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Effect of height-to-diameter ratio on stem stiffness of sugi (*Cryptomeria japonica*) cultivars

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Abstract The lumber from sugi plantations in Japan displays large intra- and intertree variation in mechanical properties, even within a stand. These variations seem to be induced by the effects of the characteristics of cultivars as well as the effects of growth traits on mechanical properties. Therefore, the effects of growth traits on mechanical properties per cultivar need to be precisely examined. In this study, we focused on the effects of growth traits, especially height-to-diameter ratio (H/D ratio), on stem stiffness per cultivar. Sixteen cultivars were classified into three groups according to the relationships between stem stiffness and growth traits. In cultivars that showed a close correlation between growth traits and stem stiffness, it was assumed that stem stiffness could be controlled to a certain extent by silvicultural practices using the H/D ratio as an indicator. In cultivars that showed a weak correlation between growth traits and stem stiffness, selecting cultivars for the production of logs with higher mechanical properties seemed to be effective; in this study, Kumotoshi, Tanoaka, and Edanaga were found to be suitable. Tree age and site index may be important factors for producing wood with higher mechanical properties.

Key words Sugi cultivars · Stem stiffness · Height-to-diameter ratio

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Introduction

Sugi (*Cryptomeria japonica*) is an important Japanese afforestation tree species. There are an enormous number of these trees, and their numbers are increasing every year. The price of sugi logs has dropped in comparison with imported logs, and thus the domestic wood industry has been purchasing sugi logs. However, the lumber self-sufficiency rate in Japan has remained at about 20%. The lumber from sugi plantations in Japan displays large intra- and intertree variation in wood properties, even within a stand. These variations have inhibited the increased use of sugi lumber. To promote the use of sugi lumber, variations in wood properties need to be controlled by silvicultural practices.

Many studies have been done to obtain the fundamental information needed for controlling the variation in the wood properties of sugi, especially the wood characteristics of sugi cultivars and sugi plus-tree clones. In plus-tree clones of sugi, the dynamic moduli of elasticity (E_d) had a greater broad-sense heritability than diameter at breast height (DBH),[1] and the clone effect had 64.9% of the total variation of E_d. Therefore, variation of the E_d of sugi might be effectively reduced by classifying the population into clones or local cutting cultivars.[2] Radial variations of the ring structure of plus-tree clones of sugi were considered to be the clonal characteristic.[3] The microfibril angle of latewood tracheids of sugi clones may be controlled genetically, and the radial growth rate seems to be unrelated to the microfibril angle.[4] In sugi cultivars, there were significant differences in wood density and E_d between cultivars,[5] and microfibril angle values and their pattern of variation within a stem varied widely among cultivars.[6] There were variations in longitudinal[7] and transverse[8] shrinkage within stems and among cultivars. These studies revealed that the genetic variation of sugi was the most important parameter for controlling wood properties.

However, the influence of the difference of plantation spacing on sugi wood properties has also been studied. Sugi trees (unknown genotype) that were the most densely planted had the greatest values of air-dried density,[9] mechanical properties,[9,10] smaller ring width, and knot diameter,[11] and the knot diameter ratio had a negative effect on the mechanical properties of the lumber.[9] Densely planted sugi clones also had smaller ring widths and larger ring density,[12] and densely planted sugi cultivars had slightly higher mature wood density and mechanical properties.[13] The effect of the difference of plantation spacing on wood properties was smaller than that of genetic variation.[12,13] Plantation spacing is thus an important parameter for controlling sugi wood properties, although the influence is lesser than that of genetic variation.

Fujisawa et al.[1] and Takata et al.[14] reported that there was no relationship and a weak negative relationship between DBH and MOE in sugi clones and sugi cultivars, respectively, and stated that the reason for the weak relationship was the difference in the regression coefficient between DBH and MOE per clone and cultivar. There have been few studies examining the effects of growth traits on the wood properties per sugi genotype because it was difficult to obtain a sufficient number of sugi trees in which the genotypes were clear. Therefore, as the next stage of studies for controlling sugi wood properties, the effects of growth traits per genotype of sugi on wood properties need to be precisely examined.

In the previous studies on the wood properties of sugi, the growth traits were usually limited to radial growth (mainly DBH), and height growth was rarely examined. However, environmental factors, such as light and wind, have a different influence on trees depending on their height. Recently, it was reported that a higher height-to-diameter ratio (H/D ratio) and greater tree height increased the MOE of 4-year-old radiata pine[15,16] and 8-year-old slash pine,[17] respectively. The results of our previous study suggested that tree height affected the mechanical properties and longitudinal variation pattern of the wood properties of sugi (cutting cultivars, unknown genotype).[18] The H/D ratio, which is closely related to silvicultural practices, may be an important parameter for controlling the wood properties of sugi. However, few studies have examined the effects of H/D ratio on sugi wood properties.

In this study, we focused on the effects of growth traits, especially the H/D ratio, on stem stiffness per cultivar. The purpose was to examine the following issues: (1) the relationship between growth traits and stem stiffness per cultivar on 17 sugi cultivars; (2) the effects of the difference of plantation spacing on stem stiffness using Tosaaka (one of the obi-sugi cultivars); and (3) the effects of growth traits on the stem stiffness of sugi cutting cultivars in plots with different tree ages and site indexes.

Materials and methods

Materials

To study issue (1), 15 obi-sugi cultivars (a major sugi cultivar group in southern Kyushu, Japan) and 2 other cultivars shown in Table 1 were used. These cultivars were 38 years old and had been planted in a plot with a density of 2000 trees/ha. This plot was located on a hillslope site at Kitagocho in Miyazaki Prefecture, Japan. Each cultivar was planted in a row from the upper to the lower part of the slope. Five to nine trees with different growth traits and no visible defects were selected per cultivar.

To study issue (2), 32-year-old Tosaaka, shown in Table 2, were used. Two experimental plots for plantation spacing were established on a hillslope site within a stand in the

Table 1. Growth traits and stem stiffness of sugi cultivars

Cultivars	n	DBH (cm)	Tree height (m)	H/D ratio	E (GPa)	R
Haara	6	25.3 (4.3)	20.8 (1.9)	83.3 (8.6)	10.1 (1.7)	0.57
Tanoaka	8	26.7 (2.2)	21.7 (0.8)	81.9 (7.0)	9.9 (0.8)	0.26
Edanaga	9	25.3 (3.6)	20.3 (1.8)	81.4 (11.2)	9.5 (0.8)	0.23
Kuro	7	32.0 (4.9)	21.8 (2.6)	68.9 (7.4)	9.3 (1.3)	0.51
Tosaaka	8	29.5 (4.1)	22.5 (1.1)	77.5 (10.7)	9.0 (0.9)	0.67
Genbe	7	24.6 (2.1)	21.0 (0.9)	85.6 (6.7)	8.6 (0.8)	0.06
Karatsuki	7	21.7 (2.5)	18.2 (1.2)	84.8 (11.9)	8.6 (0.5)	0.15
Garin	7	28.1 (2.7)	21.4 (1.9)	76.9 (11.3)	8.5 (1.4)	0.92**
Hiki	8	27.8 (2.9)	21.2 (1.0)	76.9 (6.0)	8.3 (0.6)	0.46
Tosaguro	7	27.1 (2.7)	20.3 (0.5)	75.4 (6.1)	8.2 (0.8)	0.88**
Obiaka	9	27.6 (4.8)	20.5 (1.4)	75.9 (10.4)	8.0 (1.3)	0.89**
Hidarimaki	8	29.3 (0.9)	21.2 (0.6)	72.5 (3.6)	7.9 (1.0)	0.31
Mizorogi	7	31.3 (4.5)	20.9 (0.8)	67.9 (7.9)	7.8 (1.0)	0.96**
Chirimendosa	5	21.9 (8.0)	19.4 (0.9)	94.5 (21.6)	7.8 (0.7)	0.50
Arakawa	6	35.4 (4.2)	21.9 (2.7)	61.9 (2.5)	7.7 (0.6)	0.48
Kumotoshi	8	28.1 (3.6)	24.3 (1.5)	87.4 (9.8)	10.3 (1.1)	0.12
Yabukuguri	7	29.0 (6.7)	20.1 (1.5)	71.7 (11.9)	6.9 (2.5)	–0.83*

n, number of samples; DBH, diameter at breast height; H/D ratio, ratio of height to diameter
The order of cultivars was determined according to the E ranking
Kumotoshi and Yabukuguri are not cultivars of the Obi-sugi cultivar group
The values of DBH, tree height, H/D ratio, and stem stiffness at 1.2 m above ground (E) represent the averages of tested trees and the values in parentheses represent the coefficient of variation (%)
** $P < 0.01$; * $P < 0.05$

Table 2. Growth traits and stem stiffness of Tosaaka grown with different plantation spacings

Plots	Initial density (trees/ha)	*n*	DBH (cm)	Tree height (m)	H/D ratio	*E* (GPa)
Upper slope	6944	6	15.8 (7.2)	14.2 (4.2)	90 (6.7)	10.8 (9.2)
	4823	5	15.3 (9.5)	14.1 (3.9)	92 (9.1)	10.4 (4.8)
	3349	8	18.7 (9.0)	14.5 (4.8)	78 (7.4)	9.3 (11.6)
	2326	11	21.3 (12.1)	15.5 (8.5)	73 (6.1)	8.2 (9.6)
	1615	11	24.2 (7.1)	15.7 (5.1)	65 (7.0)	7.6 (11.5)
	1122	11	26.1 (12.6)	15.7 (4.4)	61 (10.3)	7.3 (20.3)
	779	11	28.6 (5.4)	15.9 (4.4)	56 (6.5)	7.8 (18.2)
	541	9	32.0 (9.1)	16.0 (5.1)	50 (6.2)	6.7 (12.7)
	376	11	34.0 (8.1)	16.2 (6.8)	48 (4.7)	6.4 (13.8)
Lower slope	6944	6	14.1 (5.5)	13.7 (4.1)	97.1 (6.0)	10.2 (8.6)
	4823	9	17.1 (13.7)	14.3 (3.7)	84.8 (12.8)	9.2 (12.3)
	3349	11	18.5 (14.9)	14.8 (7.7)	81.0 (8.4)	8.7 (13.1)
	2326	11	20.4 (5.6)	15.0 (4.7)	73.5 (7.0)	8.5 (9.8)
	1615	10	23.4 (14.9)	15.6 (4.3)	67.8 (13.6)	7.8 (14.6)
	1122	11	26.8 (7.4)	16.1 (6.2)	60.1 (4.6)	7.1 (6.5)
	779	12	29.2 (3.4)	16.2 (5.4)	55.4 (5.1)	6.8 (13.5)
	541	10	33.3 (8.3)	16.8 (8.2)	50.4 (6.0)	6.7 (11.5)
	376	8	33.6 (9.1)	16.6 (8.1)	49.3 (5.2)	6.8 (22.2)
Control	3000	8	23.4 (8.0)	16.0 (5.1)	69 (6.8)	8.1 (19.9)

n, number of samples
The values of DBH, tree height, H/D ratio, and *E* represent averages of tested trees and the values in the parentheses represent the coefficient of variation (%)

Table 3. Growth traits and stem stiffness of cutting cultivars of different plots

Plots	Tree age (years)	*n*	DBH (cm)	Tree height (m)	H/D ratio	*E* (GPa)	*R*
A	24	28	21.8 (18.7)	17.0 (7.2)	79.7 (12.8)	6.3 (21.1)	0.83**
B	49	47	25.3 (15.8)	20.6 (6.6)	82.9 (13.6)	8.9 (16.5)	0.44**
C	46	62	24.4 (20.6)	20.4 (7.7)	86.1 (15.3)	9.1 (19.0)	0.51**
D	46	73	26.1 (19.1)	23.3 (8.4)	91.5 (13.7)	10.3 (15.6)	0.37**

n, number of samples
The values of DBH, tree height, H/D ratio, and *E* represent averages of tested trees and the values in parentheses represent the coefficient of variation (%)
** $P < 0.01$

national forest in Kitago-cho, Miyazaki Prefecture, Japan. Five to 12 trees with no visible defects were selected per each initial density (trees/ha) in each plot.

To study issue (3), plots with different tree ages and site indexes, in Table 3, were used. These plots consisted of obi-sugi cultivars, but it was not known which cultivars were in these plots. Although plots of known cultivars should have been used, suitable plots of known cultivars with the necessary conditions could not be found. These plots had been established in the experimental forest of Miyazaki University for lumber production. The same silvicultural practices (thinning, no pruning, initial density 2500–3000 trees/ha) had been carried out for all the plots.

The plots used for this study were located in the southern part of Miyazaki Prefecture. Average annual temperature and precipitation (1971–2000) of Miyazaki Prefecture were 17.2°C and 2982 mm, respectively. Altitude of the plots used for this study ranged from 100 to 350 m.

Measurement of growth traits and stem stiffness

DBH and tree height were measured with a tape measure and ultrasonic hypsometer (Vertex III; Haglof), respectively. The H/D ratio was calculated from the DBH and tree height. Stem stiffness at 1.2 m above ground (E) was measured by the nondestructive tree-bending method.[19] This method has previously been applied for evaluating the stem stiffness of sugi.[14] The span where the deflection by the bending moment was measured was 1 m, and the length of the lever arm for acting bending moment on the stem was 1.2 m.

Statistical analysis

By one-way analysis of variance (ANOVA) and multiple comparisons (statistical analysis software, SPSS ver. 16 with Regression and Advanced Models), the significant difference of measurements among cultivars and plots was examined. In issue (3), the difference of measurements among plots was examined by ANOVA and then by Tukey's HSD test and the Bonferroni test. In issue (1), because of unequal variances, the difference of measurements among cultivars was examined by Kruskal–Wallis test and then by Tamhane T2 test, Dunnett T3 test, and Games–Howell test. The results obtained by different multiple comparisons tests were almost the same.

Results and discussion

Relationship between growth traits and stem stiffness per cultivar

Trees of each cultivar were planted in a row from the upper to the lower part of the slope. In many cultivars, the trees planted at the lower part of the slope had a larger tree height and DBH than trees at the upper part of the slope. This trend seemed to be quite common in sugi plantations and is related to water availability of position in the plots. The average values of growth traits and stem stiffness of each cultivar are shown in Table 1. In all growth traits shown in Table 1, there were no significant relationships between the mean values of the rows (cultivars) and the positions of the rows in the plot; however, there was a significant difference of mean values among cultivars. Therefore, it was assumed that the effect of the position of row on growth traits was smaller than that of the cultivar.

Variations of the growth traits of Chirimendosa were greater than in the other cultivars. Many suppressed trees were included in this cultivar. Therefore, it was difficult to select a sufficient number of sample trees of this cultivar. Chirimendosa was thus excluded from the cultivars examined because of the unreliability of the data.

The effects of growth traits on stem stiffness in all trees of 16 cultivars were examined. The H/D ratio and tree height had a positive correlation with stem stiffness ($P < 0.01$, $P = 0.01$, respectively), but DBH had a negative weak relationship with stem stiffness ($P < 0.05$). To examine to what extent growth traits can be used for classifying stem stiffness, stem stiffness of all trees of 16 cultivars was separated in three groups by each growth trait. As shown in Table 4, the differences among mean values (GPa) of three groups were the largest, and each CV (%) of three groups was the smallest at classification by H/D ratio. Therefore, the H/D ratio was the most effective trait for classifying stem stiffness. However, the effects of the H/D ratio on stem stiffness in 16 cultivars were small ($R = 0.40$). Fujisawa et al.[1] and Takata et al.[14] both pointed out that the reason for the weak relationship between DBH and MOE is because of the difference in the regression coefficient per clone and cultivar in a plantation forest. As shown in Table 1, the relationships between H/D ratio and stem stiffness (R) were different among cultivars. According to the relationships of each cultivar, 16 cultivars were classified into three groups (Figs. 1–3). In the seven cultivars with a larger R ($R > 0.50$) in Table 1, the H/D ratio had a strong positive effect on stem stiffness (Fig. 1). Therefore, if the lumber from these cultivars is meant to be put to structural use, then plantation spacing and silvicultural practices that increase the H/D ratio of the trees need to be implemented. In the 8 cultivars with a smaller R ($R < 0.50$) in Table 1, the H/D ratio had little effect on stem stiffness (Fig. 2). By analyzing the data of Table 1 with multiple comparisons, the characteristics of the cultivars were examined. Karatuki

Table 4. Classification of stem stiffness of all trees in Table 1 by growth traits

	DBH (cm)		
	16–24	24–32	32–40
Mean (GPa)	8.8	8.7	8.2
SD (GPa)	1.6	1.4	1.4
CV (%)	18.2	15.6	16.9
	Tree height (m)		
	15–20	20–22	22–26
Mean (GPa)	8.1	8.7	9.1
SD (GPa)	1.7	1.2	1.3
CV (%)	21.0	14.3	14.6
	H/D ratio		
	50–70	70–90	90–110
Mean (GPa)	7.9	8.7	9.8
SD (GPa)	1.3	1.4	1.3
CV (%)	15.8	15.6	13.3

SD, standard deviation; CV, coefficient of variation

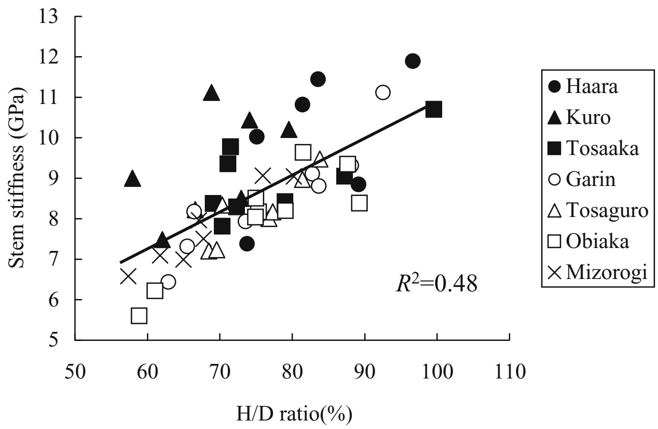

Fig. 1. Effect of height-to-diameter (H/D) ratio on stem stiffness of seven cultivars. The seven cultivars were selected according to larger R shown in Table 1

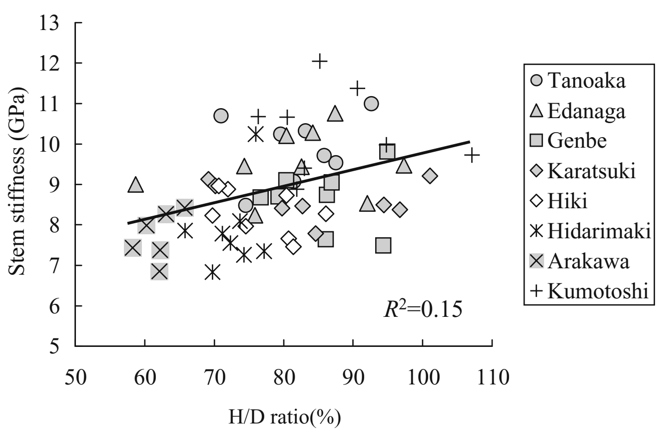

Fig. 2. Effect of H/D ratio on stem stiffness of eight cultivars selected according to the smaller R shown in Table 1

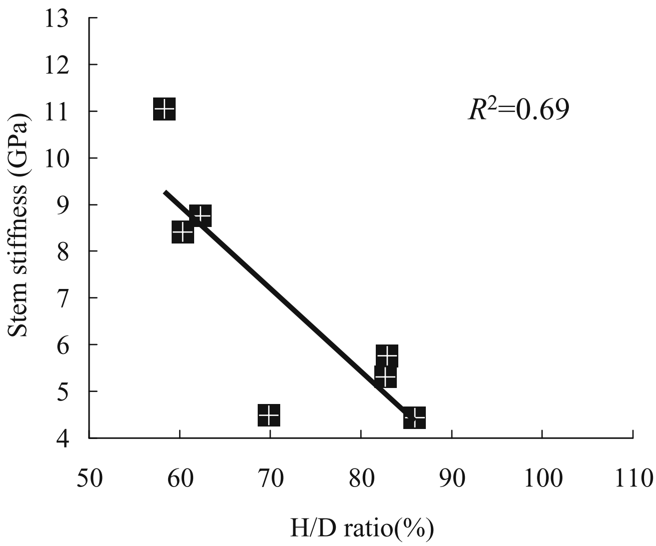

Fig. 3. Effect of H/D ratio on stem stiffness of Yabukuguri

had a significantly smaller DBH and tree height, Arakawa had a significantly larger DBH, a smaller H/D ratio, and smaller stem stiffness, and Kumotoshi had a significantly larger tree height and stem stiffness than many other cultivars ($P < 0.01$ or $P < 0.05$). Tanoaka and Edanaga also had significantly higher values for stem stiffness than the other cultivars ($P < 0.01$ or $P < 0.05$). These cultivars are included in the cultivars shown in Fig. 2. From these results, it was assumed that in the cultivars shown in Fig. 2, the growth traits and stem stiffness were more strongly determined by genetic factors than in the other cultivars. For the production of logs with higher mechanical properties, Kumotoshi, Tanoaka, and Edanaga were suitable because they had significantly higher stem stiffness than the other cultivars. In Yabukuguri, the H/D ratio had a negative strong effect on stem stiffness (Fig. 3). Therefore, if the end use of the lumber from a Yabukuguri plantation was for structural projects, then plantation spacing and silvicultural practices that make the H/D ratio of the trees small need to be planned. This result for Yabukuguri was the same as in a previous study.[13]

By highly managed silvicultural practices, variations in the wood properties of the lumber from the cultivars in Fig. 1 could be decreased, so that there is less variation than in commercial sugi lumber. For the cultivars in Fig. 2, not as much increase in stem stiffness by silvicultural practices could be expected. For production of logs with higher mechanical properties, selecting cultivars seemed to be effective. The costs of producing logs with higher mechanical properties using the cultivars in Fig. 2 would be lower than the costs using the cultivars in Fig. 1 and Yabukuguri, because highly managed silvicultural practices are not necessary.

Tosaaka grown with different plantation spacing

As previously described, in the cultivars in Fig. 1, the growth traits had strong effects on stem stiffness, and silvicultural

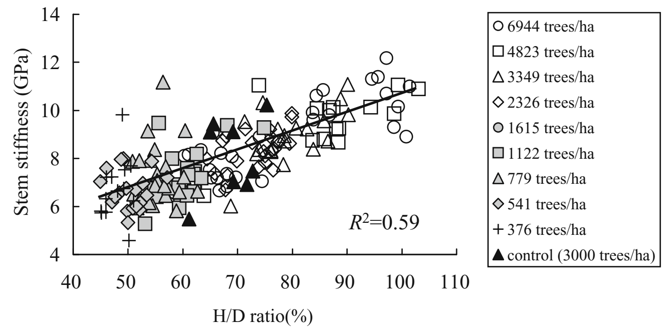

Fig. 4. Relationship between H/D ratio and stem stiffness of Tosaaka grown with different plantation spacing

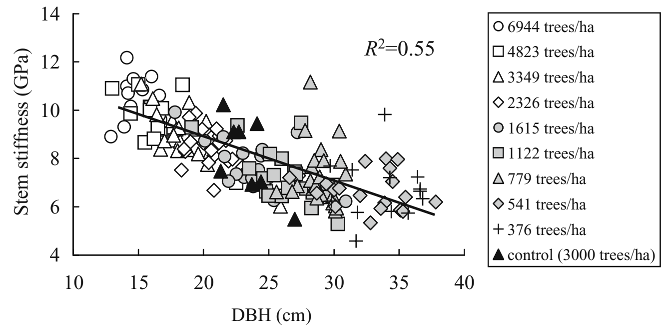

Fig. 5. Relationship between DBH and stem stiffness of Tosaaka grown with different plantation spacing

practices should thus be implemented to produce logs with higher mechanical properties. It has generally been believed that plantation spacing can control the growth traits. Therefore, the effect of plantation spacing on the stem stiffness of the cultivars in Fig. 1 was precisely examined. Tosaaka was one of the cultivars in which the H/D ratio had a larger influence on the stem stiffness. The growth traits and stem stiffness of Tosaaka grown with different plantation spacing are shown in Table 2. With the increase of initial density, the H/D ratio and stem stiffness increased, but DBH and tree height decreased in both the upper and lower slope of the experimental plots for plantation spacing. The growth traits (H/D ratio and DBH) had strong effects on stem stiffness of Tosaaka (Figs. 4, 5). However, for trees with a larger DBH (more than 25 cm) in Fig. 5, DBH had little effect on stem stiffness. From these results, it was demonstrated that by selecting the plantation spacing and using the H/D ratio as an indicator, the stem stiffness of Tosaaka could, to a certain extent, be controlled. In addition, it was recognized that classifying cultivars according to the relationships between growth traits and stem stiffness (see Figs. 1–3) was very important for producing logs with higher mechanical properties.

Sugi cutting cultivars (unknown genotypes) of the plots with different tree ages and site indexes

As shown in Table 3, there were correlations between the H/D ratio and stem stiffness in four different plots. Espe-

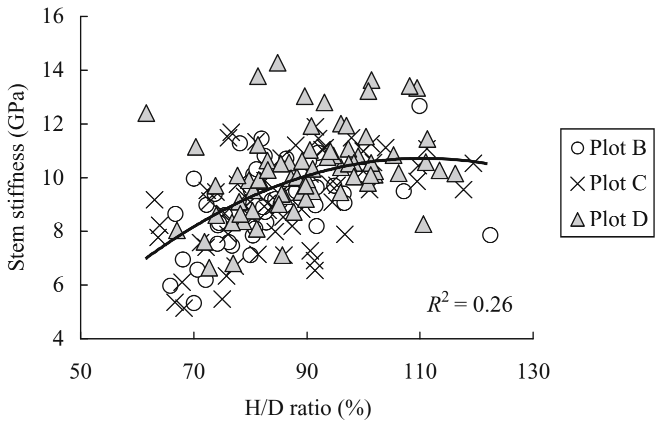

Fig. 6. Relationship between H/D ratio and stem stiffness of cutting cultivars in different plots. Plots B, C, and D are shown in Table 3

cially in plot A (younger trees), the H/D ratio had a greater influence on the stem stiffness. On younger radiata pine[15,16] and slash pine,[17] it was reported that a higher H/D ratio and larger tree height increased MOE, respectively. Growth traits may have a greater influence on the stem stiffness of juvenile wood than mature wood. In three older plots (B, C, and D), tree height, H/D ratio, and stem stiffness were significantly different ($P < 0.01$), but there was no significant difference in DBH among the plots. The tree height and stem stiffness of plot D were significantly larger than those of plots B and C ($P < 0.01$). From these results, it was demonstrated that the larger tree height of plot D, because of its higher site index, could induce a larger H/D ratio and then greater stem stiffness. From the regression curve, the influence of the H/D ratio on stem stiffness seemed to be limited to about 100 (Fig. 6). Therefore, the site index seemed important not only for produced wood volume but also the mechanical properties of produced wood.

As previously described, it was not known which cultivars were planted in these four plots. Each plot seemed to consist of multiple cultivars because the plots had been established for lumber production, not for a research project. For the production of logs with higher mechanical properties, the relationships between growth traits and stem stiffness should be examined for each known cultivar in plots with different tree ages and different site indexes. For the cultivars in Fig. 1, silvicultural practices at a younger age and selecting the plantation site according to the site index may also increase stem stiffness.

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