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ORIGINAL ARTICLE

Tree heights in the ring-formed years affect microfibril angles in the rings from juvenile to mature wood at breast height in hinoki trees (*Chamaecyparis obtusa*)

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Abstract In this study, we examined past growth traits of hinoki (*Chamaecyparis obtusa*) trees by stem analysis, as well as growth traits in the years when the rings at breast height were formed. We tried to clarify the effects of growth traits in the ring-formed years on the wood properties of the rings from juvenile to mature wood. Height to diameter ratio (H/D) had a larger correlation coefficient in relation to stem stiffness than tree height or diameter at breast height (DBH). The longitudinal variation in stiffness of logs, except for first and top logs, in each tree was assumed to be constant with the height position in the trunk. Tree height in the ring-formed year had a significant negative effect on microfibril angle (MFA) near the pith, in transition wood, and in mature wood. DBH in the ring-formed year had a significant negative effect on density in mature wood. We concluded that the effects of tree height on MFA and of DBH on density produced the effect of H/D on stem stiffness of the trunk. Greater tree height in younger age may contribute to the improvement of juvenile wood properties.

Keywords Tree height · MFA · Juvenile wood · Hinoki

Introduction

In conifers, previous studies have suggested that wood formation is controlled by indole-acetic acid (IAA) synthesized at and transported from the crown [1–6]. Other known and/or unknown regulators transported from the crown and/or root system may also control wood formation in the trunk of conifers. Both the size of the crown and/or the root system and the amounts of synthesized regulators may vary with growth traits. Therefore, the effects of growth traits on timber quality are very important subjects for studies aimed at improving timber quality on plantations. In research on the effects of growth traits on wood properties, many studies have focused on the impact of a tree's diameter [7, 8]. Few studies, however, have looked at the effect of tree height on wood properties [9, 10]. In addition, recent tree-breeding programs have attempted to increase growth rates of plantation trees with shorter rotation cycles. Production through shorter rotations with fast growth trees means that the resulting wood has larger juvenile wood ratios [11]. For future intensive plantation management, improvement of juvenile wood properties is thought to be a very important objective.

Hinoki (*Chamaecyparis obtusa*) is an important plantation species in Japan. This domestic wood is used mainly for structural purposes. In studies of softwoods and hardwoods, it is well known that differences in mechanical properties can be explained by variations in the microfibril angle (MFA), as well as variations in its density [12–14]. In hinoki trees, it has also been reported that variation in compressive strength is mainly affected by differences in density [15]. Variation in the modulus of elasticity is mainly affected by MFA [16]. Therefore, variations in MFA and density within and between hinoki trees must be examined to understand the variation in mechanical properties. In hinoki, the highest

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density is found in juvenile wood, and density then decreases gradually outward, becoming constant in older rings [15–17]. Density of hinoki trunks was higher—but more variable—further from the ground [17].

Most pines show low-value density near the tree center, with an increase toward the bark [18]. Norway spruce (*Picea abies*), however, demonstrated the same radial variations of density as hinoki [19]. In conifers, MFA varies from pith to bark, with the largest angles occurring in the first five to ten growth rings from the pith [20]. In hinoki, MFA showed the largest angle in juvenile wood near the pith and decreased gradually toward the bark, becoming constant at ring number 10–15 [16]. Hinoki plus tree families had larger ring width and slightly lower density and stiffness of logs than local families [21]. Densely planted hinoki produces a higher percentage of latewood, with higher density and mechanical properties [22]. In our previous studies, we reported significant differences in MFA, density, color of heartwood, and termite resistance among hinoki families [23, 24]. Larger diameter of trees decreased wood properties for structural use in many hinoki families. We also reported the significant positive effects of tree height to diameter ratio (H/D) on stem stiffness in sugi (*Cryptomeria japonica*) trees [10]. However, very few studies of hinoki trees have examined the effects of tree height on wood properties, especially on juvenile wood properties.

In the current study, we examined the past growth traits of hinoki trees by stem analysis, and then analyzed growth traits in the year when the rings at breast height were formed. We tried to clarify the effects of growth traits in the ring-formed year on the wood properties of the rings from juvenile to mature wood. The objectives of the current study were to examine: (1) variations of wood properties in the rings from juvenile to mature wood; (2) variations of growth traits in the year when the rings were formed; and (3) the effects of growth traits in the ring-formed year on the wood properties in rings of hinoki trees with different growth traits.

Materials and methods

Sample trees and logs

To choose the sample trees, 99 trees in a test stand were selected for measurements of stem stiffness (Fig. 1). Stem stiffness at 1.2 m above ground was measured by the nondestructive tree-bending method [25]. Based on the results shown in Fig. 1, 11 trees with different growth traits and stem stiffness in this stand except the trees in Fig. 1 were selected as sample trees (Table 1). The test stand consisted of 37-year-old hinoki trees, but there was no information on the genetic background of the trees in the stand. These trees had been planted for wood production in the experimental forest of Miyazaki University (initial densities 3000 trees/ha). Thinning and pruning were carried out at the stand. From 2001–2011, the average annual temperature and precipitation at the experimental forest were 17.3 °C and 2793 mm, respectively. The area of the test stand was 3.86 ha, and there was no compartment in the test stand. The altitude of the test stand ranged from 170 to 190 m. The diameter at breast height (DBH) and tree height were measured using a tape measure and ultrasonic hypsometer (Vertex III, Haglof, Inc), respectively.

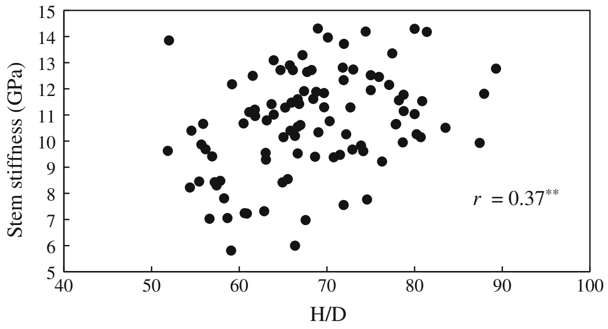

Fig. 1 Effects of H/D on stem stiffness of hinoki trees. There was a significant positive correlation between H/D and stem stiffness at breast height. *H/D* height to diameter ratio $^{**}p < 0.01$

The 11 trees were felled in 2007, and 12–16 1-m logs were cut from each tree to examine the longitudinal variation of stem stiffness. The longitudinal dynamic modulus of elasticity (E_d) of all logs was measured by tapping method [26]. The second log cut from each tree (i.e., from a location 1–2 m above the ground) was used for measurement of diameter growth at breast height, MFA, density, and mechanical properties in bending. The other logs were cut into 5-cm-thick disks in the longitudinal direction to examine the process of tree height growth. The small disks near treetops and second logs of each tree were not examined for the process of tree height growth. Therefore, the tree height growth was examined in fewer rings than diameter growth.

Stem analysis for tree height and diameter growth at breast height

To meet objective (2)—examine the variations of growth traits in the year the rings at breast height were formed—the relationships between tree age and height were obtained for each sample tree based on observation of the upper surface of the 5-cm-thick disks. Tree heights at ring-formed years were examined. The diameter of each ring was measured in two radial directions which intersect perpendicularly with each other in disks obtained at breast height.

Table 1 Growth traits and wood properties of sample trees

No.	Age	DBH (cm)	H (m)	H/D	Juvenile wood (rings $\leq$ 14)					Mature wood ($15 \leq$ rings)				
					TL (mm)	MFA (°)	Density (kg/m^3)	E_b (GPa)	σ_b (MPa)	TL (mm)	MFA (°)	Density (kg/m^3)	E_b (GPa)	σ_b (MPa)
1	37	16.7	14.2	85	2.2 (0.3)	10.2 (6.8)	411 (29)	14.8 (2.7)	116 (18)	2.5 (0.1)	8.1 (1.5)	387 (14)	13.9 (1.5)	107 (11)
2		16.8	14.2	85	2.1 (0.8)	15.7 (9.6)	410 (21)	10.9 (2.4)	90 (4)	2.8 (0.1)	8.2 (1.2)	400 (13)	15.5 (0.0)	112 (2)
3		20.3	16	79	2.2 (0.6)	22.4 (7.7)	458 (17)	7.7 (1.9)	94 (9)	3.1 (0.2)	10.2 (3.1)	446 (17)	13.1 (1.9)	98 (17)
4		17.7	13.7	77	1.9 (0.3)	20.0 (4.5)	387 (12)	6.8 (1.4)	80 (7)	2.8 (0.2)	13.5 (2.4)	383 (12)	11.2 (1.1)	92 (2)
5		19.6	15.1	77	2.2 (0.1)	11.5 (2.0)	411 (29)	11.6 (2.4)	101 (10)	2.8 (0.3)	10.6 (1.7)	387 (14)	13.1 (0.3)	99 (2)
6		22.6	15.2	67	2.2 (0.4)	16.6 (6.6)	393 (22)	9.7 (2.1)	81 (10)	3.0 (0.1)	8.3 (2.8)	383 (7)	11.6 (1.0)	90 (4)
7		22.7	15.2	67	2.5 (0.8)	15.3 (5.2)	435 (35)	11.4 (0.5)	91 (3)	3.6 (0.2)	8.5 (0.8)	391 (11)	14.6 (0.3)	102 (8)
8		25.3	16.8	66	2.2 (0.5)	19.1 (7.5)	467 (29)	8.9 (1.1)	92 (14)	3.1 (0.1)	10.9 (0.6)	417 (13)	11.0 (1.5)	96 (6)
9		30.8	17.8	58	2.4 (0.5)	21.4 (7.0)	377 (46)	7.7 (0.5)	72 (6)	3.4 (0.3)	11.0 (2.6)	325 (17)	9.0 (1.1)	74 (5)
10		30.2	16.6	55	2.4 (0.3)	19.3 (6.4)	404 (35)	7.9 (1.3)	75 (10)	2.8 (0.2)	9.9 (1.0)	359 (7)	11.1 (0.7)	85 (7)
11		29.2	15.9	54	1.7 (0.3)	32.0 (10.1)	377 (18)	6.9 (1.6)	77 (11)	2.8 (0.2)	15.2 (0.4)	333 (9)	8.7 (0.9)	76 (9)

The value of MFA, density, E_b, and σ_b represent the average value of rings in juvenile or mature wood, while the values in parentheses represent the standard deviations

DBH diameter at breast height, *H* tree height, *H/D* height to diameter ratio, *TL* latewood tracheid length, *MFA* microfibril angle of S_2 layer at secondary wall of latewood tracheid, E_b modulus of elasticity in bending, σ_b modulus of rupture in bending

The average values of the two diameters were obtained as DBH. The height to diameter ratio (H/D) in each ring at breast height was also calculated.

Measurements of tracheid length, MFA, and density

To meet objective (1)—assess variations of wood properties in the rings from juvenile to mature—the tracheid length, MFA, and density of each tree were measured from the second logs. The 20-cm-length edge grain boards with the pith in the center were cut into three parts, in the longitudinal direction. Latewood tracheid length (TL) was measured from small specimens cut from the latewood of every three rings from pith to bark on one side of edge grain specimens. The small specimens were macerated for measurement of TL. Density was measured from 9 to 12 small specimens of edge grain wood cut from pith to bark continuously on each side. Heartwood extractives were removed by immersing samples in methanol (72 h, room temperature) and hot water (48 h, 90 °C). Density was calculated from green volume and kiln dry weight. Variation in density was measured from pith to bark on both sides. In this study, basic density is simply described as "density". MFA of the tangential wall was measured from 24-μm-thick tangential sections cut from latewood of every 3–5 rings from pith to bark on one side of edge grain specimens. MFA was measured by the iodine-staining method [27]. I_2 crystallizes in gaps between microfibrils and sections were observed with a light microscope. On light microscopy, MFA was measured using image analysis software (Image J [28]). MFA of each ring was obtained by averaging the MFA of 30 latewood tracheids.

Measurements of mechanical properties in bending

Small clear specimens (*L* 320 mm, *R* 20 mm, *T* 10 mm) were prepared from the 80-cm-length edge grain boards with the pith in the center. Specimens were obtained from pith to bark continuously on one side, and then air-dried at 20 °C and 60 % relative humidity. The average value of moisture content of all specimens was 6.5 %. The static bending test was conducted by flatwise three-pointed loading using a universal testing machine and a span of 280 mm. Modulus of elasticity (E_b) and modulus of rupture (σ_b) in bending of specimens were calculated from the load–deflection curves. To examine the effects of growth traits (tree height, DBH, and H/D) on mechanical properties, the growth traits of rings positioned in the center of specimens were related to the mechanical properties of specimens. In the current study, based on the radial variation of TL, we estimated the wood of rings numbered $\leq$14 and that of rings numbered $\geq$15 as juvenile wood and mature wood, respectively. The juvenile wood was

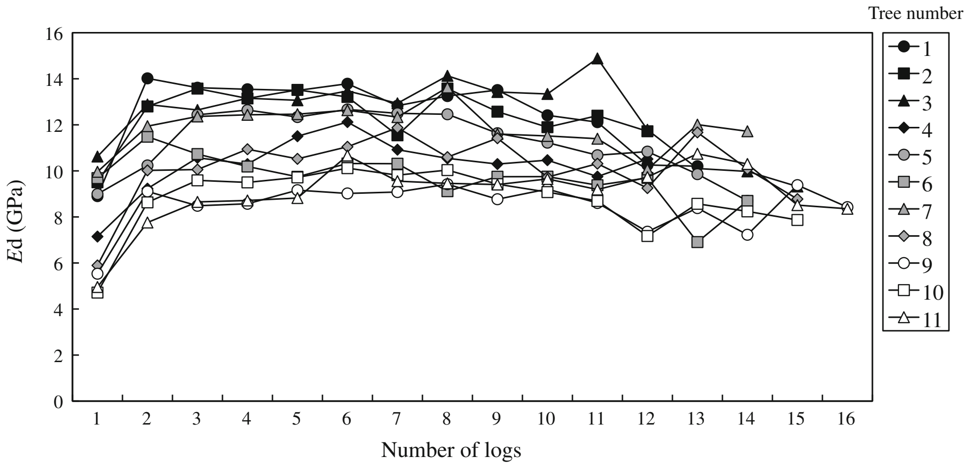

Fig. 2 Longitudinal variation of E_d in logs of sample trees. The length of each log was 1-m. Sections of each log were numbered from base to top of trees. E_d longitudinal dynamic modulus of elasticity

classified into wood near the pith (rings numbered ≤ 7) and transition wood (rings numbered ≥ 8).

Results

Inter- and intra-tree variation of stem stiffness

As shown in Fig. 1, H/D ($r = 0.37$, $p = 0.00015$) had a larger correlation coefficient in relation to stem stiffness than tree height ($r = 0.043$, $p = 0.67$) or DBH ($r = 0.32$, $p = 0.0012$) in the 99 trees of the test stand. In the stand, H/D and stem stiffness varied from 51.9 to 89.3 and from 5.8 to 14.3 GPa, respectively. As shown in Table 1, to meet objectives (1), (2), and (3), we selected 11 trees according to the range of H/D in Fig. 1. Longitudinal variations of E_d in the logs from the 11 test trees are shown in Fig. 2. The variation in E_d of logs, except for the first and top logs, in each tree was assumed to be relatively constant with the position in the trunk. The E_d of second logs varied among trees with different H/D from 7.8 to 14.0 GPa. Therefore, the difference in stem stiffness among trees was assumed to be larger than the longitudinal variation of E_d of logs, except for the first and top logs.

Variation of growth traits and wood properties among trees

The growth traits in the ring-formed year (the year when the ring at breast height was formed) are presented in Fig. 3. In trees numbered 1–7, the rate of diameter growth was assumed to begin declining at ring number 12, although the rate of diameter growth in the other trees was assumed to be constant until ring number 30. In tree No. 5, in the smaller ring numbers, tree height was larger than other trees, although in the larger ring numbers, it was about the same height as other trees. In tree No. 9, DBH was smaller than other trees in the smaller ring numbers, although in the larger ring numbers, its DBH was larger than other trees. These individual variations of growth traits according to the ring-formed year might be important to understand inter- and intra-tree variations of wood properties.

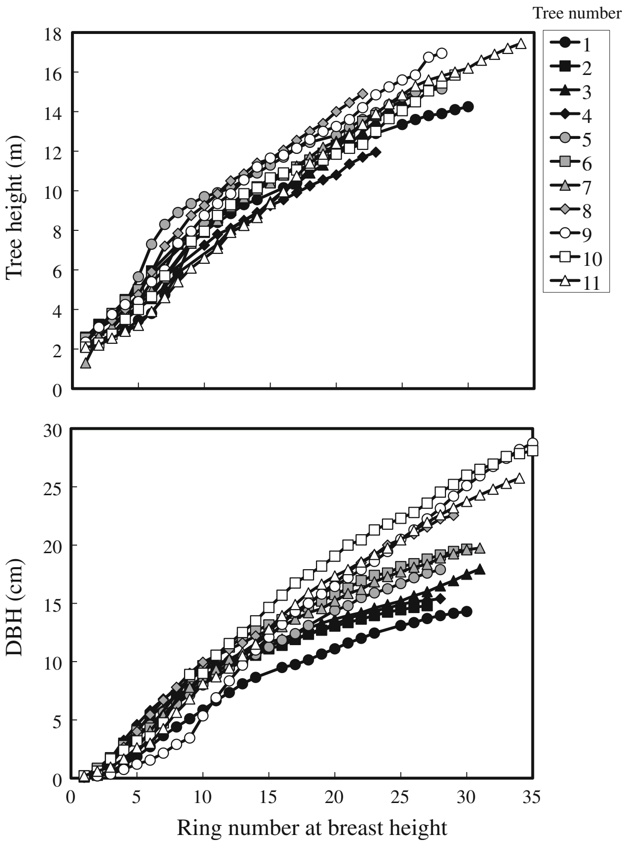

Fig. 3 Growth traits in the ring-formed year. Tree height in the ring-formed year was obtained by stem analysis. DBH was a diameter of trunk without bark. *DBH* diameter at breast height

As can be seen in Table 1, wood properties varied among trees. In juvenile wood (rings ≤ 14), MFA and

Table 2 Correlation coefficients between growth indexes and wood properties

Wood properties	Growth indexes		
	Tree height	DBH	H/D
MFA$_{3,5,6}$	−0.48 (0.036)*	−0.42 (0.072)	0.14 (0.56)
MFA$_{9,10,12}$	−0.50 (0.029)*	−0.20 (0.41)	0.047 (0.85)
MFA$_{15\sim}$	−0.47 (0.0009)**	−0.24 (0.11)	−0.17 (0.25)
Density$_{3\text{-}8}$	−0.15 (0.49)	−0.20 (0.37)	0.23 (0.31)
Density$_{9\text{-}14}$	−0.16 (0.49)	0.061 (0.79)	−0.23 (0.31)
Density$_{15\sim}$	−0.31 (0.027)*	−0.52 (0.00008)**	0.49 (0.0002)**
TL$_{3,5,6}$	0.47 (0.041)*	0.60 (0.0066)**	−0.51 (0.026)*
TL$_{9,10,12}$	0.18 (0.46)	0.55 (0.014)*	−0.55 (0.015)*
TL$_{15\sim}$	0.40 (0.0062)**	0.58 (0.00003)**	−0.53 (0.00019)**
$E_{b4\text{–}7}$	0.15 (0.60)	0.29 (0.30)	0.17 (0.55)
$E_{b8\text{–}14}$	−0.015 (0.94)	0.012 (0.95)	−0.068 (0.73)
$E_{b15\sim}$	−0.18 (0.20)	−0.40 (0.0034)**	0.50 (0.00015)**
$\sigma_{b4\text{–}7}$	0.37 (0.18)	0.093 (0.74)	0.40 (0.14)
$\sigma_{b8\text{–}14}$	−0.21 (0.28)	−0.25 (0.19)	−0.027 (0.89)
$\sigma_{b15\sim}$	−0.32 (0.02)*	−0.49 (0.00018)**	0.51 (0.0001)**

The values represent the correlation coefficients between growth parameters and wood properties and the values in parentheses represent the *p* values. The small numbers of symbols of wood properties shows ring numbers in which the wood properties were measured. Tree height was obtained by stem analysis (Fig. 3)

DBH diameter at breast height, *H* tree height, *H/D* tree height to diameter ratio, *MFA* microfibril angle, *TL* latewood tracheid length, E_b modulus of elasticity in bending, σ_b modulus of rupture in bending

* $p < 0.05$, ** $p < 0.01$

density varied from 10.2° to 32.0° and 377–458 kg/m^3, respectively. In mature wood (rings $\geq$15), MFA and density varied from 8.1° to 15.2° and 325–446 kg/m^3, respectively. It should be noted that variation of MFA in juvenile wood among trees was very large. E_b and σ_b in juvenile wood varied from 6.8 to 14.8 GPa and from 72 to 116 MPa, respectively. E_b and σ_b in mature wood varied from 8.7 to 15.5 GPa and from 74 to 112 MPa, respectively. In terms of mechanical properties, variations among trees in juvenile wood were also larger than in mature wood. We examined the effects of MFA and density on mechanical properties using average values of MFA, density, E_b, and σ_b in juvenile and mature wood in each sample trees (Table 1). In mature wood, MFA had a significant negative effect on E_b, and density had a significant positive effect on σ_b ($p < 0.05$, $n = 11$). In contrast, in juvenile wood, MFA had a significant negative effect on both E_b and σ_b ($p < 0.01$ and 0.05, respectively, $n = 11$), although density did not have a significant effect on either.

Effects of growth traits in the ring-formed year on the wood properties at breast height

Pearson's correlation coefficients between growth indexes and wood properties were examined, and the results are presented in Table 2. It was notable that H/D had significantly larger positive effects on E_b and σ_b in mature wood. These results were consistent with those in Fig. 1, and were easily predicted. We found no growth trait that had a significant effect on mechanical properties in juvenile wood. Tree height had a significant negative effect on MFA near the pith, in transition wood, and in mature wood (Table 2; Fig. 4). It was ascertained that trees with greater height at the ring-formed year had smaller MFAs in all types of wood. As shown in Fig. 4, MFA decreased with increasing of tree height from wood near the pith to mature wood. Therefore, tree height may be able to explain not only the variation of MFA among trees, but also the radial variation of MFA from pith to bark. However, DBH had no significant effect on MFA. DBH did, however, have a significantly larger negative effect on density in mature wood. It was established that trees with larger DBH had smaller densities in mature wood. However, no growth index was found to have a significant effect on density near the pith or in the transition wood. DBH also had larger significant effects on TL near the pith, in transition wood, and in mature wood. From these results, we concluded that tree height was an important growth index for controlling MFA.

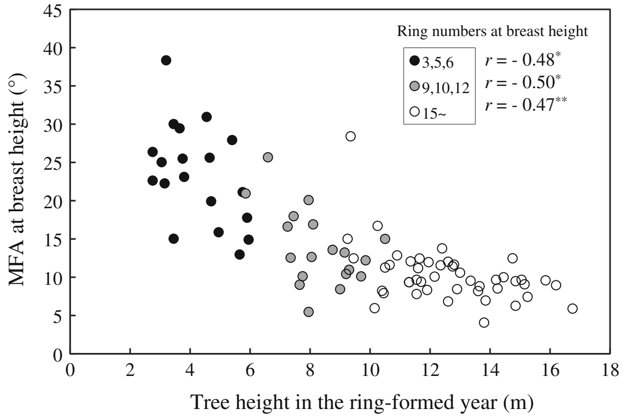

Fig. 4 Effect of tree height on MFA of rings at breast height. Tree height in the ring-formed year was obtained by stem analysis (Fig. 3). *MFA* microfibril angle $^*p < 0.05$, $^{**}p < 0.01$

Discussion

In a previous study, we showed that H/D significantly affected stem stiffness in sugi trees [10]. We concluded that H/D was a useful index for producing wood with superior mechanical properties in sugi plantations. In hinoki trees, we also demonstrated that H/D had a larger effect on stem stiffness than tree height or DBH (Fig. 1). Therefore, controlling the H/D by selecting tree densities and/or selecting appropriate hinoki families might contribute to wood production with superior mechanical properties in hinoki plantations [10]. In hinoki trees, the E_d of logs except for first and top logs was assumed to be relatively constant in longitudinal variation (Fig. 2). This result was consistent with a previous study [29]. In sugi trees, the E_d of logs increased with height position [9], and the logs with the largest E_d were between 6 and 8 m above ground. Here, longitudinal variation of E_d of logs in hinoki trees was assumed to be smaller than in sugi trees.

The average values of E_b and σ_b in all specimens were 10.6 GPa and 88.2 MPa (Table 1, $n = 105$). It has been reported that average values of E_b and σ_b of 115–120-year-old hinoki trees were 10.7 GPa and 82.4 MPa [30]. The results of our bending tests were close to those of a previous study. In the study on hinoki half-sib families, MFA and density varied from 7.9° to 32.8° and 306–469 kg/m^3, respectively [23]. These results were also close to the results of the current study (Table 1). We reported that there were families with smaller radial variation of MFA and density [23]. Table 1 indicates that trees with larger H/D had smaller difference of MFA and density between juvenile and mature wood. These trees had juvenile wood with superior properties for structural use. Trees with both superior wood properties for structural use and larger diameter growth are desirable for plantation management. However, in the current study, trees with superior wood properties for structural use had smaller diameters.

As mentioned in the introduction, it is well known that variations in the mechanical properties of many species can be well accounted for by variations in MFA and density. In the current study, MFA and density significantly affected mechanical properties in mature wood. As shown in Table 2, it was demonstrated that larger tree height was associated with smaller MFA, while smaller DBH was connected to higher density. We concluded that larger tree height and smaller DBH resulted in larger H/D. Therefore, the effects of both tree height on MFA and DBH on density may be said to produce the effects of H/D on stem stiffness seen in Fig. 1.

As shown in Table 2 and Fig. 4, tree height in ring-formed year significantly affected MFA near the pith, in transition, and in mature wood. However, DBH in ring-formed year had no significant effect on MFA near the pith, in transition or in mature wood. In hinoki trees, it was recognized that the density of juvenile wood was relatively large in both the current and previous studies [23]. In the current study, density had no significant effect on mechanical properties in juvenile wood. Therefore, MFA were found to be more important for improvement of juvenile wood properties. Based on the obtained relationships, it was suggested that taller tree height at a young age could contribute to improved juvenile wood properties. On the other hand, DBH in the ring-formed year significantly affected density in mature wood, although not in transition or juvenile wood. We found that larger diameter growth in mature trees resulted in lower density in mature wood.

In studies of sugi cultivars, we reported that crown length had a significant positive effect on IAA amounts in cambial-region tissues, and that distance from crown base had a negative effect on IAA amounts in cambial-region tissues [31]. The effect of distance from crown was larger than that of crown length. As plantation trees grow taller, crown base move up to higher position by natural pruning. Therefore, it is assumed that as trees grow taller, the amounts of IAA in the trunk become smaller, because IAA is synthesized at and transported from the crown. In our previous study on juvenile and mature sugi trees, we reported that put together all samples (juvenile and mature sugi trees), MFA increased with IAA amounts in samples with IAA $\leq$200 ng/cm^2 [32]. The samples at lower trunk in juvenile trees had significantly larger IAA amounts, larger MFA, and larger latewood width than the samples in mature trees ($p < 0.01$). From these results, we hypothesized that as trees grew taller, IAA amounts in the cambial-region tissues decreased, and that as IAA in these tissues decreased, MFA became smaller. If the hypothesis in sugi trees holds true for hinoki trees, taller tree height might have induce smaller amounts of IAA in cambial-region tissues in the ring-formed year, resulting in smaller MFA.

The results in Fig. 4 are thought to be important because they demonstrate the possibility of improvement of juvenile wood properties by silvicultural practices. It is assumed that growth traits of plantation trees are affected by the genetic factor of planted trees and the environmental factor of the plantation site. We reported the variation of wood properties among hinoki half-sib families (plus trees selected as trees with various superior traits, e.g., fast growth and trunk straightness) and the effect of diameter growth on wood properties [23]. In the previous study, we did not examine the effect of tree height on wood properties. There may be hinoki plus trees with superior tree height growth in younger age. Based on the results from Fig. 4, these plus trees may have superior juvenile wood properties. In 4-year-old radiata pine (*Pinus radiata*) and 8-year-old slash pine (*Pinus elliottii*), a larger H/D and greater tree height increased the stiffness of juvenile wood, respectively [33–35]. These results in other conifer trees are consistent with Fig. 4. In sugi trees, it was reported that site indexes and local environment of plantations also affected height growth of trees [36, 37]. We studied on a sugi cultivar stand, in which trees of each cultivar were planted in a row from the upper to the lower part of the slope [10]. Many sugi cultivars planted at the lower part of the slope had a larger tree height and DBH than trees at the upper part of the slope. Therefore, selecting hinoki families with superior height growth and/or selecting plantation sites with larger site indexes may increase tree height in younger age, and improve juvenile wood properties by decreasing MFA. We reported that a positive effect of crown length and a negative effect of the distance from crown base on IAA amounts in cambial-region tissues in sugi cultivars [31]. We reported the possible effects of IAA amounts on MFA [32]. If these results in sugi trees held true in hinoki trees, creating shorter crown length and higher position of crown base by pruning in juvenile trees might decrease IAA amounts in cambial-region tissues, and thus induce smaller MFA. In generally, pruning is believed to be a silvicultural practice for the production of lumbers with smaller number of knots. According to our previous and current studies, pruning may have additional effects on juvenile wood properties. More studies on juvenile hinoki trees should be conducted for a better understanding of juvenile wood properties.

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