUCTION

Elucidating the growth characteristics of trunk diameters in aged forests is important for quantitatively evaluating carbon sequestration and storage in long-rotation and old-growth forest stands (Fujimori, 2001; Hiroshima et al., 2020). In such circumstances, an increase in aged tree trunk diameter by thinning has been reported in several regions (Latham and Tappeiner, 2002; Takeuchi, 2005; Hood et al., 2018; Pretzsch, 2020). Based on Pressler's law (Pressler, 1865), this result can be interpreted as an effect of the increased leaf mass and trunk cross-sectional area increment of older trees due to the improved light interception of the crown after thinning.

The trunk cross-sectional area increments below the crown in young coniferous trees, excluding the butt swell, are often nearly constant regardless of relative height. This phenomenon is expected from Pressler's law, unless the tree is sparse, long-crown-length, or highly affected by crowding (Onaka, 1950; Kajihara, 1983; Sato et al., 1993; Yamamoto, 1994; Waguchi, 2009). Contrastingly, in mature coniferous trees (Osumi et al., 2000; Fujimori, 2001), the effects of butt swell have been observed on a heightening trend in trunk cross-sectional area increment at a relative height of 0.1 (approximately 2.0 m above ground level), which deviates from Pressler's law (Kajihara, 1983; Cortini et al., 2013). This result suggests that the vertical distribution pattern of the cross-sectional area increment of the lower trunk may change during the mature stage. However, few studies have examined the vertical distribution of the cross-sectional area increment of the lower trunk in aged conifer trees (Kajihara, 1983; Cortini et al., 2013).

Waguchi (2009) estimated the average relative trunk form from permanent plot data in mature cypress plantations and found that in regularly-thinned mature stands, the creation of growth space required for crown expansion may allow for a heightening in the cross-sectional area increment of the lower trunk in several trees, even at a relative height greater than 0.1.

* Corresponding author. E-mail: gm.syoshida@gmail.com
[1] Faculty of Agriculture, Iwate University, Morioka 020-8550, Japan
[2] The Kyushu University Museum, Fukuoka 812-8581, Japan

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Table 1 General description of each stand immediately before the sample trees were felled

Site	Plot	Area (ha)	Age (year)	Density (trees ha^{-1})	Volume (m^3 ha^{-1})	Sr (%)	Mean DBH (cm)	Mean Height (m)
Oita	OA	0.25	91	208	839	16.8	59.1	39.2
	OB	0.25	91	212	555	17.8	54.5	36.3
Kagoshima	KA	0.16	90	650	802	15.0	38.0	24.6
	KB	0.16	90	550	726	16.1	39.3	25.2
Iwate	I	0.12	89	458	709	15.4	40.7	26.5
Yakushima	YA	0.20	161	167	1229	24.2	89.0	29.9
	YB	0.20	207	170	940	22.0	74.2	27.0
Fukuoka	F	0.70	263	134	2389	16.9	108.1	48.2

Sr indicates the relative spacing index.

However, no study has confirmed whether the heightening trend for the cross-sectional area increment of the lower trunk occurs in several trees in aged plantations that are thinned regularly.

In old-growth stands, where many canopy trees have been harvested, high cross-sectional areas and volume increments persist for several decades among the remaining trees (Sekiya, 1967b; Sawata et al., 2007). Some of these trees have low values of the ratio of height to diameter at breast height (H/D ratio), such as less than 50 (Sawata et al., 2007), which is expected to result in heightening cross-sectional area increment of the lower trunk. However, no studies have examined the vertical distribution of the cross-sectional area increment of the lower trunk in older coniferous trees with low H/D ratios.

In this study, we analyzed the vertical distribution of cross-sectional area increment of the lower trunk in aged Sugi (*Cryptomeria japonica*) trees, using annual ring data from disks collected from three mature plantations under different density management and three old-growth stands ≥ 160 years of age. The characteristics of trees that tend to heighten in the cross-sectional area increment of the lower trunk were discussed, as well as the crowding of stands in which such growth most likely occurs.

MATERIALS AND METHODS

Materials

In this study, annual ring data on disks collected from one mature Sugi plantation in Oita, Kagoshima, and Iwate prefectures; two old natural Sugi stands on Yakushima Island in Kagoshima Prefecture; and one old Sugi plantation in Fukuoka Prefecture (Table 1), were used as data sources (Table 2). Of these, the data for plantations in the Kagoshima Prefecture were the same as those of Yoshida et al. (2002), and the data for Iwate Prefecture were the same as those of Nishimura et al. (1992) and Yoshida and Ishii (1993). The Yakushima data for 161-year-old trees was the same as that of Sekiya (1967a, b) and Yoshida and Tsujimoto (1981) for 207-year-old trees. For Fukuoka Prefecture, data was the same as that of Inoue and Sekiya (1956).

The plantation in the Oita Prefecture (plots OA and OB) was site quality class 1 and 93 years of age in 2014 (Yoshida et al. 2018). In this plantation, low thinning was conducted at 57 years of age to result in a relative spacing index (Sr) of 14% (relative yield index Ry=0.79) for the entire plantation. Later, medium- (plot OA: 39% in number, and Sr=17.5% and Ry=0.65 after low thinning) and heavily-thinned (plot OB: 45% in number, and Sr=19.1% and Ry=0.61 after low thinning) experimental plots were established at 77 years of age. Because overcrowding is defined as < 15% of Sr in Sugi stands (Kunisaki, 2013; Yoshida et al., 2018), overcrowding was eliminated by thinning in both the plots. Disks were collected from felled trees (dominant trees: OA1, OB1, and OB2 and intermediate trees: OB3) in each plot at 93 years of age (Table 2). A total of 23 disks from the OA1 were collected every 2.0 m from 2.2 m to 39.2 m above ground level. From OB1 to OB3, where a commercial log 4.5 m in length was produced, 9–10 disks in total for each were collected at approximately 4 m intervals below the crown, including at the ground level and at 2 m intervals inside the crown.

The plantation in Kagoshima Prefecture (plots KA and KB) was site quality class 2 and 90 years of age in 1997 (Yoshida et al., 2002). Low thinning was conducted at 71 years of age, resulting in an Sr=14% (Ry=0.84) for the entire plantation. Later, medium- (plot KA: 7% in number, and Sr=15.0% and Ry=0.80 after low thinning) and heavily-thinned (plot KB: 24% in number, and Sr=16.1% and Ry=0.76 after low thinning) experimental plots were established at 77 years of age. In other words, overcrowding was eliminated in the heavily-thinned plot KB, whereas the degree of crowding in the medium-thinned plot KA was the same as the 15% criterion value for overcrowding. Disks were collected from felled trees (dominant trees: KA1, KA2, and KB1; intermediate trees: KA3 and KB2) in each plot at 90 years of age (Table 2). After commercial logs 3 m in length were produced, 7–8 disks in total for each were collected at 3–4 m intervals below the crown, including at the ground level and 2 m intervals inside the crown.

The plantation in Iwate Prefecture (plot I) was site quality class 3 and 89 years of age in 1990 (Nishimura et al., 1992). No thinning history was recorded in this plantation between 54 and 88 years of age. This record is supported by the drastically decreasing trend in the increment of DBH from 60 to 89 years of age, demonstrated by Sugita et al. (2017). However, although

Table 2 Characteristics of sample trees immediately after felling

Site	Sample code	DBH (cm)	Height (m)	Crown class	Treatment (thinning)	Felling age (year)
Oita	OA1	65.1	41.6 (36.0)	D	M	93
	OB1	54.8	34.2 (29.0)	D	H	93
	OB2	51.3	35.3 (31.0)	D	H	93
	OB3	41.1	32.7 (30.2)	I	H	93
Kagoshima	KA1	32.7	25.2 (20.6)	D	M	90
	KA2	36.8	24.8 (21.9)	D	M	90
	KA3	28.9	23.0 (20.2)	I	M	90
	KB1	39.0	24.5 (19.2)	D	H	90
	KB2	32.1	21.0 (18.7)	I	H	90
Iwate	I1	51.0	30.7 (25.7)	D	U	89
	I2	55.1	28.9 (24.4)	D	U	89
	I3	49.0	28.1 (22.9)	D	U	89
	I4	45.3	28.0 (23.6)	D	U	89
	I5	32.2	24.8 (19.7)	I	U	89
	I6	36.5	25.9 (20.8)	I	U	89
	I7	39.1	26.0 (21.6)	O	U	89
	I8	26.4	24.5 (19.0)	O	U	89
Yakushima	YA1	87.0	37.0 (21.9)	D	unknown	161
	YB1	66.0	27.6 (11.7)	I	unknown	207
Fukuoka	F1	104.0	51.5 (27.2)	D	unknown	263

Value in parenthesis of "Height" indicates the estimated height at 60 years of age (59 years of age in Iwate). In the crown class, D, I, and O represent the dominant, intermediate, and overtopped trees, respectively. M and H indicate trees in plots that have been thinned to medium and heavy levels, respectively, within the last 20 years. U indicates trees in a sparse plot that have not been thinned within the last 30 years.

thinning was not applied for a long time, the degree of crowding at 89 years of age was Sr=15.4% (Ry=0.63), which did not lead to overcrowding. The median DBH increment increased, and the quartile range of DBH increment narrowed from 40 to 59 years of age (Sugita et al., 2017), suggesting that thinning occurred at approximately 50 years of age. Therefore, plot I was induced to a sparse degree of crowding around the age of 50 years and then slowly approached overcrowding over time. At 89 years of age, a total of 13 to 16 disks were collected from each of the felled trees (dominant trees: I1–I4, intermediate trees: I5 and I6, and overtopped trees: I7 and I8 in Table 2) at 0.2 m and 1.2 m above ground level and 2 m intervals above 1.2 m.

The old-growth stands in Yakushima (plots YA and YB) are in a multi-cohort natural forest around Wilson's Stump (Sekiya, 1967a; Yoshida and Tsujimoto, 1981), and were investigated by Kyushu University staff in 1961 and Kagoshima University staff in 1980. The dominant tree, YA1 (161 years of age, H/D ratio of 42.5), was felled in 1961, and 12 disks were collected in total at 0.2, 1.2, and 2.2 m above ground level and 4 m intervals above 2.2 m. The intermediate tree, YB1 (207 years of age, H/D ratio of 41.8), was felled in 1980, and 10 disks in total were collected at 0.2, 1.2, and 3.2 m above ground level, and 3 m intervals above 3.2 m.

The plantation in the Fukuoka Prefecture (plot F) is an old stand approximately 260 years of age, commonly known as "Gyoja-sugi." A stand inventory was conducted in 1954 in an area where the forest canopy was closed (Inoue and Sekiya, 1956). The dominant tree, F1 (263 years of age, H/D ratio of 49.5), was felled in 1954, and 16 disks in total were collected at 0.2, 1.2, and 2.2 m above ground level and 4 m intervals above 2.2 m.

For the measuring of annual ring widths, a conventional procedure (Avery and Burkhart, 2002) was performed by the then staff of Kyushu University (Inoue and Sekiya, 1956; Sekiya, 1967a; Yoshida et al., 2002), Kochi University (Nishimura et al., 1992), and Kagoshima University (Yoshida and Tsujimoto, 1981).

Statistical Analysis

First, to determine the mean radial growth characteristics of the sampled trees in each plot, we examined the changes in the mean cross-sectional area increment over time. According to Pressler's law, the trunk cross-sectional area increment below the crown in coniferous trees, excluding the butt swell, is often nearly constant along the trunk, except in sparsely forested or suppressed trees. Therefore, the mean of the periodic average cross-sectional area increment by each relative height, $PCAI_{it}$, excluding the butt swell and the crown interior, was used as an index of the mean radial increment.

$$PCAI_{it} = (CA_{t}\_0.ih_{t-n} - CA_{t-n}\_0.ih_{t-n}) / n \quad (1)$$

where $PCAI_{it}$ is the periodic average cross-sectional area increment at an arbitrary relative height ($0.1 \times i\ h$, hereafter $0.ih$) at t years of age. i is equal to 2, 3, 4, … 6, and h is the tree height. t is 60, 65, 70, … 90 for plots OA, OB, KA, and KB; 59, 64, 69, … 89 for plot I; 60, 70, 80, … 160 for plot YA; 60, 70, 80, … 200 for plot YB; and 60, 70, 80, 90, 100, 120, 140, 160, … 260 for plot F. $CA_{t}\_0.ih_{t-n}$ is the cross-sectional area at t years of age for a height of $0.ih$ at the age of t-n years, and $CA_{t-n}\_0.ih_{t-n}$ is the cross-sectional area at t-n years of age for a height of $0.ih$ at the age of t-n years. n is the interval between annual ring measurements, which is 5 for plots OA, OB, KA, KB, and I; 10 for plots YA and YB; and 10 for t =60–100, and 20 for t =100–260 for plot F. The trunk radii at each relative height and age for calculating the cross-sectional area were estimated by linear interpolation from the corresponding radii of the upper and lower disks at any relative height.

The Sr immediately before the most recent thinning was 13.7% in the Oita plantation and 12.7% in the Kagoshima plantation, both of which were overcrowded. The mean crown length ratio of overcrowded aged Sugi stands is approximately 30% (Honda and Kunisaki, 2018; Kunisaki et al., 2022), and a relative height of $0.7h$ or higher corresponded to the interior of the crown. The mean crown length ratio of the sample trees in the Iwate plantation was calculated to be 38%, based on information from Nishimura et al. (1992) and Yoshida and Ishii (1993). Therefore, in this study, the $PCAI_{it}$ from $0.7h$ to $0.9h$ was excluded for calculating the mean cross-sectional increment of each sample tree. The $PCAI_{it}$ at $0.1h$ was also excluded from the analysis to avoid the butt swell effect. Hence, the mean cross-sectional area increment at t years for each sample tree, $MCAI_t$, was calculated as follows:

$$MCAI_t = \sum_{i=2}^{6} PCAI_{it} / 5 \qquad (2)$$

Second, to examine whether the cross-sectional area increment of the lower trunk from $0.2h$ to $0.4h$ was higher than that of $MCAI_t$, the Wilcoxon signed-rank test was performed. The null hypothesis is that the differences in the $PCAI_{it}$ (i = 2, 3, 4) minus the $MCAI_t$ is a distribution symmetric about zero. By contrast, the alternative hypothesis is that the differences in the $PCAI_{it}$ minus the $MCAI_t$ are statistically different from a distribution symmetric about zero. The overall significance level was set at 0.05, and the significance levels for the individual combinations were corrected using the Holm method. The age range for the test was ≥60 years of age (≥59 years of age for trees in the Iwate Prefecture).

A generalized linear mixed model, with the presence or absence of a heightening trend in cross-sectional area increment at the lower trunk as the response variable, Sr immediately before and H/D ratio immediately after the felling of the sample tree as fixed effects, plot as a random effect, binomial distribution as the error structure, and logit as the link function, was performed to analyze the 20 sample trees. Akaike's information criterion (AIC) was calculated for four models, including the null model, based on the combination of fixed effects, and the best model was defined as the model with the smallest AIC. The variance inflation factor for the Sr and H/D ratio was 3.7, which met the threshold value of less than 10 (Nakazawa, 2007), and therefore, no multicollinearity effects were recognized. R version 4.2.2 (R Core Team, 2020) was used for all statistical analyses.

RESULTS

Figure 1 shows the change in mean cross-sectional area increment, $MCAI_t$, over time in the three mature plantations. For the Oita plantation sample trees (OA1 to OB3), the $MCAI_t$ decreased at 40 to 50 years of age, remained almost constant or decreased until 75 years of age, and then increased. The $MCAI_t$ at 90 years of age was higher than that at 60 years of age for all sample trees. For the Kagoshima plantation sample trees (KA1–

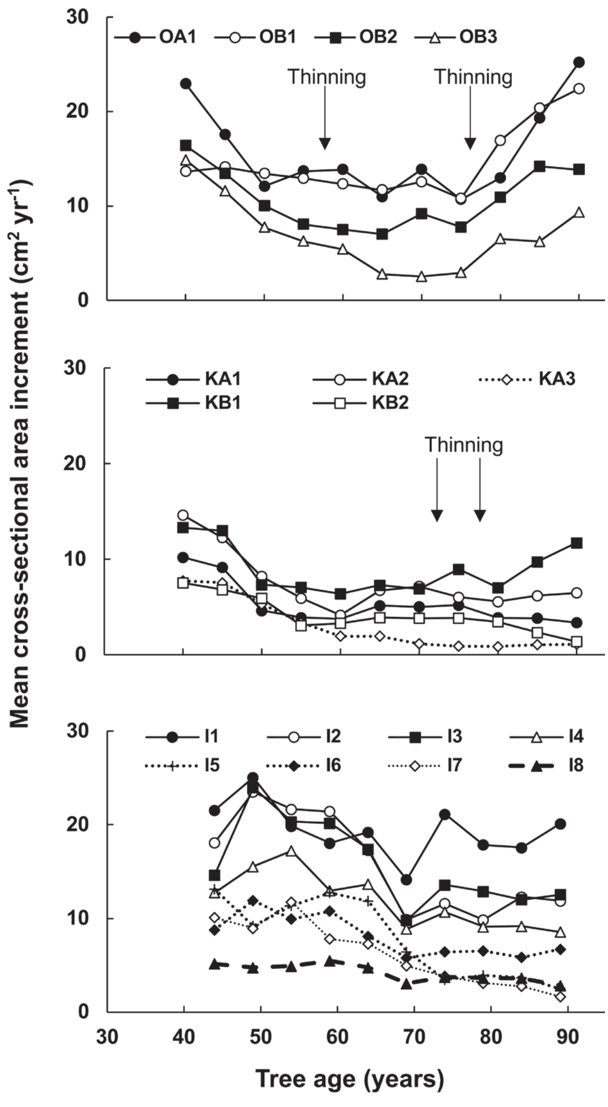

Fig. 1. Mean cross-sectional area increment of sample trees in mature plantations.
Mean cross-sectional area increment indicates the mean of periodic average cross-sectional area increment from $0.2h$ to $0.6h$ of relative height.

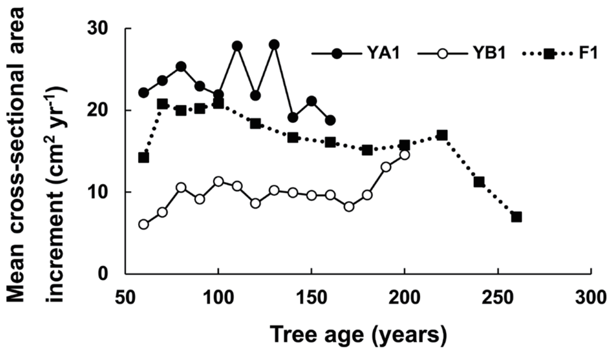

Fig. 2. Mean cross-sectional area increment of sample trees in old-growth stands.

KB2), the $MCAI_t$ decreased at 40–50 years of age and remained almost constant or decreased until 70 years of age. The $MCAI_t$ of the dominant tree, KB1, in the heavily-thinned plot increased thereafter, whereas those of the other trees remained almost constant. For the intermediate tree, KA3, in the medium-thinned plot, $MCAI_t$ was close to zero. Only KA2 and KB1 had a higher $MCAI_t$ at 90 years than at 60 years. For the sample trees of the Iwate plantation (I1–I8), except for I8, the trees showed a high $MCAI_t$ with an increase and decrease from 44 to 59 years of age, followed by a decrease until 69 years of age. The $MCAI_t$ of the dominant trees, I1 and I3, increased thereafter, whereas those of the other trees showed a nearly constant or decreasing rate thereafter. Only I1 showed a higher $MCAI_t$ at 89 years than at 59 years.

Figure 2 shows the change in $MCAI_t$ over time in the three old-growth stands. Among trees in the Yakushima stands, YA1 showed a high $MCAI_t$ of approximately ≥20 cm^2 per year in the age range of 60–160 years. In contrast, YB1 showed an $MCAI_t$ of approximately 10 cm^2 per year from 80–180 years of age, followed by a large increase in $MCAI_t$. In addition, F1 showed an $MCAI_t$ of approximately ≥15 cm^2 per year in the age range of 60–220 years, followed by a large decrease in the $MCAI_t$.

The results of the Wilcoxon signed-rank test for the differences between the $PCAI_{it}$ from 0.2*h* to 0.4*h* and the $MCAI_t$ in each sample tree are shown in Table 3. The $PCAI_{it}$ at 0.2*h* and 0.3*h* was significantly higher for the dominant tree OA1 in the medium-thinned plot, dominant tree OB1 in the heavily-thinned plot, and YA1 and YB1 in the Yakushima stands (Table 3, Figs. 3 and 4). In the trees of the thinning experiment plots, OA1 and OB1, the $PCAI_{it}$ at 0.2*h* began to heighten in the age range of 60–70 years before thinning was applied at 77 years of age, and the $PCAI_{it}$ at 0.3*h* increased in the age range of 80–90 years after thinning (Fig. 3). The $PCAI_{it}$ at 0.2*h* was significantly higher for the dominant tree KB1 in the heavily-thinned plot and for F1 in the old plantation (Table 3, Figs. 3 and 4). However, the $PCAI_{it}$ at 0.2*h* for KB1 was only slightly higher than that for $MCAI_t$ (Fig. 3). In contrast, no significant differences were observed for the dominant tree OB2 and the intermediate trees OB3 and KB2 in

Table 3 Median difference (cm^2 yr^{-1}) for the cross-sectional area increment between the mean and relative height of sample trees

Sample code	0.2*h*	0.3*h*	0.4*h*	H/D ratio	Sr (%)	Crown class	Treatment (thinning)
OA1	3.9*	0.9*	-1.1*	63.9	16.8	D	M
OB1	3.3*	1.2*	0.1	62.4	17.8	D	H
OB2	1.6	0.6	-0.1	68.8	17.8	D	H
OB3	0.3	-0.0	-0.2	79.6	17.8	I	H
KA1	0.4	-0.0	-0.4	77.1	15.0	D	M
KA2	1.4	0.1	-0.7	67.4	15.0	D	M
KA3	-0.1	-0.1	-0.1	79.6	15.0	I	M
KB1	0.8*	0.2	-0.1	62.8	16.1	D	H
KB2	-0.1	0.1	-0.1	65.4	16.1	I	H
I1	0.0	-0.4	-0.5	60.2	15.4	D	U
I2	-1.6	-0.8	-0.2	52.5	15.4	D	U
I3	-1.4	0.1	0.7	57.3	15.4	D	U
I4	-2.1*	-2.3*	-0.3	61.8	15.4	D	U
I5	-0.2	-0.1	-0.3	77.0	15.4	I	U
I6	-0.2	-0.7	-0.4	71.0	15.4	I	U
I7	-0.6	-0.9	0.1	66.5	15.4	O	U
I8	-0.5*	-0.3	0.1	92.8	15.4	O	U
YA1	7.5*	2.2*	-1.3*	42.5	24.2	D	unknown
YB1	1.4*	0.7*	-0.1	41.8	22.0	I	unknown
F1	4.5*	1.5	-1.6*	49.5	16.9	D	unknown

The Wilcoxon signed-rank test was performed. The alternative hypothesis was that the differences in cross-sectional area increment of each relative height ($0.1 \times i\ h$, i=2, 3, 4) minus the mean cross-sectional area increment from 0.2*h* to 0.6*h* are stochastically different from a distribution symmetric about zero. * indicates statistical significance at the 5% level by Holm correction. The H/D ratio indicates those of the sample trees immediately after felling. The Sr indicates the values immediately before the sample trees were felled.

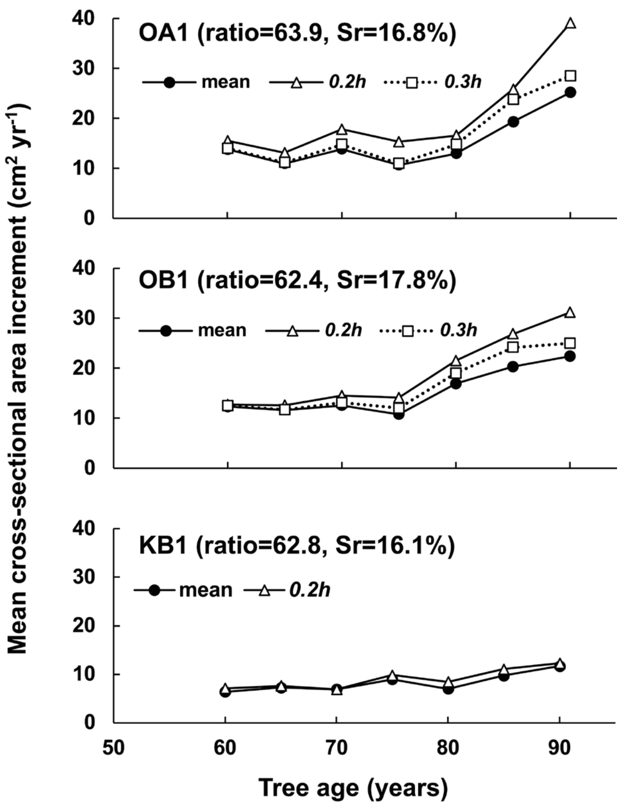

Fig. 3. Comparisons among cross-sectional area increment between the mean and 0.2*h* or 0.3*h* in the sample trees of OA1, OB1, and KB1 in mature plantations.
Only trees with a heightening trend are shown. "mean" indicates the mean of periodic average cross-sectional area increment from 0.2*h* to 0.6*h* of relative height. "ratio" indicates the H/D ratio of sample trees just after felling. Sr indicates the relative spacing index immediately before felling.

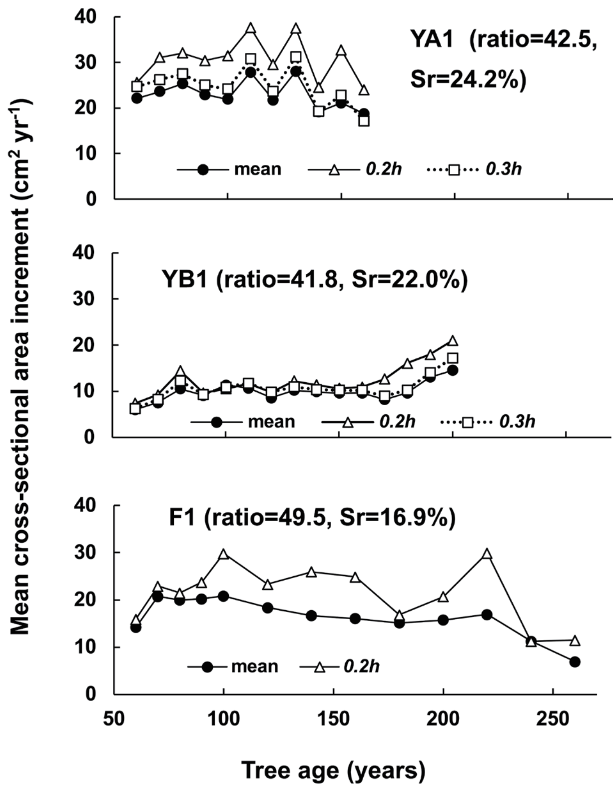

Fig. 4. Comparisons of cross-sectional area increment between the mean and 0.2*h* or 0.3*h* in the sample trees of YA1, YB1, and F1 in old-growth stands.
Only trees with a heightening trend are shown. "mean" indicates the mean of periodic average cross-sectional area increment from 0.2*h* to 0.6*h* of relative height. "ratio" indicates the H/D ratio of sample trees just after felling. Sr indicates the relative spacing index immediately before felling.

the heavily-thinned plots and KA1–KA3 in the medium-thinned plot (Table 3). No significant differences were found in the sparse plot I, which had not been thinned for a long time, with exceptions for I4 and I8 (Table 3). In the dominant tree I4, $PCAI_{it}$ was significantly lower at 0.2*h* and 0.3*h*. In the overtopped tree I8, the $PCAI_{it}$ was significantly lower at 0.2*h*. The $PCAI_{it}$ at 0.4*h* was significantly lower for the dominant trees, OA1, YA1, and F1 (Table 3).

The best model with a H/D ratio and Sr as fixed effects (Table 4) showed that the lower the H/D ratio and the higher the Sr was, the higher the probability was of a heightening trend in the cross-sectional area increment of the lower trunk (Fig. 5). The probability of >95% occurrence was estimated to occur at ≤71 for the H/D ratio if Sr=19% and at ≤55 for the H/D ratio if Sr=17%, whereas it is estimated to occur at ≤39 for the H/D ratio if Sr=15%, indicating the need to induce extremely low H/D ratios (Fig. 5).

Table 4 Linear predictors and Akaike's information criterions (AICs) of the generalized linear mixed model with a heightening trend of cross-sectional increment of lower trunk as the response variable

Linear predictor	AIC
−21.07 − 0.31 *R* + 2.41 *S*	17.5
25.26 − 0.42 *R*	19.3
−24.49 +1.43 *S*	20.6
−0.02	25.5

R and *S* indicate the H/D ratio and relative spacing index, respectively.

DISCUSSION

Of nine total sample trees in the thinning experiment plots (OA, OB, KA, and KB), only three had a significantly higher cross-sectional area increment at 0.2*h* than the mean cross-sectional area increment (Table 3 and Fig. 3). These results did not

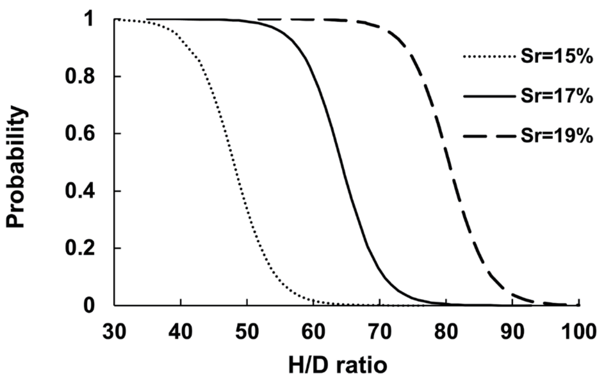

Fig. 5. Estimated probability of occurrence of mature trees with a heightening trend in the cross-sectional area increment of the lower trunk.
The values of the H/D ratio and Sr indicate the most recent value.

strongly support the former hypothesis (Waguchi, 2009) that several trees in mature forests that are thinned regularly may show a heightening trend in the cross-sectional area of the lower trunk.

In contrast, the cross-sectional area increment at 0.2*h* was significantly higher than the mean cross-sectional area increment for all three sample trees in old-growth stands (Table 3 and Fig. 4), implying that the heightening trend of the cross-sectional area increment in the lower part of the trunk persisted for 100–200 years. As a result of the large-scale logging of Sugi on Yakushima Island for approximately 200 years from 1642 onward (Haraguchi, 1997), Sugi multi-cohort forests were formed, consisting mainly of forest trees approximately 200 years of age, interspersed with highly aged trees (>500 years of age) (Yoshida and Imanaga, 1990; Suzuki, 1997). A large canopy gap was formed near the center of plot YA (Sekiya, 1967a), and the YA was sparse, with Sr=24.2% (Table 1). YB was also sparse with Sr=22.0% (Table 1). The forests, including the old plantation F, were managed by the Fukuoka Domain and then logged on a large scale between the incorporation of the national forest (1869) and 1916 (Inoue and Sekiya, 1956). Subsequently, a long-term rotational logging circle was established in 1919 to produce large timber (Inoue and Sekiya, 1956; Mineo and Matsushita, 2021). This spared F1, which was 223 years of age at the time, from subsequent felling, and the increased degree of crowding is thought to have substantially reduced the mean cross-sectional area increment. In other words, although the trees remained at a moderate degree of crowding, Sr=16.6%, due to the lack of logging for approximately 40 years, they were considered sparse before that, owing to multiple logging events.

The Sr of plots with trees with higher cross-sectional area increment of 0.2*h* ranged from 16.1–24.2%, showing a weak trend in crowding compared with the 15.0% and 15.4% in plots where it was not observed (Table 1 and Table 3). Based on the best model, it was estimated that if density was managed and an ≥Sr=19% was maintained, which represents an unclosed canopy, most of the trees with a H/D ratio of ≤71 would show a heightening trend in the cross-sectional area increment at the lower trunk (Table 4 and Fig. 5). This result suggests that if the canopy is sparse, a heightening trend of the cross-sectional area increment at the lower part of the trunk can be observed in most of the trees.

Of the three trees that showed a heightening trend of the cross-sectional area increment at the lower trunk in the thinning experiment plots at medium and heavy levels, the cross-sectional area increments at 0.2*h* in the dominant trees OA1 and OB1 (H/D ratios of 63.9 and 62.4, respectively) were higher than the mean cross-sectional area increments, even prior to the most recent thinning at 77 years of age (Table 3 and Fig. 3). In contrast, no heightening trend in the cross-sectional area increment of the lower trunk was observed for the dominant tree OB2 (H/D ratio of 68.8) and intermediate trees OB3 and KB2 (H/D ratio of 79.6 and 65.4, respectively) in the heavily-thinned plots (Table 3). Therefore, in addition to implementing medium- or heavy-thinning, the H/D ratio may be closely related to this heightening trend (Fig. 5).

In the dominant trees I1 to I4 of plot I, which had been sparse for a long time, albeit not recently thinned, the H/D ratio was low (52.5 to 61.8), but no trend of a heightened cross-sectional area increment at the lower trunk was observed (Table 2). This observation may be due to the low probability of occurrence (0.03–0.40) at H/D ratios of 52.5–61.8 when Sr was 15.4%, as shown in Fig. 5. Instead, a lowering trend in the cross-sectional area increment at 0.2*h* was observed in the dominant tree I4 and overtopped tree I8 (Table 3), which suggested that crowding intensified locally in plot I (Onaka, 1950; Waguchi, 2009; Sumida et al., 2013). Therefore, to clarify the pattern of the increasing trend in the cross-sectional area increment of the lower trunk, it will be necessary to study not only the degree of crowding of the entire stand as indexed by Sr but also the influence of local crowding, such as the inter-tree competition index.

Numerous review articles have described tree acclimation to wind loads and the effects of acclimation on trunk form changes (e.g., Mitchell, 2013; Lehnebach et al., 2018; Gardiner, 2021). Generally, as trees grow and become larger, wind loads on trees increase, and acclimation to these loads leads to the development of butt swells (Mitchell, 2013; Gardiner, 2021). Field experiments combining thinning and guy-wiring tests that manipulate the effects of wind loads, have been conducted in young forests, and it was confirmed that the amount of trunk growth below the wire anchorage position was significantly lower in the sample trees in the thinning and guy-wiring plots than in the thinning plots (Nicoll et al., 2019; Dongmo Keumo Jiazet et al., 2022). In other words, thinning further promotes tree acclimation (expansion of butt swells) to wind load. This trend is consistent with the fact that the cross-sectional area increments at 0.2*h* in the sample trees OA1 and OB1 began to increase before thinning at 77 years of age and then increased considerably after thinning, including the cross-sectional area increments at 0.3*h* (Fig. 3). Therefore, in future studies, it is crucial to study the heightening trend of cross-sectional area increment of the lower trunk, including the acclimation of trees to wind loads (Tasissa and Burkhart, 1997; Cortini et al., 2013; Dongmo Keumo Jiazet et al., 2022).

CONCLUSIONS

In this study, of the nine sample trees of aged Sugi in the thinning experiment plots, only three showed a cross-sectional area increment of 0.2*h* at the lower trunk, which was significantly higher than the mean cross-sectional area increment. By contrast, all three old-growth trees had a significantly higher cross-sectional area increment at 0.2*h* compared with the mean cross-sectional area increment. A generalized linear mixed model with the H/D ratio and Sr as fixed effects was used for all 20 sample trees. The lower the H/D ratio and the higher the Sr was, the higher the probability was of trees showing a heightening trend in the cross-sectional area increment of the lower trunk.

As only one to three sample trees were present in each plot in this study and the interval between disk sampling was inconsistent, additional research on the vertical distribution characteristics of trunk cross-sectional area increments of aged trees is warranted for various species and regions in the future.

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