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Preliminary evaluation of the feasibility for the establishment of short-rotation *Cryptomeria japonica* forestry for producing dimensional lumber using male-sterile full-sib families developed in Tokyo

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Abstract

The aim of this study is to preliminarily clarify the wood properties and lumber qualities of trees of male-sterile *Cryptomeria japonica* full-sib families, and to evaluate the possible short-rotation forestry using these families, although the number of trees and families used in this study is limited. The standing tree characteristics, wood properties, and dimensional lumber quality (1820 × 38 × 89 mm; visual grading according to the Japanese Agricultural Standards for structural lumber and finger jointed structural lumber for wood frame construction [JAS 0600], and static bending properties) were investigated in 14-year-old trees (12-year-old forest stand) from five male-sterile *C. japonica* full-sib families developed by the Tokyo Metropolitan Agriculture and Forestry Research Center, Tokyo, Japan. The mean values of stem diameter at 1.2 m above the ground, tree height, and stress-wave velocity of stems in all 22 trees from five families were 15.2 cm, 12.3 m, and 2.45 km/s, respectively. Mean value was also 7.7 mm in annual ring width, 0.31 g/cm^3 in basic density, 26.9° in microfibril angle, 5.60 GPa in modulus of elasticity (MOE), and 58.7 MPa in modulus of rupture (MOR). In lumber quality ($n = 34$), annual ring width, bow, crook, twist, slope of grain, air-dry density, MOE, and MOR were 9.4 mm, 0.28%, 0.18%, 1.4°, 0.09%, 0.37 g/cm^3, 4.79 GPa, and 33.4 MPa, respectively. Although the lumber was obtained from 14-year-old trees, about 90% of lumber pieces exceeded the characteristic value of MOR (28.4 MPa) in the select structural visual grading class of JSII of JAS 600. In addition, the preliminary calculated value of the 95% lower tolerance limit with a confidence level of 75% of the MOR of lumber was 23.1 MPa. Therefore, from the viewpoint of the bending properties of lumber, short-rotation *C. japonica* forestry producing structural lumber might be established, owing to the improvement of mechanical properties by tree breeding in male-sterile families, although the tested samples were limited.

Keywords Male-sterile family, Wood property, Lumber quality, Short-rotation forestry

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Introduction

Cryptomeria japonica (L.f.) D.Don (Japanese cedar in English and sugi in Japanese) is a tree species native to Japan and has long been used for afforestation and reforestation. Its planted area increased significantly following the post-World War II extensive afforestation policy [1]. As of 2022, *C. japonica* accounted for approximately 44%

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of Japan's plantation area [2], making it a representative reforestation species in Japan. Its timber is used as a construction material, particularly as structural lumber for wooden houses. Therefore, *C. japonica* is also an important timber species in Japan.

Hay fever is an allergic disease caused by various types of plant pollen [3]. In Japan, pollen from extensively planted *C. japonica* trees after World War II is the primary causative agent [3]. Consequently, forest tree breeding programs have advanced the development of less-pollen and male-sterile *C. japonica* clones or families to reduce the pollen release from plantation trees [4–7]. These developed less-pollen and male-sterile *C. japonica* clones or families have been used in reforestation efforts. Among these, male-sterile *C. japonica* families are primarily developed by crossing natural mutants that do not produce pollen but can produce seeds (as female parents) with elite trees already selected for growth and wood-quality traits in tree breeding programs having a heterozygous male-sterility gene (as pollen parents) [4, 6–8].

Recently, efforts have been made to use fast-growing tree species to enhance the profitability and productivity of Japan's forestry industry. Many of the fast-growing species being introduced in Japan for lumber production are broad-leaved tree species, such as *Eucalyptus* species [9], *Melia azedarach* L. [10, 11], *Liriodendron tulipifera* L. [12], and *Paulownia* species [13]. Among coniferous species, attempts are also being made to utilize *Cunninghamia lanceolata* (Lamb.) Hook. [14]. Meanwhile, for *C. japonica*, which has been used in Japanese forestry to date, clones or families with faster growth and good wood quality have been developed to improve forestry profitability and productivity through breeding programs for this species [5, 15]. If the plantation aims to produce timber, particularly structural lumber for wooden houses, from short-rotation forestry, the candidate coniferous species would be desirable due to their tree stem shapes and silvicultural management considerations. Furthermore, if the candidate species is available among the coniferous species already used in Japanese forestry, preparation of seedlings, silvicultural management, logging methods, and wood processing that have been developed can be directly applied in short-rotation forestry. Thus, the improved *C. japonica* developed through tree-breeding programs should be considered a candidate species for short-rotation forestry to produce structural lumber. However, there are no documented cases of structural lumber produced from these developed *C. japonica* clones with shortened harvest cycles, nor have evaluations of such lumber been conducted.

The objectives of this study are to clarify the wood properties of male-sterile *C. japonica* full-sib families and to evaluate the possibility of the establishment of short-rotation *C. japonica* forestry for producing structural lumber without pollen release from plantations using developed male-sterile families. In line with these objectives, the standing tree characteristics, wood properties, and lumber quality were investigated in 14-year-old trees from five male-sterile *C. japonica* families developed by the Tokyo Metropolitan Agriculture and Forestry Research Center, Tokyo, Japan. In addition, the correlations among these traits were also clarified. Based on the results, the potential for short-rotation *C. japonica* forestry in Japan using male-sterile families was discussed in terms of wood quality, although the number of tested trees and families was limited and many issues remain to be addressed, including yield, processability, and economic considerations.

Materials and methods

Materials

A total of 22 trees from five male-sterile full-sib families (family ID I, II, III, IV, and V, respectively) of 14-year-old (12-year-old forest stand) *Cryptomeria japonica* (L.f.) D.Don was used in this study (Table 1). These trees were provided from the progeny test site of Tokyo Metropolitan Agriculture and Forestry Research Center, located in Hinode, Tokyo, Japan. The trees were planted at the progeny test site established in 2013, comprising 24 full-sib families and randomized complete blocks with three replications (4400 trees/ha). Thinning was performed in 2018, and pruning was conducted in 2021. The five male-sterile full-sib families used in the present study (F2 family) were developed using five seed and two pollen parents (Table 1). The seed parents of the mating seed parent (To308MS and ToMS212 in Table 1) were male-sterile *C. japonica* trees to produce the F_1 family [6]. The

Table 1 Mating combinations of seed and pollen parents of five male-sterile full-sib families

Family ID	*n*	Mating combination (F_2)		
		Mating of the seed parent (F_1)		Pollen parent
		Seed parent	Pollen parent	
I	3	To308MS	Minamitama5	Oi7
II	5	ToMS212	Nishitama21	Oi7
III	5	To308MS	Minamitama5	Oi7
IV	4	To308MS	Minamitama5	Naka4
V	5	To308MS	Nishitama24	Naka4
Total	22			

n, number of trees. The seed parents of the F_1, To308MS and ToMS212, in this table are male-sterile *C. japonica* [6]. Pollen parents of F_1, Minamitama5, Nishitama21, and Nishitama24 are plus trees without the male-sterility gene [6]. Pollen parents of F_2, Oi7 and Naka4, are plus trees with a heterozygous male-sterility gene [6]

seed parents (To308MS and ToMS212) were crossed to produce the F1 family with the pollen parent of mating the seed parent (Minamitama5, Nishitama21, and Nishitama24 in Table 1; without male-sterility genes), which were plus trees in the tree breeding program of *C. japonica* selected in Tokyo Metropolitan Agriculture and Forestry Research Center [6]. The obtained cross-bred offspring (F_1 families; To308MS and ToMS212 by Minamitama5, Nishitama21, and Nishitama24) were again crossed with the pollen parents (Oi7 and Naka4 in Table 1), which were plus trees with a heterozygous male-sterility gene. Finally, the male-sterile *C. japonica* families used (F_2 families) in the present study were obtained [6]. Before planting the seedlings of the male-sterile family, gibberellin was applied to 1- and 2-year-old seedlings, and the formation of pollen was confirmed at 2 and 3 years.

Standing-tree characteristics

Stem diameter at 1.2 m above the ground, tree height, and stress-wave velocity of stems were measured for all 22 trees as standing-tree characteristics (Fig. 1). Stem diameter at 1.2 m above the ground and tree height were measured with a tape measure and a measuring rod, respectively. For determining the stress-wave velocity of stems, stress-wave propagation time between 0.2 and 1.0 m above the ground was measured in two positions of the stem by a handheld stress-wave timer (Fakopp microsecond timer, Fakopp Enterprise, Hungary). The stress-wave propagation time for each individual tree was determined by averaging 10 measurements. The stress-wave velocity (SWV) of stems was calculated by the following formula (Eq. 1):

$$\mathrm{SWV(Km/s)} = L/t \tag{1}$$

where L (mm) is the span between sensors (here is 800 mm), t (μs) is the measured stress-wave propagation time.

Dynamic Young's modulus of logs

After measuring the standing-tree characteristics, the trees were harvested. Then, logs measuring 2.5 m were collected from 0.2 to 2.7 m above ground (Fig. 1). The dynamic Young's modulus of the log was determined by the tapping method [16] using a smartphone application (FFTWave, E.N. Software, Tottori, Japan) installed in a smartphone (AQUOS sense 4, Sharp Corporation, Osaka, Japan) equipped with a microphone. The log density at testing was calculated from the average diameter of both ends (including bark), the length of the log, and the weight of the log (measured by an electric balance). Dynamic Young's modulus of logs ($E_{\mathrm{fr_Log}}$) was calculated by the following formula (Eq. 2):

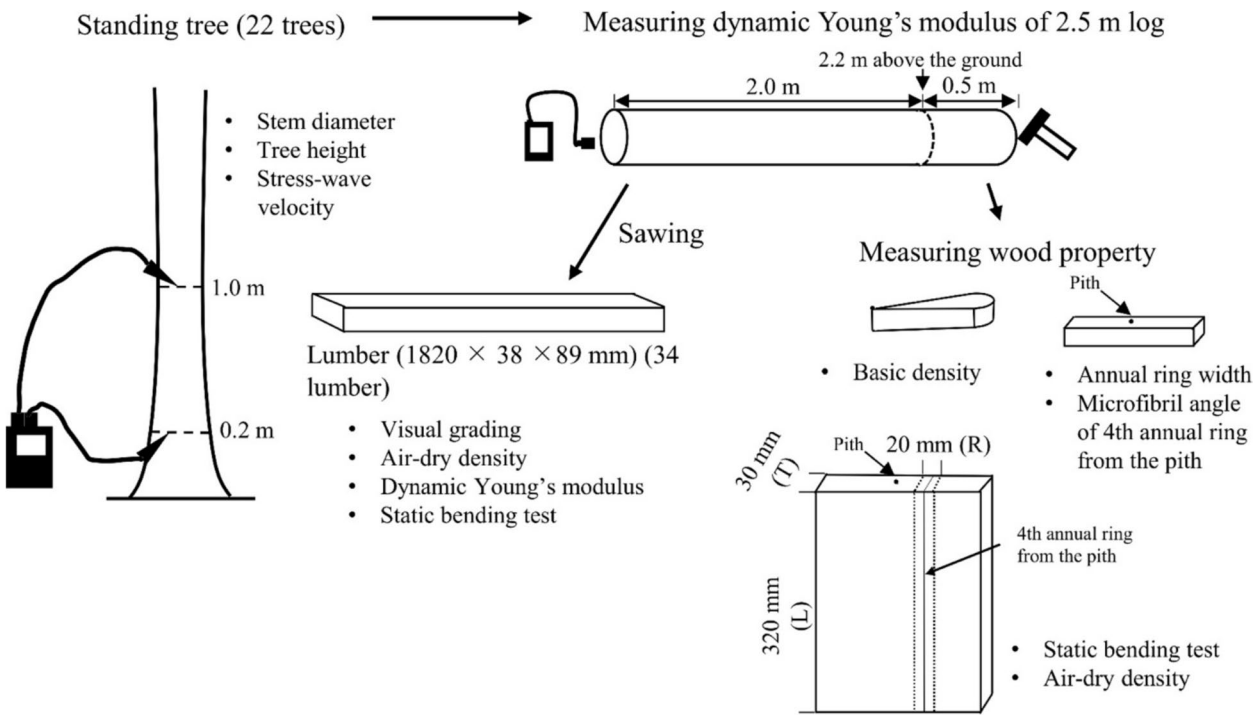


Fig. 1 Illustration of experimental procedures. R, radial direction; T, tangential direction; L, longitudinal direction

$$E_{\mathrm{Fr_Log}}\,(\mathrm{GPa}) = (2lf)^2\rho \times 10^{-9} \quad (2)$$

where l (m) is the length of the log, f (Hz) is the first resonance frequency, and ρ (kg/m^3) is the log density at testing.

Wood properties

After measuring the dynamic Young's modulus of logs, logs were cut into two logs with 2.0 m (from 0.2 to 2.2 m above the ground) and 0.5 m (2.2–2.7 m above the ground) in length (Fig. 1). A pith to bark radial board (3 cm in thickness), two strips (2 cm in thickness and 3 cm in width), and wedge-shaped specimens (central angle = 30°) were obtained from a 50 cm log to prepare a small-clear specimen. The remaining 2 m-long logs were used to prepare dimensional lumber.

The transverse section of the strip specimen for measuring annual ring width was sanded by a belt sander. Images of sanded transverse Sects. (600 dpi) of strips were captured by a personal computer with a scanner (LiDE 400, Canon, Tokyo, Japan). Annual ring width was measured using an image analysis software (ImageJ version 1.53t, [17]). Annual ring width was determined in two directions from pith to bark at each annual ring. The average of these measurements was calculated as the tree's representative annual ring width.

To measure the basic density, wedge-shaped specimens were used. The wedge-shaped specimens were again cut into small blocks at three annual ring intervals from the pith. Basic density was determined as the oven-dry weight divided by the green volume measured by water displacement.

The microfibril angle of the S2 layer in latewood tracheids (MFA) was determined by measuring the angle of the slit-like pit apertures of bordered pits in the latewood tracheids [18, 19]. Small wood blocks, including the 4th annual ring from the pith, were obtained from the strip to facilitate comparison of MFA with the previous study [20]. Tangential Sects. (20 μm thick) were cut from the small wood blocks using a sliding microtome (ROM-710, Yamatokohki, Saitama, Japan). After staining with 1% safranin, the sections were dehydrated through a graded ethanol series. The dehydrated sections were soaked in xylene and mounted on the slide with Bioleit (Okenshoji, Tokyo, Japan). Photomicrographs of tangential sections were taken using a light microscope (BX53, Olympus, Tokyo, Japan) and a digital camera (TC-1500, Sato Syouji Inc., Kanagawa, Japan). The angle of the slit-like pit apertures of bordered pits in the latewood tracheids was measured using ImageJ. The MFA of 40 tracheids was measured in each tree.

A small-clear specimen (20 [R] × 20 [T] × 320 [L] mm) was prepared from each radial board (Fig. 1). The specimen included the 4th annual ring from the pith at the center of the cross section to facilitate the comparison of MFA with the previous study [20]. A total of 22 specimens were obtained. Static bending tests were conducted using a universal testing machine (MSC-5/500-2, Tokyo Testing Machine, Tokyo, Japan). A load was applied to the center of the tangential section of the specimen at 5 mm/min with a span of 280 mm. The data on the load and deflection were recorded using a personal computer. The modulus of elasticity ($\mathrm{MOE_{SC}}$) and modulus of rupture ($\mathrm{MOR_{SC}}$) were calculated using the following formula (Eqs. 3 and 4):

$$\mathrm{MOE_{SC}(GPa)} = \frac{\Delta P l^3}{4\Delta y b h^3} \quad (3)$$

$$\mathrm{MOR_{SC}(MPa)} = \frac{3P_{\max} l}{2bh^2} \quad (4)$$

where ΔP (N) is the difference in the load between 10 and 40% values of the maximum load, l (mm) is the length of span, Δy (mm) is deflection due to ΔP, b (mm) is the width of the specimen, h (mm) is the height of the specimen, and $P_{\max}$ (N) is the maximum load.

After the static bending test, a small block was collected from each specimen to measure air-dry density and moisture content at the time of testing. The moisture content was determined by oven-dry method. Mean value and standard deviation of moisture content were 11.1 ± 0.3%.

Lumber qualities

The logs with 2 m in length were sawn into lumber with a cross section of 50 × 100 mm as many as possible (Fig. 1). Five, seven, seven, eight, and seven pieces of lumber were obtained from logs of Family ID I, II, III, IV, and V, respectively. The number of lumber pieces with pith and without pith was 16 and 18, respectively. The lumber was air-dried outside the laboratory for about 4 months (from June to October, 2024). After air-drying, the lumber was planed to 38 × 89 mm in cross section, and the length was then adjusted to 1820 mm.

The following lumber qualities were measured according to the Japanese Agricultural Standards (JAS) for structural lumber and finger jointed structural lumber for wood frame construction (JAS 600, [21]): knot size, existence and size of holes, the slope of grain, distortion (bow, crook, and twist), wane, and surface checks. Based on the results, the lumber was assigned into four grades (select structural [SS], No. 1, No. 2, and No. 3) according to JAS 600 [21]. After visual grading, the dynamic Young's modulus of lumber ($E_{\mathrm{fr_lumber}}$) was determined by the same methods using Eq. 2.

A four-point static bending test for the lumber was conducted using a full-scale bending test machine (IPA-100R, Maekawa, Tokyo, Japan). The static bending test conditions were as follows: load position, edgewise; load speed, 14 mm/min; support span, 1602 mm; distance between load points, 534 mm. The deflection was measured by a displacement transducer (SDP-200D, Tokyo Measuring Instruments Laboratory, Tokyo, Japan) at mid position of the span. The MOE_L and MOR_L of sawn lumber were calculated by the following formulas [22] (Eqs. 5 and 6):

$$\mathrm{MOE}_L(\mathrm{GPa}) = \frac{a(3L^2 - 4a^2)\Delta P}{4bh^3\Delta y} \times 10^{-3} \tag{5}$$

$$\mathrm{MOR}_L(\mathrm{MPa}) = \frac{3aP}{bh^2} \tag{6}$$

where a is the upper span (mm), L is the lower span (mm), ΔP is the load between 10 and 40% of the maximum load (N), Δy is the deflection corresponding to ΔP, b is the width of the timber (mm), h is the height of the timber (mm), and P is the maximum load (N).

A small-clear specimen (ca. 38 by 89 by 10 mm) was obtained from the timber after the bending test to determine the moisture content and air-dry density at the time of testing. The moisture content of the specimen was measured by oven-dry method. The mean ± standard deviation of moisture content at testing was 11.7 ± 0.4%.

Data analysis

Data were analyzed using R software (R version 4.4.2, [23]). To evaluate the effect of family on determined characteristics, the following linear mixed-effect model (Eq. 7) was developed by using the lmer function in the lme4 packages and the lmerTest packages [24]:

$$y_{ij} = \mu + \mathrm{Family_j} + e_{ij} \tag{7}$$

where y_{ij} is the ith measured property of $\mathrm{Family_j}$, μ is the overall average value of the measured property as a fixed effect, Family_j is the random effect of the jth family, and e_{ij} is the residual.

The variance component ratio of the family (V_f[%]) was also calculated for each measured property using the following equation (Eq. 8):

$$V_f(\%) = \frac{\sigma_f^2}{\sigma_f^2 + \sigma_e^2} \tag{8}$$

where $\sigma^2{}_f$ is the variance components of the family and $\sigma^2{}_e$ is the residual variance.

To evaluate the relationships between measured characteristics, Pearson's correlation coefficients were calculated. When the correlations between standing tree characteristics and lumber qualities were examined, the mean values of lumber qualities in each log were used.

Because the moisture content of lumber at the bending test was lower than the standard condition, the MOE_L and MOR_L at 15% moisture content were calculated by the following formula (Eq. 9) described by Japan Housing and Wood Technology Center [22]:

$$P_2 = P_1(\alpha - 15\beta)/(\alpha - \beta M) \tag{9}$$

where P_2 is the MOE_L or MOR_L value at a moisture content of 15%, P_1 is the MOE_L or MOR_L value at testing, M is the moisture content at testing, α is 1.44 and 1.75 for MOE_L and MOR_L, respectively, and β is 0.0200 and 0.0333 for MOE_L and MOR_L, respectively.

The 95% lower tolerance limit with a confidence level of 75% ($TL_{75\%,95\%}$) of MOR_L was preliminarily calculated in the present study. Whether the MOR_L data followed a normal distribution was assessed using the Shapiro–Wilk test. If the distribution pattern followed the normal distribution, $TL_{75\%,95\%}$ was calculated by the following formula [22] (Eq. 10):

$$\mathrm{TL}_{75\%95\%} = \mu - K\sigma \tag{10}$$

where μ is the mean value, K is a constant ($K = 1.853$, $n = 34$), and σ is the standard deviation.

The effect of visual grading grade on lumber quality was evaluated by Eq. 7, but a random effect was used for visual grading grade. The variance component ratio of visual grade was also calculated by Eq. 8.

Results

Standing-tree characteristics

Table 2 shows the mean values and standard deviations of standing-tree characteristics and dynamic Young's modulus of logs at the family and individual levels. The means at family level ranged from 14.4 cm (Family II) to 16.3 cm (Family IV) for stem diameter, 11.3 m (Family I) to 12.9 m (Family V) tree height, 2.40 km/s (Family III) to 2.52 km/s (Family II) for stress-wave velocity of stems, and 4.46 GPa (Family III) to 5.03 GPa (Family IV) for dynamic Young's modulus of logs. The mean value and standard deviation of all trees were 15.2 ± 2.0 cm in stem diameter, 12.3 ± 1.4 m in tree height, 2.45 ± 0.18 km/s in stress-wave velocity of stems, and 4.75 ± 0.60 GPa in dynamic Young's modulus of log, respectively (Table 2).

Wood properties of the small-clear specimens

The mean value and standard deviation of wood properties at the family and individual levels are listed in Table 3. The minimum and maximum family mean annual ring widths were observed in Family II (7.0 mm) and Family IV (8.5 mm), respectively. The mean values of MFA at the

Table 2 Standing-tree characteristics and dynamic Young's modulus of logs

Family ID	*n*	*D* (cm)		TH (m)		SWV (km/s)		E_{fr_Log} (GPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
I	3	14.7	2.3	11.3	1.5	2.44	0.08	4.71	0.31
II	5	14.4	1.5	12.4	0.8	2.52	0.16	4.83	0.61
III	5	15.4	2.6	11.9	2.0	2.40	0.27	4.46	0.35
IV	4	16.3	1.4	12.7	0.4	2.45	0.05	5.03	0.83
V	5	15.4	2.6	12.9	1.5	2.42	0.24	4.75	0.79
Mean/total	22	15.2	2.0	12.3	1.4	2.45	0.18	4.75	0.60
V_f (%)		–		–		–		–	

n, number of sample trees, *SD* standard deviation, *D* stem diameter at 1.2 m above ground, *TH* tree height, *SWV* stress-wave velocity of stem, E_{fr_Log} dynamic Young's modulus of log, V_f, variance component ratio of family, – the model did not converge

Table 3 Wood properties of small-clear specimen

Family ID	*n*	ARW_{SC} (mm)		MFA (°)		BD (g/cm^3)		AD_{SC} (g/cm^3)		MOE_{SC} (GPa)		MOR_{SC} (MPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
I	3	7.7	1.2	29.5	0.2	0.30	0.03	0.31	0.02	5.64	1.87	58.3	10.7
II	5	7.0	0.8	23.6	2.2	0.29	0.02	0.32	0.03	5.45	0.81	60.6	10.1
III	5	7.7	1.3	26.4	4.9	0.31	0.01	0.30	0.02	4.84	0.47	52.4	6.6
IV	4	8.5	0.3	26.8	1.2	0.32	0.03	0.31	0.03	6.20	0.94	61.6	7.9
V	5	7.8	1.1	29.4	5.0	0.32	0.03	0.32	0.03	5.99	1.15	60.9	9.9
Mean/total	22	7.7	1.0	26.9	4.0	0.31	0.02	0.31	0.03	5.60	1.06	58.7	8.9
V_f (%)		7.7		20.0		–		–		6.0		–	

n, number of sample trees, *SD* standard deviation, *MFA* microfibril angle, ARW_{SC} annual ring width of tree, BD basic density, AD_{SC} air-dry density of small-clear specimen, MOE_{SC} modulus of elasticity of small-clear specimen, MOR_{SC} modulus of rupture of small-clear specimen, V_f variance component ratio of famil, – the model did not converge

family level ranged from 23.6 (Family II) to 29.5 (Family I). The mean values of basic density and air-dry density at the 4th annual ring from pith were almost identical at the family level, around 0.31 g/cm^3. The MOE_{SC} in Family III showed the lowest value (4.84 GPa), and Family IV showed the highest value (6.20 GPa). A similar tendency was observed in MOR_{SC}: the highest and lowest values were in Family IV (61.6 MPa) and Family III (52.4 MPa), respectively.

Radial variations of annual ring width and basic density are shown in Fig. 2. With a few exceptions, annual ring width ranged from 3 to 12 mm in each annual ring (Fig. 2). On the other hand, basic density showed the highest value at the 3rd annual ring from the pith, and then decreased toward the bark (Fig. 2).

Lumber qualities

The mean values and standard deviations of all lumber pieces are shown in Table 4. The mean ± standard deviation of all lumber pieces was 9.4 ± 2.3 mm for annual ring width, 0.28 ± 0.04% for bow, 0.18 ± 0.20% for crook, 1.4 ± 0.9° for twist, 0.09 ± 0.06% for slope of grain, 0.37 ± 0.04 g/cm^3 for air-dry density, 5.12 ± 0.78 GPa for dynamic Young's modulus of lumber, 4.79 ± 0.70 GPa for MOE_L, and 33.4 ± 6.3 MPa for MOR_L, respectively.

In the present study, about 30% of lumber pieces were classified as SS grade. The mean values of air-dry density and mechanical properties were similar among grading classes (Table 5). Among measured qualities, a relatively higher variance component ratio for grade was estimated only for crook (18.2%). The percentage of SS grade lumber pieces was higher in Family I (about 60%) compared to the other families (Fig. 3). On the other hand, lumber pieces of Family IV were not assigned to the SS grade. The main downgrading factor was the bow, irrespective of grade class (Table 6). On the other hand, about 90% lumber pieces exceeded the characteristic value of MOR in the SS class of species group JSII in JAS 0600 [21] (Table 7). The frequency distribution of MOR_L values is shown in Fig. 4. As a result of the Shapiro–Wilk test, *p* values exceeded 0.05, indicating that the distribution of MOR_L was assumed to follow a normal distribution. $TL_{75\%,95\%}$ of the MOR_L was 23.1 MPa.

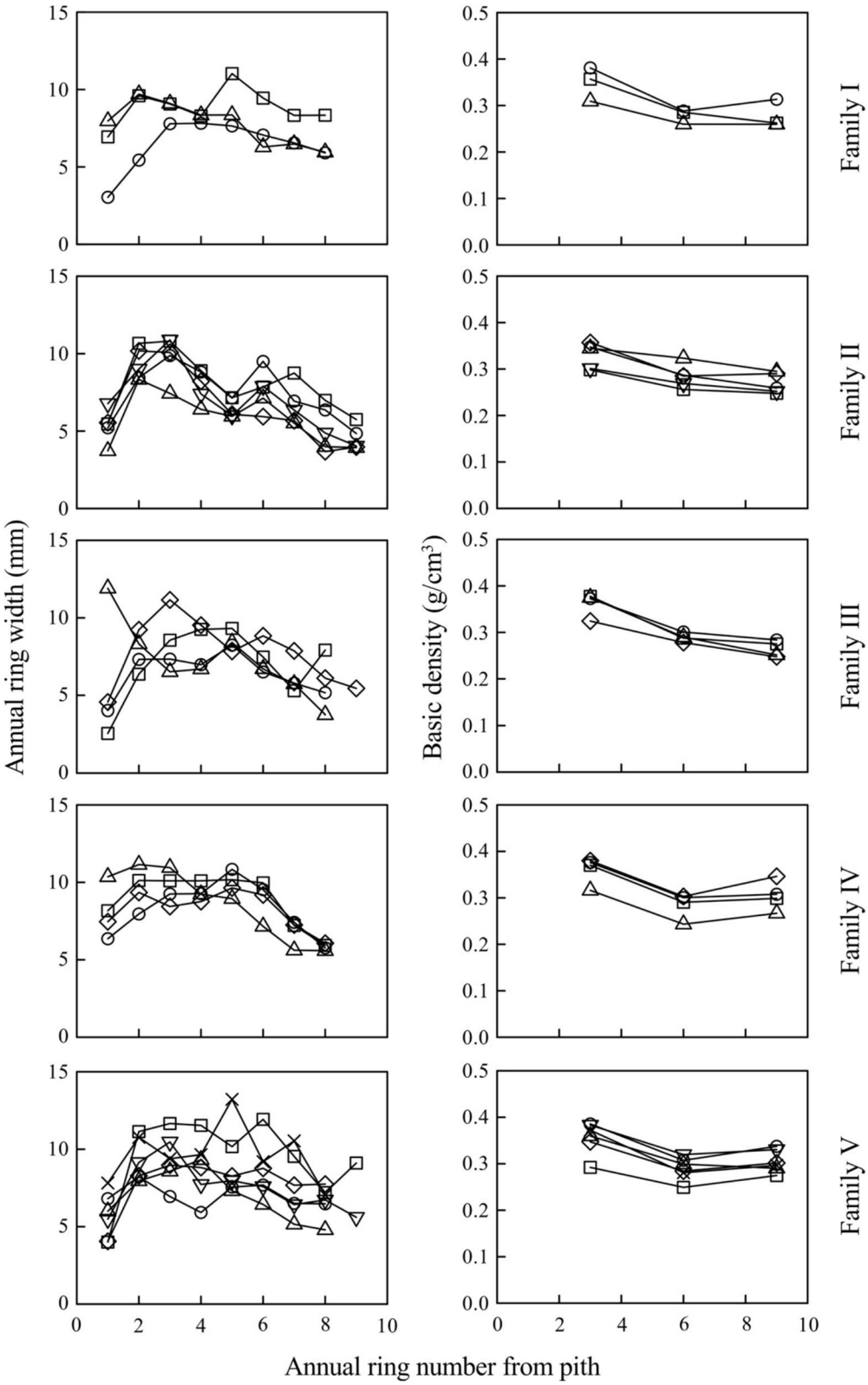


Fig. 2 Radial variations of annual ring width and basic density. Different symbols indicate individual trees

Table 4 Lumber quality

Family ID	*n*	ARW_L (mm)		Bow (%)		Crook (%)		Twist (°)		Slope of grain (%)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
I	5	9.8	1.1	0.28	0.01	0.06	0.07	1.3	0.3	0.07	0.03
II	7	8.1	1.7	0.29	0.05	0.09	0.04	1.4	0.7	0.10	0.07
III	7	10.0	3.2	0.27	0.05	0.26	0.23	1.8	1.6	0.14	0.06
IV	8	9.5	1.7	0.29	0.05	0.12	0.09	1.2	1.0	0.06	0.04
V	7	9.5	2.9	0.28	0.04	0.31	0.31	1.4	0.6	0.07	0.05
Mean/total	34	9.4	2.3	0.28	0.04	0.18	0.20	1.4	0.9	0.09	0.06
V_f (%)		–		–		9.2		–		17.4	

Family ID	*n*	AD_L (g/cm^3)		E_{fr_Lumber} (GPa)		MOE_L (GPa)		MOR_L (MPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
I	5	0.36	0.04	4.74	0.32	4.75	0.55	29.1	5.4
II	7	0.37	0.05	5.49	0.86	5.01	0.76	32.1	4.9
III	7	0.36	0.04	4.02	0.75	4.64	0.75	33.5	6.0
IV	8	0.36	0.04	4.95	0.83	4.60	0.66	36.6	7.2
V	7	0.37	0.05	5.27	0.90	4.92	0.81	34.2	6.9
Mean/total	34	0.37	0.04	5.12	0.78	4.79	0.70	33.4	6.3
V_f (%)		–		–		–		3.4	

n, number of sample trees, *SD* standard deviation, ARW_L annual ring width of lumber, AD_L air-dry density of lumber, E_{fr_Lumber} dynamic Young's modulus of lumber, MOE_L modulus of elasticity of lumber, MOR_L modulus of rupture of lumber, V_f variance component ratio of family, – the model did not converge

Table 5 Lumber qualities in each visual grading class

Grading class	*n*	Bow (%)		Crook (%)		Twist (°)		Slope of grain (%)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
SS	10 (29.4%)	0.28	0.14	0.10	0.06	1.06	0.63	0.10	0.06
No. 2	11 (32.4%)	0.28	0.04	015	0.12	1.75	1.32	0.10	0.06
No. 3	5 (14.7%)	0.28	0.04	0.05	0.03	1.35	0.15	0.04	0.04
Out	8 (23.5%)	0.28	0.05	0.28	0.30	1.41	0.94	0.09	0.07
V_g (%)		–		18.2		2.0		–	

Grading class	*n*	AD_L (g/cm^3)		E_{fr_Lumber} (GPa)		MOE_L (GPa)		MOR_L (MPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
SS	10 (29.4%)	0.35	0.18	5.06	2.56	4.78	2.41	32.9	16.9
No. 2	11 (32.4%)	0.36	0.04	5.13	0.73	4.81	0.67	33.6	7.5
No. 3	5 (14.7%)	0.39	0.04	5.20	0.95	4.71	0.79	33.6	4.6
Out	8 (23.5%)	0.38	0.05	5.14	0.99	4.83	0.94	33.5	6.8
V_g (%)		–		–		–		–	

n, number of lumber pieces, *SD* standard deviation, AD_L air-dry density of lumber, $E_{fr\text{-}Lumber}$ dynamic Young's modulus of lumber, MOE_L modulus of elasticity of lumber, MOR_L modulus of rupture of lumber, V_g variance component of grade, – the model did not converge. Value in parentheses in "*n*" indicates the percentage of the number of lumber pieces assigned to each visual grading class. No lumber assigned to No. 1

Relationships between measured properties

Table 8 shows correlation coefficients between measured properties at individual tree levels. A significant positive correlation was found between stem diameter and tree height ($r=0.732$, $p<0.001$). However, no significant correlations were found between growth characteristics and log properties, wood properties, or lumber properties, with a few exceptions. The stress-wave velocity of stems was positively correlated with dynamic Young's modulus of log ($r=0.519$, $p=0.013$) and lumber

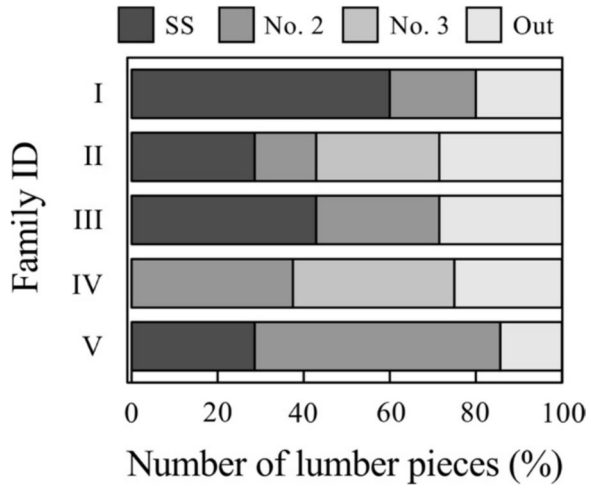


Fig. 3 Percentage of lumber pieces assigned to each visual grading class in each family. *n*, number of lumber pieces

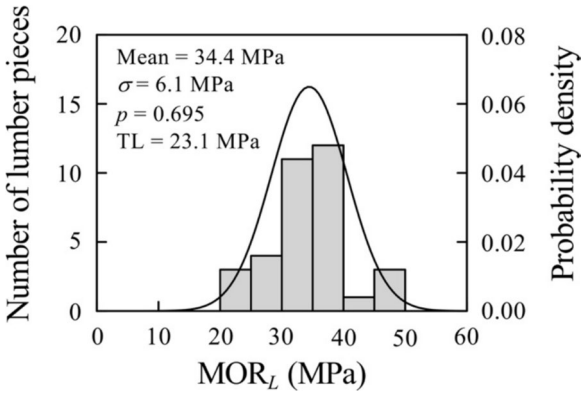


Fig. 4 Frequency distribution of MOR_L. Number of lumber pieces = 34; *σ*, standard deviation; *p*, probability obtained by Shapiro–Wilk test as a test of normality of normal distribution; TL, 5% lower limit with a 75% confidence level (5% tolerance limit); MOR_L, modules of rupture of lumber; Bars and curves in the figure indicate number of trees in each class, and probability density of normal distribution, respectively

Table 6 Quantity (%) of downgraded lumber in each grade

Factor	SS to No. 2 (*n* = 11)	No. 2 to 3 (*n* = 5)	No. 3 to out (*n* = 8)
Knot	0.0	0.0	0.0
Wane	2.9	2.9	2.9
Crack	8.8	0.0	5.9
Bow	14.7	11.8	11.8
Crook	8.8	0.0	2.9
Twist	2.9	0.0	0.0
Slope of grain	0.0	0.0	0.0

n, number of lumber pieces. No lumber is assigned to No.1

Table 7 Number of lumber pieces exceeding the characteristic value of MOR in each visual grading class of species group JSII in JAS 600 [21]

Grading class	Characteristic value of MOR (MPa)	*n*	Ratio (%)
SS	28.4	30	88.2
No. 1	20.4	4	11.8
No. 2	19.5	0	0.0
No. 3	11.3	0	0.0

n, number of lumber pieces. Species group JSII in JAS 0600 [21] includes *C. japonica* and similar species

($r = 0.675$, $p = 0.001$), and MOE_L ($r = 0.669$, $p = 0.001$). Dynamic Young's modulus of log and air-dry density showed a significant positive correlation with MOE_L ($r = 0.848$, $p < 0.001$, and $r = 0.722$, $p < 0.001$, respectively) and MOR_L ($r = 0.508$, $p = 0.016$ and $r = 0.582$, $p = 0.005$, respectively). No significant correlation was found between MOE_{SC} and MOE_L, or between MOR_{SC} and MOR_L. MFA was not significantly correlated with other properties.

The correlation coefficients for lumber qualities are shown in Table 9. Amounts of bow were highly correlated with dynamic Young's modulus and MOE_L ($r > 0.900$). Twist was positively correlated with the slope of grain ($r = 0.357$, $p = 0.038$). Air-dry density was positively correlated with MOE_L ($r = 0.419$, $p = 0.014$) and MOR_L ($r = 0.505$, $p = 0.002$). In addition, a significant correlation ($r = 0.902$, $p < 0.001$) was found between dynamic Young's modulus and MOE_L. Meanwhile, MOE_L was not significantly correlated with MOR_L.

Among-family variation of measured properties

The variance component ratios of the family in measured properties are listed in Tables 2, 3 and 4. The highest variance component ratio of the family was found in MFA (20.0%), followed by the slope of grain (17.4%), crook (9.2%), annual ring width of small clear specimen (7.7%), MOE_{SC} (6.0%), and MOR_L (3.4%), respectively. On the other hand, the intercept-only linear mixed-effect model with a random effect of family did not converge for the other measured properties.

Discussion

Mean values of wood properties and lumber qualities

Table 10 lists the wood properties of juvenile wood in *C. japonica* reported by other researchers [19, 20, 25–27]. The mean values of basic density, air-dry density, MFA, and MOR_{SC} in the present study (Table 3) were similar to those reported in previous studies (Table 10). On

Table 8 Relationships between standing tree characteristics and wood properties

Factor 1	Factor 2	*r*	*p* value	Factor 1	Factor 2	*r*	*p* value
D	TH	0.732	< 0.001	E_{fr_Log}	Bow	0.834	< 0.001
	SWV	−0.152	0.499		Crook	−0.248	0.266
	E_{fr_Log}	−0.575	0.005		Twist	−0.030	0.894
	MFA	−0.015	0.947		SG	−0.173	0.442
	AD_{SC}	−0.530	0.011		AD_L	0.701	< 0.001
	MOE_{SC}	−0.231	0.302		E_{fr_Lumber}	0.794	< 0.001
	MOR_{SC}	−0.404	0.062		MOE_L	0.848	< 0.001
	Bow	−0.384	0.078		MOR_L	0.508	0.016
	Crook	−0.197	0.379	MFA	AD_{SC}	−0.110	0.625
	Twist	−0.347	0.114		MOE_{SC}	0.074	0.743
	SG	−0.057	0.802		MOR_{SC}	0.127	0.573
	AD_L	−0.797	< 0.001		Bow	−0.280	0.207
	E_{fr_Lumber}	−0.281	0.204		Crook	0.253	0.256
	MOE_L	−0.415	0.055		Twist	−0.153	0.497
	MOR_L	−0.294	0.184		SG	−0.388	0.074
TH	SWV	0.080	0.725		AD_L	−0.095	0.674
	E_{fr_Log}	−0.248	0.267		E_{fr_Lumber}	−0.265	0.234
	MFA	−0.300	0.176		MOE_L	−0.240	0.283
	AD_{SC}	−0.248	0.266		MOR_L	−0.054	0.812
	MOE_{SC}	0.092	0.682	AD_{SC}	MOE_{SC}	0.451	0.035
	MOR_{SC}	−0.122	0.590		MOR_{SC}	0.664	0.001
	Bow	−0.064	0.779		Bow	0.722	< 0.001
	Crook	−0.230	0.304		Crook	−0.230	0.303
	Twist	−0.384	0.077		Twist	−0.032	0.889
	SG	−0.149	0.509		SG	−0.347	0.113
	AD_L	−0.519	0.013		AD_L	0.692	< 0.001
	E_{fr_Lumber}	0.041	0.855		E_{fr_Lumber}	0.718	< 0.001
	MOE_L	−0.104	0.645		MOE_L	0.722	< 0.001
	MOR_L	0.133	0.556		MOR_L	0.582	0.005
SWV	E_{fr_Log}	0.519	0.013	MOE_{SC}	MOR_{SC}	0.819	< 0.001
	MFA	−0.390	0.073		Bow	0.375	0.085
	AD_{SC}	0.573	0.005		Crook	−0.020	0.928
	MOE_{SC}	0.273	0.219		Twist	−0.220	0.325
	MOR_{SC}	0.395	0.069		SG	−0.366	0.094
	Bow	0.688	< 0.001		AD_L	0.065	0.773
	Crook	−0.429	0.046		E_{fr_Lumber}	0.418	0.053
	Twist	−0.121	0.593		MOE_L	0.385	0.077
	SG	0.005	0.982		MOR_L	0.379	0.082
	AD_L	0.242	0.277	MOR_{SC}	Bow	0.626	0.002
	E_{fr_Lumber}	0.675	0.001		Crook	−0.009	0.969
	MOE_L	0.669	0.001		Twist	−0.119	0.597
	MOR_L	0.182	0.417		SG	−0.488	0.021
E_{fr_Log}	MFA	−0.084	0.709		AD_L	0.335	0.128
	AD_{SC}	0.792	< 0.001		E_{fr_Lumber}	0.697	< 0.001
	MOE_{SC}	0.481	0.023		MOE_L	0.638	0.001
	MOR_{SC}	0.631	0.002		MOR_L	0.312	0.157

Number of trees = 22; *r*, correlation coefficient. *D*, stem diameter at 1.2 m above ground; *TH* tree height; *SWV* stress-wave velocity, E_{fr_Log} dynamic Young's modulus of log, *MFA* microfibril angle, AD_{SC} air-dry density of small-clear specimen, MOE_{SC} modulus of elasticity of small-clear specimen, MOR_{SC} modulus of rupture of small-clear specimen, *SG* slope of grain, AD_L air-dry density of lumber, E_{fr_Lumbe} dynamic Young's modulus of lumber, MOE_L modulus of elasticity of lumber, MOR_L modulus of rupture of lumber. Bold values indicate a correlation coefficient with a *p* value less than 0.05.

Table 9 Relationships between lumber qualities

Factor 1	Factor 2	*r*	*p* value	Factor 1	Factor 2	*r*	*p* value
Bow	Crook	−0.254	0.148	Twist	AD_L	0.302	0.083
	Twist	−0.068	0.703		E_{fr_Lumber}	−0.140	0.429
	SG	−0.128	0.470		MOE_L	−0.052	0.770
	AD_L	0.394	0.021		MOR_L	0.168	0.343
	E_{fr_Lumber}	0.906	< 0.001	SG	AD_L	−0.190	0.281
	MOE_L	0.996	< 0.001		E_{fr_Lumber}	−0.110	0.534
	MOR_L	0.313	0.072		MOE_L	−0.126	0.479
Crook	Twist	0.162	0.359		MOR_L	−0.126	0.479
	SG	−0.084	0.635	AD_L	E_{fr_Lumber}	0.339	0.050
	AD_L	0.120	0.500		MOE_L	0.419	0.014
	E_{fr_Lumber}	−0.215	0.222		MOR_L	0.505	0.002
	MOE_L	−0.235	0.181	E_{fr_Lumber}	MOE_L	0.902	< 0.001
	MOR_L	0.070	0.693		MOR_L	0.307	0.078
Twist	SG	0.357	0.038	MOE_L	MOR_L	0.314	0.070

Number of lumber pieces = 34, *r* correlation coefficient, SG slope of grain, AD_L air-dry density of lumber; E_{fr_Lumber} dynamic Young's modulus of lumber, MOE_L modulus of elasticity of lumber, MOR_L modulus of rupture of lumber. Bold values indicate a correlation coefficient with a *p* value less than 0.05

Table 10 Wood properties of juvenile wood and lumber (38 × 89 mm in transverse section) quality of *C. japonica* reported in the previous research

Type	Age of trees	*n*	MFA (°)	AD (g/cm^3)	MOE (GPa)	MOR (MPa)	References
Small-clear specimen	24	–	–	0.32 to 0.42	2.92 to 7.47	–	Hirakawa and Fujisawa [19]
	78	–	20.7	0.37	6.99	62.2	Zhu et al. [25]
	26	–	17.7 to 20.5	0.37 to 0.40	3.36 to 4.03	47.0 to 50.6	Iizuka et al. [26]
	55	–	20.5	0.33	3.91	46.2	Ishiguri et al. [27]
	20	–	26.2 to 35.3	0.36 to 0.44	2.84 to 3.67	47.3 to 61.1	Takahashi et al. [20]
Lumber	19	6	–	0.45	8.15	53.0	Hiraiwa et al. [32]
	26	248	–	0.39 to 0.41	5.15 to 5.56*	39.9 to 42.7*	Ishiguri et al. [30]
	30	8	–	0.54	9.17	58.1	Hiraiwa et al. [32]
	48	19	–	0.47	8.40	56.4	Hiraiwa et al. [32]
	50 <	92	–	0.40	7.27	46.6	Shiiba et al. [31]

n, number of samples, *MFA* microfibril angle, *AD* air-dry density, *MOE* modulus of elasticity, *MOR* modulus of rupture. * three-pointed load bending test

the other hand, MOE_{SC} in the present study showed relatively higher values. When the superior *C. japonica* trees are selected by the tree breeding program in Japan, Young's modulus of wood is also considered as one of the criteria [5, 15, 28]. The mating seed parents of *C. japonica* used in the present study were plus trees in the tree breeding program, suggesting that Young's modulus of wood might not be low. Therefore, MOE_{SC} in the present study showed relatively higher values than in the previous study. On the other hand, basic density gradually decreased from the pith to the bark side in all tested families (Fig. 2). This tendency is usually confirmed in *C. japonica* [27, 29].

The quality of dimensional lumber (38 by 89 mm in cross section) of *C. japonica* is listed in Table 10. The listed data includes lumber composed of mature wood. The mean values of MOE_L and MOR_L obtained in this study were lower than those reported by several researchers [30–32]. In the present study, lumber was obtained from very young trees (14 years). In general, juvenile wood formed until around the 15th to 20th annual ring from the pith and exhibits lower strength properties than mature wood [27]. Thus, the wood in the present study may be juvenile and exhibit lower strength properties than mature wood. This is also true for lumber: the strength properties of lumber consisting of juvenile wood were lower than those of mature wood in several softwood species [33, 34]. The existence of juvenile wood is related to the lower values of the bending properties of lumber tested in the present study. Although

the mean values of bending properties were lower than those reported in previous studies, including mature wood values, MOR_L values of approximately 90% of the lumber exceeded the characteristic value of MOR in the SS class (28.4 MPa) of JAS 600 (Table 7). These results indicated that, from the viewpoint of strength properties, dimensional lumber with enough strength properties might be produced from the young trees of plus trees selected by the tree breeding programs. In addition, the results suggest that short-rotation *C. japonica* forestry (approximately 15–20 years) for producing structural lumber might be established using plus trees selected by tree breeding programs, although the data were obtained from a limited number of sample trees and families. Furthermore, it is expected that the pollen-free Japanese cedar cultivars "Kokobare Funen 1" to "Kokobare Funen 7", developed in Tokyo [7], might also show sufficient wood properties and bending performance for structural lumber, because these cultivars were selected from families derived from the same or similar breeding schemes as the materials examined in this study.

The lumber assigned to the SS class by visual grading accounted for about only 30% of the total lumber (Table 5). As shown in Table 6, the primary downgrading factors are lumber deformation, including bow, crook, and twist. In general, lumber sawn from juvenile wood exhibits pronounced bow and crook, because the warp in lumber is large near the pith [35, 36]. As described above, all the lumber was juvenile wood. Thus, the degree of deformation of lumber was relatively higher (Table 5). On the other hand, these deformations can be reduced by controlling the kiln-drying operations: setting the drying temperature at a relatively lower temperature, and applying load on stacking lumber during kiln drying [37]. In the present study, the lumber was air-dried, resulting in relatively larger values of deformations. Therefore, visual grading results might be improved by applying the appropriate kiln-drying schedule for the lumber.

Relationships between measured properties

As shown in Table 8, growth characteristics were not significantly correlated with stress-wave velocity of stems, and almost all mechanical properties of small-clear specimens and lumber, suggesting that the mechanical properties of wood do not depend on the growth characteristics of trees. These tendencies are the same in *Chamaecyparis obtusa* [38]. On the other hand, stress-wave velocity of stems was positively correlated with dynamic Young's modulus of logs, dynamic Young's modulus of lumber, and MOE_L (Table 8). Stress-wave velocity of stems has been utilized as a nondestructive method to predict the Young's modulus of logs or lumber in *C. japonica* [15, 39] and other softwoods [38, 40, 41]. Thus, the lumber mechanical qualities of young *C. japonica* can also be predicted by the stress-wave velocity of the stem.

To predict the mechanical properties of lumber, relationships between lumber qualities and wood properties of small-clear specimens have been studied in several softwoods [42–44]. In the present study, there were significant positive correlations between air-dry density and MOE_L or MOR_L, but no significant correlations were found in MOE and MOR between small-clear specimens and lumber (Table 8). However, the p value of correlation coefficients (Table 8) between MOE_{SC} and dynamic Young's modulus of lumber ($p=0.053$), MOE_L ($p=0.077$), and MOR_L ($p=0.082$) were slightly larger than the p value of 0.05, suggesting that weak relations might exist. On the other hand, no correlation was found between MOR_{SC} and MOR_L ($r=0.312$, $p=0.157$, Table 8). In general, full-size lumber contains defects attributed to tree growth, such as knots and the slope of grain. The effect of knots on lumber strength varies with their size and position [45]. In the present study, knot position in lumber was not considered when the load was applied during the static bending test. These factors might be related to the weak correlations between lumber properties and wood properties of small-clear specimens in the present study. On the other hand, significant positive correlations were found between bow and dynamic Young's modulus of lumber or MOE_L (Table 9). It has been reported that lumber prone to surface checking during kiln drying typically exhibits a high Young's modulus [46, 47]. The magnitude of deformation, such as bow, crook, and twist, of lumber might be related to the occurrence of surface checking during kiln drying. Further research is needed to clarify the relationships between the deformation of lumber during kiln drying and the Young's modulus of lumber.

Among-family variations

Among-family variation or heritability in growth characteristics and wood properties has been reported in *C. japonica* [15, 20, 28, 29, 39, 48]. Young's modulus and density of wood in *C. japonica* show relatively higher genetic variation compared to growth characteristics ([15, 28, 39, 48]. Miyashita et al. [39] reported broad-sense heritability of 0.78 for stress-wave velocity, 0.81 for dynamic Young's modulus of logs, and 0.80 for basic density from 10-year-old *C. japonica* trees. Takahashi et al. [20] found the relatively high narrow-sense heritability in air-dry density (0.51), MOE (0.38), and MFA (0.29) in *C. japonica*. In the present study, the heritabilities of growth characteristics and wood properties were small or not estimated, because the models failed to converge (Tables 2–4). These results might be related to the limited number of seed and pollen parents:

genetic diversity was low in the *C. japonica* used in the present study.

Concluding remarks

In the present study, standing-tree characteristics, wood properties, and lumber qualities were investigated for 14-year-old trees of five male-sterile *C. japonica* families developed by the Tokyo Metropolitan Agriculture and Forestry Research Center, Tokyo, Japan, although the number of the sample trees and families was limited. The results of the present study showed that, even in juvenile wood, male-sterile *C. japonica* families developed through tree breeding programs possess adequate wood properties and lumber qualities for producing structural lumber. These results suggest that short-rotation *C. japonica* forestry producing structural lumber might be established by using developed clones or families in tree breeding programs, even in the number of sample trees was limited. In the present study, lumber was produced only from the first logs (harvested from 0.2 to 2.2 m above the ground). Therefore, it is necessary to consider using smaller-diameter logs obtained from positions 2.2 m or higher above the ground for other applications, such as biofuel production. In addition, it will be necessary to examine the economic viability of short-rotation *C. japonica* forestry through a combination of lumber and biofuel production. Furthermore, while this study discussed the potential for establishing short-rotation forestry from the perspective of lumber bending properties, future research should address other aspects, such as improving lumber quality.

Abbreviations

MFA	Microfibril angle of S2 layer
MOE	Modulus of elasticity
MOE_{SC}	Modulus of elasticity of small-clear specimen
MOE_L	Modulus of elasticity of lumber
MOR	Modulus of rupture
MOR_{SC}	Modulus of rupture of small-clear specimen
MOR_L	Modulus of rupture of lumber
SS	Select structural
SWV	Stress-wave velocity
$TL_{75\%,95\%}$	The 95% lower tolerance limit with a confidence level of 75%
V_f	Variance component ratio of family

Author contributions

The research layout was designed by I.N., S.H., and F.I. Experiments were conducted by Y.W., I.N., N.O., and F.I. The manuscript was analyzed and drafted by Y.W., I.N., and F.I. All authors contributed to the final manuscript by discussing the findings and conclusions.

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Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors state that they have no competing interest.

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