Journal of Wood Science

ORIGINAL ARTICLE

Open Access

Evaluation of stem diameter, Pilodyn penetration, and stress-wave velocity of stem in almost 320 clones of the first-generation plus trees of *Chamaecyparis obtusa* selected from the Kanto breeding region

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Abstract

Tree breeding programs in Japan have aimed to improve both growth and wood quality traits in *Chamaecyparis obtusa*. To enhance breeding for wood quality, it is essential to understand the genetic variability of traits related to growth, wood density, and stiffness. In the present study, we evaluated stem diameter (DBH), Pilodyn penetration (PP), and stress-wave velocity (SWV) in approximately 320 clones of first-generation plus trees of *C. obtusa* selected from the Kanto breeding region. All clones were planted in the breeding material stock garden in Ibaraki, Japan, and measurements were taken at age 28 years. Clonal repeatability for DBH, PP, and SWV was 0.474, 0.439, and 0.302, respectively, indicating that these traits can be improved by tree breeding. The genetic correlation between DBH and PP was positive ($r = 0.205$), while that between DBH and SWV was low and negative ($r = -0.150$), suggesting the potential for simultaneous improvement of growth and stiffness. A total of 316 clones were grouped into four distinct groups, differing in clonal characteristics for growth and wood quality by cluster analysis, and several clones exhibited superior performance in both DBH and SWV. These findings provide valuable insights into the genetic variability of key traits in *C. obtusa* and contribute to the development of efficient selection strategies for wood quality improvement in future hinoki breeding programs.

Keywords Clonal repeatability, Wood quality, Wood density, Young's modulus, Tree breeding

Introduction

Forest tree breeding aims to achieve near-optimal short-term genetic gains in a few traits of high economic or social importance using genetic variability in variation of phenotype [1]. Specifically, the main objectives in tree breeding include increasing yield and improving quality [1, 2]. In Japan, tree breeding programs were started in the 1950s; individual trees with superior growth and straightness of stem from plantations were selected as the first-generation plus trees [3, 4]. The selected first-generation plus trees were propagated by grafting and cutting, and have been used as breeding materials to produce the next-generation population by crossing [3, 4]. Progeny test sites and breeding-population sites have been established using open-pollinated and full-sib families originating from the first-generation plus-tree clones, and have been used for evaluation and selection of next-generation plus trees.

In the selection of second-generation plus trees in tree breeding programs in Japan, both growth traits and wood

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quality are major target traits. However, evaluation of wood quality is costly and time-consuming, and requires felling the targeted trees for collection of wood samples. Therefore, as nondestructive selection criteria for wood quality, Pilodyn penetration and stress-wave velocity are used when selecting the next-generation plus trees in the progeny tests [5–9]. Pilodyn penetration and stress-wave velocity can be measured easily and nondestructively in standing trees without felling; they are negatively correlated with wood density [5–8, 10–13] and positively correlated with Young's modulus [8, 12, 14–17], respectively. Therefore, both nondestructive measurements in standing trees have been used widely in tree breeding programs for *Pinus taeda* [18], *Larix kaempferi* [7], *Picea abies* [13], *P. sitchensis* [19], *Abies sachalinensis* [20], *Cryptomeria japonica* [8], *Chamaecyparis obtusa* [6]. Evaluating the heritability of Pilodyn penetration and stress-wave velocity and their genetic correlations with growth traits could be an important insight into promoting tree breeding for wood quality.

C. obtusa ('hinoki cypress' in English and 'hinoki' in Japanese) is a common endemic coniferous species in Japan [21, 22], and widely distributed in Shikoku, Kyushu, and across Honshu from the Kanto region westward [21–23]. This species is the major subject species for tree breeding in Japan, and tree breeding in this species has been conducted in the Kanto, Kansai, and Kyushu breeding regions [24]. Because wood in *C. obtusa* is used as construction lumber [21, 22], wood quality, including mechanical properties, in this species is recognized as one of the most important target traits for tree breeding in Japan. The inheritance and genetic variability of growth traits and wood quality in *C. obtusa* have been investigated using the first-generation plus-tree clones or families originating from them [6, 9, 25–29], resulting in many wood properties being suggested for genetic control. However, the inheritance and genetic variability vary widely depending on the number and combination of families or clones submitted for analysis. To more accurately evaluate the inheritance of target traits for tree breeding in *C. obtusa*, it is desirable to have more genotypes available for analysis. For this purpose, it would be useful to evaluate target traits in the first-generation plus trees, since they are the base population for genetic improvements.

To date, about 1,000 first-generation plus trees in *C. obtusa* have been selected across Japan, with around 400 of them originating from the Kanto breeding region [30]. In the present study, in order to collect the findings on the genetic variability for growth, wood density, and Young's modulus to promote tree breeding for wood quality in *C. obtusa*, we measured stem diameter, Pilodyn penetration, and stress-wave velocity in almost 320 clones of the first-generation plus trees selected in the Kanto breeding region. Clonal repeatability for all traits and genetic correlations among traits were estimated. In addition, we attempted to evaluate the overall performance of each clone in stem diameter, Pilodyn penetration, and stress-wave velocity and to classify all clones according to differences in clonal characteristics for growth and wood quality.

Materials and methods

Sample trees

Grafted clones of the first-generation plus trees planted into the breeding material stock garden were used in the present study. The breeding material stock garden is located in Hitachi, Ibaraki, Japan (36°33′N, 140°35′E), and was established in April 1994. Of all 402 genotypes of first-generation plus trees selected in the Kanto breeding region, the grafts of a total of 324 plus trees were planted in the breeding materials stock garden (Fig. 1). The Kanto breeding region is divided into four breeding districts: Kita-Kanto, Kanto-Heiya, Chubu-Sangaku, and Tokai, based on the difference in climate conditions (Fig. 1, [23, 31]). The climatic conditions at the selection sites of plus trees of *C. obtusa* differed among breeding districts:

Breeding district	AMT (°C)	AP (mm)
Kita-Kanto	9.5	1578
Kanto-Heiya	12.4	1846
Chubu-Sangaku	10.7	2345
Tokai	12.0	2586

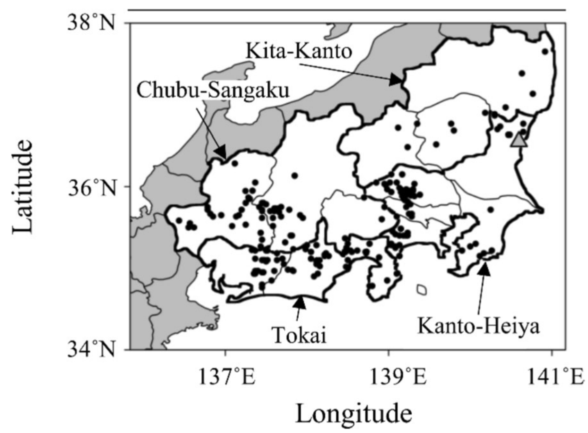

Fig. 1 Locations of the breeding material stock garden and selected forest of plus trees. Area highlighted in white is the Kanto breeding region. Grey triangle and black points indicate the locations of the breeding material stock garden and selected forest of plus trees, respectively. The table presents the average climatic values (annual mean temperature [AMT, °C] and annual precipitation [AP, mm]) at the plus-tree selection sites for each breeding district, calculated using the 1-km mesh scale dataset of Japan's digital national land information [32]

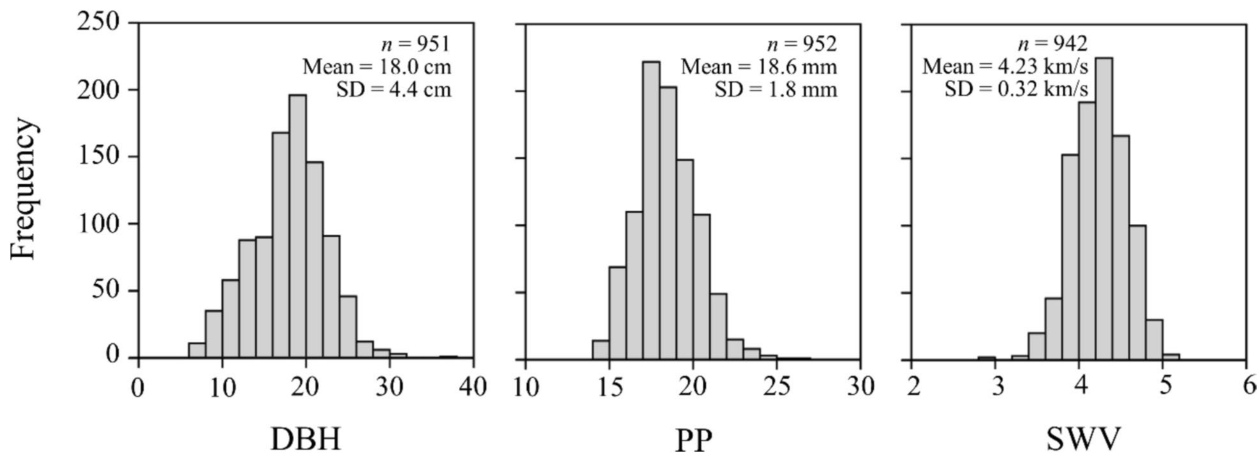

Fig. 2 Histograms of DBH, PP, and SWV. DBH, stem diameter at breast height; PP, pilodyn penetration; SWV, stress-wave velocity; n, number of individuals; SD, standard deviation

Table 1 Fundamental statistical values and repeatability of all traits

Trait	n_c	n_i	Mean	SD	Min	Max	CV (%)	Repeatability
DBH (cm)	321	951	18.0	4.0	6.8	28.0	22.3	0.474
PP (mm)	318	952	18.6	1.5	15.2	23.4	8.2	0.439
SWV (km/s)	321	942	4.24	0.25	3.46	4.91	6.0	0.302

n_c, number of clones; n_i, number of individuals; DBH, stem diameter at breast height; PP, pilodyn penetration; SWV, stress-wave velocity; SD, standard deviation; Min., minimum; Max., maximum; CV, coefficient of variation. All statistical values were calculated based on the mean value of each clone

the Kita-Kanto district was characterized by lower temperatures and relatively dry conditions; the Kanto-Heiya district by higher temperatures and dry conditions; the Chubu-Sangaku district by relatively lower temperatures and more humid conditions; and the Tokai district by higher temperatures and humid conditions. To minimize the interaction of genetics and environments on growth traits and wood properties, crossing for next-generation and establishment of seed orchards and/or scion gardens have been implemented primarily within the respective breeding districts [31]. The breeding material stock garden is the only one that stocks almost all of the selected plus trees from all breeding districts in the Kanto breeding region, and their clones are preserved in their natural form without any tree shape induction. In the present study, a total of 952 ramets of 321 plus-tree clones (2.96 ramets per clone on average) were studied, except for plus trees with poor growth. The plus-tree clones analyzed in the present study comprised 13, 134, 89, and 86 clones selected from the Kita-Kanto, Kanto-Heiya, Chubu-Sangaku, and Tokai breeding districts, respectively (Fig. 1). Ten individuals per clone were planted in a row at 1.5 m intervals with a spacing of 3.5 m between clones. All individuals used in the present study were identified through genotyping using Simple Sequence Repeats (SSR) markers to confirm their genetic identity within each clone.

Stem diameter, Pilodyn penetration, and stress-wave velocity

In 2022, the stem diameter at 1.2 m above the ground of all studied 28-year-old trees was measured using a caliper. In addition, Pilodyn penetration (PP) was measured at 1.2 m above the ground using the Pilodyn 6 J Forest instrument (Proceq Co., Switzerland). Stress-wave velocity (SWV) was measured at the stem position from 0.7 to 1.7 m above the ground using a TreeSonic timer (FAKOPP, Hungary). The Pilodyn penetration and stress-wave velocity were measured in two perpendicular directions on the stem of standing trees. The average value of two measurements was used as an individual representative value.

Statistical analysis

All statistical analyses were performed using R version 4.1.2 [33]. Variance of clone for all traits was estimated by the linear mixed-effect model with restricted maximum likelihood estimation (REML) using the "lmer" function of the "lme4" package [34] in the following formula:

$$y_{ijk} = \mu + B_i + C_j + e_{ijk}, \quad (1)$$

where y_{ijk} is the measurement value of stem diameter, Pilodyn penetration, or stress-wave velocity of the kth individual of the jth clone in the ith block, μ is the general mean, B_i is the fixed effect of the ith block, C_j is the random effect of the jth clone, and e_{ijk} represents the residuals. In the present study, no interaction effect of clone and replicate block was considered because there were no replications between blocks in all clones. Random effects and residuals were assumed to follow normal distributions with mean zero and constant variance, and residuals were assumed to be independent.

Clonal repeatability of clone (broad-sense heritability) for all traits was estimated by following the formula:

$$R = \frac{\sigma_c^2}{\sigma_c^2 + \sigma_e^2}, \tag{2}$$

where R is the clonal repeatability of the clone and ${\sigma_c}^2$ and ${\sigma_e}^2$ the variances of the clone and residuals.

To categorize clones based on the clonal characteristics for growth, wood density, and stiffness, cluster analysis using the Ward hierarchical clustering algorithm was performed using the random effects of the clone for stem diameter, Pilodyn penetration, and stress-wave velocity as variables. The optimal number of clusters was determined by the Jain–Dubes methods [35]. Cluster analysis was performed on a total of 316 plus-tree clones with no missing values in all measurements. To characterize the genetic ability of clones, the differences in the random effect parameters among groups were tested by analysis of variance (ANOVA). In addition, the Tukey-HSD test was performed for traits for which significant differences were detected by ANOVA.

Results and discussion

Histogram and clonal mean

The histogram for stem diameter, Pilodyn penetration, and stress-wave velocity is illustrated in Fig. 2. All traits were approximately normally distributed with 18.0 ± 4.4 cm in stem diameter, 18.6 ± 1.8 mm in Pilodyn penetration, and 4.23 ± 0.32 km/s in stress-wave velocity. Table 1 shows the clonal mean for all traits. In stem diameter at 28-year-old, the mean and standard deviation were 18.0 and 4.0 cm, respectively, with a range from 6.8 to 28.8 cm. In the table of characteristics of plus trees of *C. obtusa*, the stem diameter of 30-year-old trees in families originating from the first-generation plus trees ranged from 15.1–22.1 cm in the Kansai breeding region [36] and 17.1–20.7 cm in the Kyushu breeding region [37]. Therefore, plus-tree clones selected in the Kanto breeding region showed comparable radial growth compared to the families in the other breeding regions. On the other hand, the means of clones for Pilodyn penetration and stress-wave velocity were 18.6 mm and 4.24 km/s, respectively, and were similar values to the previous study on *C. obtusa* trees of approximately the same ages [9, 38–40].

Clonal repeatability

Genetic variations and the narrow-sense and/or broad-sense heritability, including the clonal repeatability for growth traits and wood properties in *C. obtusa*, had been estimated by many researchers, clarifying that many traits, including growth and wood quality, are genetically controlled and can be improved through tree breeding [6, 9, 27–29]. However, such estimated heritability varies widely depending on the number and combination of families or clones submitted for analysis. The number of clones in the present study accounts for about 80% of all selected plus trees in the Kanto breeding region, and clone identification was performed by genotyping. Therefore, the calculated coefficient of variation and repeatability provides a more accurate assessment of the range of genetic variation and inheritance in stem diameter, Pilodyn penetration, and stress-wave velocity, information which could be valuable for tree breeding for the wood quality of *C. obtusa* in the Kanto breeding region. The repeatability in stem diameter, Pilodyn penetration, and stress-wave velocity was 0.474, 0.439, and 0.302, respectively (Table 1), suggesting that radial growth, wood density, and Young's modulus in *C. obtusa* might be heritable traits. This result supported the previous studies on the inheritance of growth traits and wood properties in *C. obtusa* [6, 9, 27, 28, 40].

Phenotypic variation

The coefficient of variation in stem diameter was observed as the largest value (22.3%) in all traits (Table 1), indicating that stem diameter is expected to have higher genetic gain. On the other hand, coefficients of variation in Pilodyn penetration and stress-wave velocity were 8.2% and 6.0%, respectively (Table 1). Mishima et al. [41] evaluated the standing tree for 14-year-old 745 clones of *C. japonica*, about 77% of all selected plus trees in the Kanto breeding region. They reported that coefficients of variation in stem diameter, Pilodyn penetration, and stress-wave velocity were 21.1%, 13.5%, and 8.3%, respectively [41]. In addition, coefficients of variation in stem diameter, Pilodyn penetration, and stress-wave velocity were reported in the ranges of 12–28%, 6–12%, and 5–12%, respectively, in *P. taeda* [18], *Larix decidua* [42], *P. abies* [13], and *A. sachalinensis* [20]. The genetic variability of stem diameter, Pilodyn penetration, and stress-wave velocity observed in the present study was comparable to those reported for other softwood species in previous studies. The variation of wood properties, including wood density, is reported to be smaller than that of *C. japonica* in the previous study [43]. Our

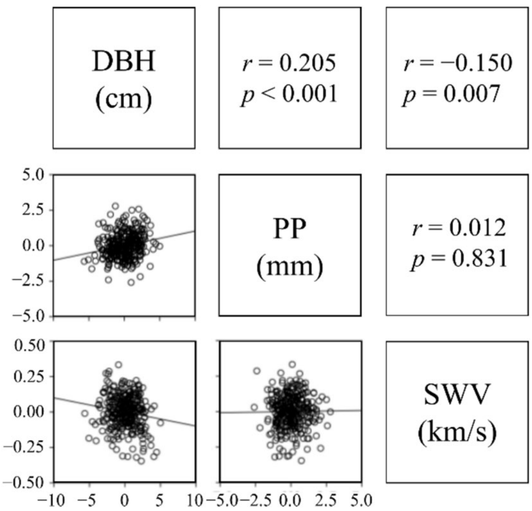

Fig. 3 Genetic correlations among traits. DBH, stem diameter at breast height; PP, pilodyn penetration; SWV, stress-wave velocity; *r*, genetic correlations estimated using the random effect of clones; *p*, *p*-values of correlation coefficients

study also showed a smaller coefficient of variation in Pilodyn penetration compared to *C. japonica* [41]. For stress-wave velocity, the coefficient of variation was also smaller than that of *C. japonica*; however, this was caused by a higher average in stress-wave velocity, and there is a small difference in standard deviation, 0.25 km/s in this study and 0.23 km/s in *C. japonica* [41]. Our study showed a large phenotypic variation in stress-wave velocity in *C. obtusa* compared to *C. japonica* and other coniferous species. This large phenotypic variation and relatively higher clonal repeatability indicate the significant potential of genetic improvement of Young's modulus in *C. obtusa*.

Genetic correlation among traits

As well as many target species for tree breeding [7, 8, 13, 18–20], Pilodyn penetration and stress-wave velocity in *C. obtusa* have been reported to be useful criteria for assessing wood density and Young's modulus, respectively, based on strong correlations between them [6, 38]. Therefore, analysis using nondestructive and simple measurable criteria can be an alternative to analysis of the relationship between growth and true target traits of tree breeding for wood quality. Genetic correlations among traits are shown in Fig. 3. Stem diameter was significantly positively correlated with Pilodyn penetration ($r = 0.205$), implying that clones with superior growth rates may tend to exhibit lower wood density. On the other hand, the genetic correlation between stem diameter and stress-wave velocity was significant but low ($r = -0.150$), suggesting that stem diameter and Young's modulus could be improved simultaneously by tree breeding in *C. obtusa*. Young's modulus of wood in softwood species has been known to be affected by wood properties such as wood density and microfibril angle [8, 44–47], and a similar trend has also been observed in *C. obtusa* wood [9, 27]. In the present study, no significant genetic correlation between Pilodyn penetration and stress-wave velocity was found ($r = 0.012$). This result suggested that wood density might not strongly affect Young's modulus in *C. obtusa*. The results obtained from the analysis using alternative criteria in the present study will provide important insights for evaluating the possibility of simultaneous improvements in growth and wood quality in *C. obtusa*. In future research, mechanical properties such as Young's modulus and strength, and wood properties such as wood density and MFA, should be directly measured and their genetic correlations should be verified.

Clonal characteristics for growth and wood quality

As shown in the results of clonal repeatability and genetic correlation in the present study, stem diameter, Pilodyn penetration, and stress-wave velocity in *C. obtusa* were suggested to be heritable, and simultaneous improvement by tree breeding could be feasible. To create a crossing design for simultaneous improvement of growth and wood quality, it is of primary importance to understand the clonal characteristics of each plus-tree. In the

Table 2 Number of clones and median values of random effect of clones for DBH, PP, and SWV in each group

Group	Number of clones					DBH (cm)	PP (mm)	SWV (km/s)
	Kita-Kanto	Kanto-Heiya	Chubu-Sangaku	Tokai	All districts			
I	2 (15.4%)	26 (19.7%)	11 (12.4%)	18 (22.0%)	57 (18.0%)	1.280	0.162	0.024
II	4 (30.8%)	26 (19.7%)	27 (30.3%)	23 (28.0%)	80 (25.3%)	0.231	0.565	−0.067
III	5 (38.5%)	39 (29.5%)	25 (28.1%)	20 (24.4%)	89 (28.2%)	−0.606	−0.135	0.036
IV	2 (15.4%)	41 (31.1%)	26 (29.2%)	21 (25.6%)	90 (28.5%)	0.173	−0.468	−0.005
Total	13 (100%)	132 (100%)	89 (100%)	82 (100%)	316 (100%)			

DBH, stem diameter at breast height; PP, pilodyn penetration; SWV, stress-wave velocity. Values in parentheses indicate the percentage of clones from each breeding district assigned to each group. Percentages are calculated within each district (column-wise), not within groups. Percentages may not sum to 100% due to rounding

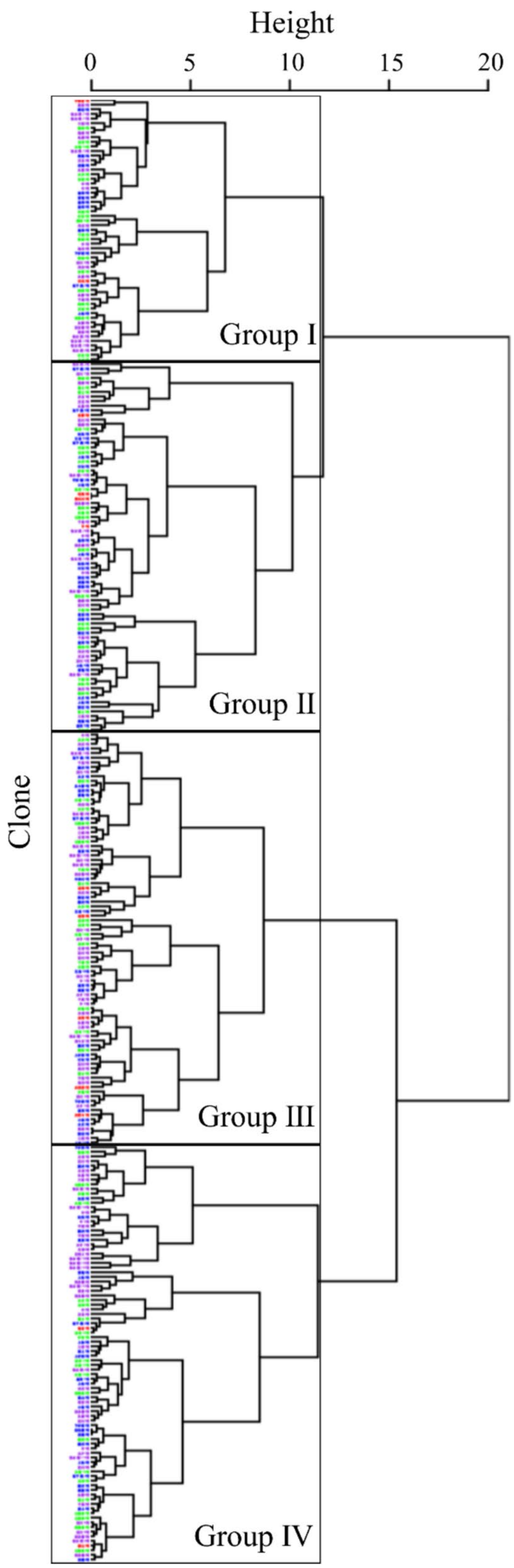

Fig. 4 Cluster dendrogram of clones based on DBH, PP, and SWV. Clones in red, purple, blue, and green were selected from Kita-Kanto, Kanto-Heiya, Chubu-Sangaku, and Tokai breeding regions, respectively

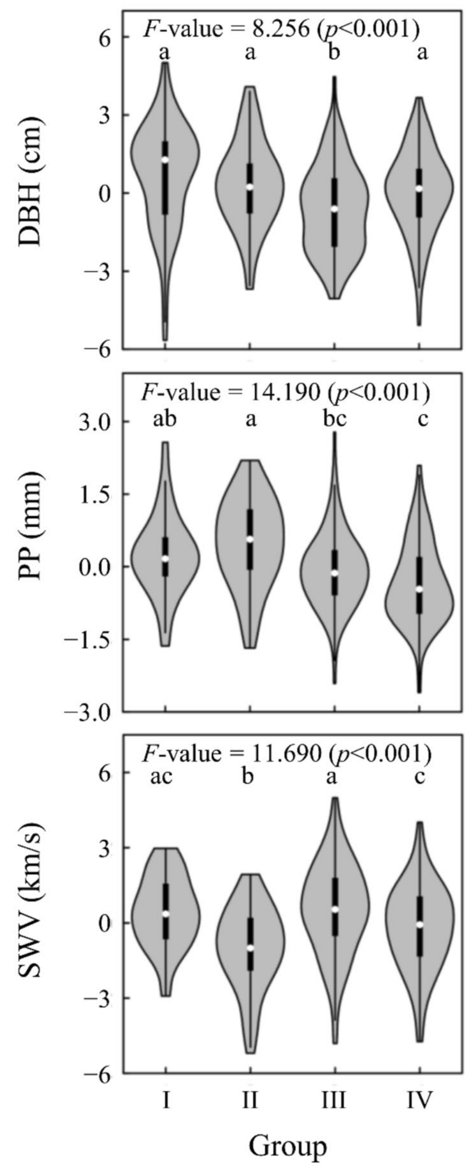

Fig. 5 Frequency distributions of the random effects of clone for each trait in clones classified into each group. DBH, stem diameter at breast height; PP, pilodyn penetration; SWV, stress-wave velocity. White points, black boxes, and black lines represent median values, the interquartile range, and the range of the data, excluding outliers, respectively. *F*-values were calculated by ANOVA with groups as a factor. Values in parentheses are *p*-values in *F*-values. Different letters indicate significant differences at the 5% level based on the Tukey-HSD test

present study, we tried to comprehensively evaluate the growth, wood density, and Young's modulus of each plus-tree clone using stem diameter, Pilodyn penetration, and stress-wave velocity as criteria, respectively, and classify them by clonal characteristics of the first-generation plus trees.

As the result of cluster analysis, of a total of 316 clones, 18.0%, 25.3%, 28.2%, and 28.5% belonged to Groups I, II, III, and IV, respectively (Table 2 and Fig. 4). Median values and the frequency distributions of the random effects of the clone in each group are shown in Table 2 and Fig. 5, respectively. In the results of the ANOVA test, significant differences in the random effects of the clone were found in all traits (Fig. 5). In stem diameter, the mean random effects in Group III were lower than those of other groups (Fig. 5). In addition, the significant differences in mean random effects of the clone for Pilodyn penetration were found between Group I and IV, between Group II and III, and between Group II and IV (Fig. 5). Mean random effect of the clone for stress-wave velocity in Group II was significantly lower than those of other groups (Fig. 5). Based on these results, we attempted to characterize the genetic ability of clones in each group. The clones classified into Group I were suggested to exhibit faster growth and slightly lower wood density but relatively higher Young's modulus. Clones in Group II showed relatively rapid growth with lower wood density and Young's modulus. In contrast, clones in Group III exhibited slower growth with higher wood density and Young's modulus. Average growth and Young's modulus and the highest wood density were found in clones of Group IV. Based on the result of a classification of plus trees, plus-tree clones classified in Group I had superior genetic ability in both growth and Young's modulus, suggesting the possibility of simultaneously improving growth and wood quality by using these clones as mating parents to produce the progeny.

To assess the geographic variation of clonal characteristics, the number of clones of each group by breeding district from which each clone originated was investigated (Table 2 and Fig. 4). Except for the Kita-Kanto breeding district where the number of clones was limited, clones from all breeding districts were roughly evenly grouped into each group. This result suggests that the genetic ability for growth, wood density, and Yong's modulus is not dependent on the origin of the plus trees. On the other hand, the adaptability of trees to environments varies among genotypes, known as the interaction between genetics and environments [48]. In other words, the results of the classification of plus trees and the ranking of plus-tree clones for growth and wood quality in the present study may be variable in other planting environments. In future studies, therefore, it is necessary to evaluate the genetic variability for growth traits and wood quality in more diverse environments in order to find genotypes with superior growth and wood quality throughout the Kanto breeding region.

Conclusion

To collect the findings on the genetic variability for growth, wood density, and Young's modulus to promote tree breeding for wood quality, stem diameter, Pilodyn penetration, and stress-wave velocity were measured on 28-year-old first-generation plus-tree clones in *C. obtusa* planted into the breeding material stock garden, which represents approximately 80% of all *C. obtusa* plus trees selected from the Kanto breeding region. Stem diameter in the present study was similar to 30-year-old first-generation plus trees in the Kansai and Kyushu breeding regions. Based on the clonal repeatability, all traits were suggested to be heritable traits. In addition, the genetic correlation between stem diameter and stress-wave velocity was low, suggesting the possibility of simultaneous improvement of growth and Young's modulus. All plus-tree clones were classified into four groups with different clonal characteristics for growth and wood quality by cluster analysis. As a result, relatively superior plus-tree clones were found for both growth and stress-wave velocity. Evaluation of plus-tree clones in standing trees in the present study will provide valuable information to promote tree breeding for wood quality. However, since Pilodyn penetration and stress-wave velocity are criteria for relative evaluation of wood density and Young's modulus, respectively, further study is needed to directly measure wood density and mechanical properties, and to evaluate their inheritance and genetic correlations among them.

Abbreviations

PP Pilodyn penetration
SWV Stress-wave velocity

Acknowledgements

We would like to express our appreciation to all the staff of the Forest Tree Breeding Center of the Forestry and Forest Products Research Institute for their assistance in conducting this study.

Author contributions

The research layout was designed by Y.T., M.M., and E.F. SSR genotyping was performed by S.N. and T.H. The manuscript was analyzed and drafted by Y.T. All authors contributed to the final manuscript by discussing the findings and conclusions.

Funding

None declared.

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 do not have any competing interests.

Received: 29 October 2025 Accepted: 8 January 2026
Published online: 22 January 2026

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