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Variations in Growth Characteristics and Stress-wave Velocities of *Zelkova serrata* Trees from Eight Half-sib Families Planted in Three Different Initial Spacings

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Abstract

Zelkova serrata is an important hardwood species for the timber industry in Japan. Tree breeding programs for this species have mainly focused on growth characteristics such as stem diameter (*D*), tree height (TH), stem form, and branching. In order to fulfill timber industry needs, wood quality improvement should be included in the tree breeding program of this species. In the present study, growth characteristics, such as *D* and TH, and the stress-wave velocity (SWV), which is highly correlated with Young's modulus of wood, were measured for 20-year-old *Z. serrata* from eight half-sib families planted in a progeny test site with three different initial spacings. Significant differences in all the measured characteristics were found among the eight half-sib families. The variance components of the half-sib families for *D*, TH, and SWV were 27.2%, 47.3%, and 33.5%, respectively. These results indicate that all the measured characteristics of this species could be improved by tree breeding programs. In addition, only low correlation coefficients were obtained between the growth characteristics and SWV, indicating that extensive selection on SWV in tree breeding programs may not always lead to a reduction in yield volume.

Key Words: *Zelkova serrata*, wood quality, stress-wave velocity, spacing effect, growth characterists

Introduction

In general, plus-trees in tree breeding programs are selected on the basis of growth rate, stem form, pest resistance, and soil adaptability (Zobel and Jett 1995). On the other hand, Zobel and van Buijtenen (1989) also have emphasized that wood quality improvement should be an integral part of tree breeding programs. However, because a negative decline of wood quality associated with the selection for growth characteristics has been concerned in tree breeding programs, selecting plus-trees based on wood quality is important (Ratcliffe et al. 2014).

The measurement of the stress-wave velocity (SWV), one of the acoustical nondestructive methods, can be uti-

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lized in evaluating Young's modulus of standing trees (Wang et al. 2001; Ishiguri et al. 2007). Wang et al. (2001) reported that SWV of standing trees is significantly and positively correlated with Young's modulus of an individual log or lumber. Furthermore, Young's modulus has been also known to have major effect on product design and important in engineering (Bucur 2006). In addition, a rapid estimation of wood quality is crucial for the success of wood quality improvement in tree breeding programs (Ratcliffe et al. 2014). Therefore, SWV is important and appropriate for evaluating Young's modulus of wood in tree breeding programs.

Zelkova serrata (Thunb.) Makino belongs to the family Ulmaceae. This species is endemic to Japan, Taiwan, Korea, and northeast China. It is commonly found in Japan, except in Hokkaido and Okinawa (Mertz 2011), and is an important hardwood species in the Japanese timber industry. Its wood has a beautiful grain, is relatively dense, and high strength (Itoh et al. 2011; Mertz 2011). Therefore, *Z. serrata* has been extensively used in traditional woodworking in Japan, such as finecabinet making, carving (Buddhist sculpture), turning (bowl), structural and decorative timber in traditional Japanese buildings, shrines, and temples (Mertz 2011).

Trees with superior growth characteristics, such as stem diameter (*D*), tree height (TH), stem form, and branching, have been selected in *Z. serrata* tree breeding programs (Endo et al. 1998; Yoshino et al. 2006; Kidoguchi et al. 2010). In addition, Isamoto (2000) reported that wood density and anatomical characteristics differed between the three *Z. serrata* strains. However, information regarding variations in the wood properties of *Z. serrata* remains to be limited.

In the present study, *D*, TH, and SWV were measured in 20-year-old *Z. serrata* trees from eight half-sib families that were planted in Kisarazu, Chiba Prefecture, Japan, and the relationships between growth and properties of the wood were investigated. Wood quality improvement in *Z. serrata* breeding programs is also discussed, based on the results obtained in the present study.

Materials and Methods

The *Z. serrata* progeny test site was located in the Forestry Research Institute, Kisarazu, Chiba Prefectural Agriculture and Forestry Research Institute, Japan (35°34′ N, 140°03′E). At the test site, nine half-sib families originating from Chiba, three types of seedlings purchased from three different places, and one clone (Musashino No. 1) were planted in 1993. These were planted with three different initial spacings: (A) 1.2x1.2 m, 7,000 trees/ha, (B) 1.4x1.4 m, 5,000 trees/ha, and (C) 1.8x1.8 m, 3,000 trees/ha (Endo et al. 1998). The site had three replicate blocks for each initial spacing and each block comprised a family row plot. Several trees died naturally before sampling, and tree mortality during the 20 growth years was considerably high in all three spacings; survival in spacing A was low compared with that in spacings B and C. The mortality rates in all three spacings were 21.2%, 9.7%, and 8.4% in spacings A, B, and C, respectively.

In February and May 2013, *D*, TH, and SWV were measured for a total of 771 trees from eight half-sib families in the three different initial spacings and three replicate blocks. One family contained an insufficient number of trees; therefore, only eight half-sib families were measured. *D* at 1.3 m above the ground was measured using a diameter tape. TH was measured using an altimeter (VERTEX IV, Haglöf). The stress-wave propagation time of the stem was measured using a stress-wave timer (FAKOPP Microsecond Timer, FAKOPP Enterprise), according to the methods described by Ishiguri et al. (2007). The start and the stop sensors were set on the surface of the stem from 0.5 to 1.5 m above the ground. The stress-wave propagation time was measured six times at the same position on the stem by hitting the start sensor with a small hammer. In addition, SWV of the stem was determined by dividing the distance between the sensors by the mean value of the stress-wave propagation time.

A two-way analysis of variance (ANOVA) was performed to evaluate the variation in *D*, TH, and SWV among the eight half-sib families and the initial spacings. Furthermore, a multiple comparison test (Tukey-Kramer) was also conducted to categorize the mean values of each half-sib family in each initial spacing.

Estimates of variance components were used to predict the relative importance of the various determinants of the phenotype, which were expressed as the repeatability or heritability of each characteristic (*D*, TH, and SWV) (Falconer and Mackay 1996). The estimation was undertaken from expected mean square as results of ANOVA

Table 1. Mean values of *D*, TH, and SWV in 20-year-old *Zelkova serrata* from eight half-sib family

Family code	Spacing A				Spacing B				Spacing C			
	n	*D* (cm)	TH (m)	SWV (km/s)	*n*	*D* (cm)	TH (m)	SWV (km/s)	*n*	*D* (cm)	TH (m)	SWV (km/s)
A	17	8.0^{abc}	9.8^{a}	2.99^{abc}	23	8.4^{abc}	10.0^{ab}	2.92^{abc}	21	9.3^{ab}	8.9^{ab}	2.80^{ab}
B	43	5.9^{c}	7.1^{b}	3.07^{ab}	33	6.4^{c}	7.7^{c}	3.02^{ab}	26	9.3^{ab}	9.8^{ab}	2.83^{ab}
C	37	9.4^{a}	9.7^{a}	2.95^{bc}	32	8.7^{abc}	10.4^{a}	2.94^{ab}	33	10.5^{ab}	10.1^{ab}	2.84^{ab}
D	69	7.1^{bc}	8.4^{ab}	3.08^{a}	51	7.7^{abc}	9.2^{abc}	3.04^{a}	22	11.4^{ab}	10.8^{a}	2.85^{ab}
E	33	6.6^{bc}	7.1^{b}	2.96^{bc}	37	7.3^{abc}	8.0^{bc}	2.89^{bc}	27	9.6^{ab}	8.4^{b}	2.82^{ab}
F	43	8.9^{ab}	9.6^{a}	2.96^{bc}	40	8.9^{ab}	10.0^{a}	2.88^{bc}	25	12.2^{a}	10.6^{a}	2.84^{ab}
G	23	6.5^{bc}	8.1^{ab}	2.83^{c}	36	7.0^{bc}	8.0^{bc}	2.78^{c}	33	9.1^{b}	8.7^{b}	2.71^{b}
H	18	8.8^{abc}	9.5^{a}	2.99^{abc}	24	9.7^{a}	9.8^{abc}	2.90^{abc}	25	10.6^{ab}	9.4^{ab}	2.97^{a}
Mean		7.6	8.7	2.98		8.0	9.1	2.92		10.3	9.6	2.83
CV (%)		16.9	13.3	2.7		14.0	11.9	2.8		11.0	9.2	2.5

D, stem diameter; TH, tree height; SWV, stress-wave velocity; CV, coefficient of variation; *n*, number of trees.
Spacing A: 1.2x1.2 m, Spacing B: 1.4x1.4 m, Spacing C: 1.8x1.8 m. Means followed by different letters are significant at the 5% level.

(Lynch and Walsh 1998). In addition, genetic groups under analysis are sampled randomly and the initial spacing being interpreted as fixed factors. Therefore, the following ANOVA model was used for assessing the interactions between each characteristic:

$$Y_{(ijk)} = \mu + S_i + F_j + (SF)_{ij} + \varepsilon_{ijk}$$

where Y_{ijk} is the characteristic of the *k*th tree of the *j*th half-sib family in the ith spacing, μ is the overall mean, S_i is the environmental effect of the *i*th spacing, F_j is the genetic effect of the *j*th half-sib family, $(SF)_{ij}$ is the interaction between the *j*th family and the *i*th spacing, and ε_{ijk} is the random error.

Table 2. Two-way analysis of variance of D, TH, and SWV in *Zelkova serrrata*

Factor	D_f	F value		
		D	TH	SWV
Spacing	2	39.11**	9.73**	47.27**
Family	7	8.53**	11.64**	13.82**
Family x spacing	14	1.02^{ns}	1.72*	1.50^{ns}

D, stem diameter; TH, tree height; SWV, stress-wave velocity; ns, no significance; **, significance at the 1 % level; *, significance at the 5% level; D_f, degree of freedom.

Results and Discussion

Among family variation

The mean family values of *D* in the initial spacings A, B, and C were 5.9-9.4 cm, 6.4-9.7 cm, and 9.1-12.2 cm, respectively (Table 1). The mean values of TH were 7.1-9.7 m, 7.7-10.4 m, and 8.4-10.8 m in the initial spacings A, B, and C, respectively. The mean family values of SWV in the initial spacings A, B, and C were 2.83-3.08 km/s, 2.78-3.04 km/s, and 2.71-2.97 km/s, respectively.

In the present study, significant differences in *D*, TH, and SWV were found among the eight half-sib families in all the initial spacings (Table 2). In a previous study, significant differences in *D* and TH were observed in 4-year-old *Z. serrata* trees planted at the same site of the present study (Endo et al. 1998). Among-family variation or clonal variation in growth characteristics and wood quality have been reported in other hardwood species (Wu et al. 2011; Hidayati et al. 2013). Wu et al. (2011) reported that significant differences in *D*, TH, and SWV were found among 19 *Eucalyptus* hybrid clones planted in southern China. In 12-year-old *Tectona grandis* trees planted in Indonesia, significant differences in growth characteristics (*D*, TH, and stem volume) and the SWV were observed among 15 clones (Hidayati et al. 2013). Our results for *D*, TH, and SWV are consistent with those obtained by previous studies on *Z. serrata* and other hardwood species

(Endo et al. 1998; Wu et al. 2011; Hidayati et al. 2013).

Variance components

Fig. 1 shows the distribution of variance components for each measured characteristic. In the present study, the half-sib family variance components for *D*, TH, and SWV were 27.2%, 47.3%, and 33.5%, respectively. Theoretically, the ratio between genotypic and phenotypic variances can be simply expressed as heritability or repeatability (Falconer and Mackay 1996); therefore, moderate repeatability values (variance components of the half-sib family) for *D*, TH, and SWV were observed in the present study. Low to moderate repeatability values (0.12-0.56) have been obtained for *D* and TH in *E. globulus*, *Acacia auriculiformis*, and *T. grandis* (Volker et al. 1990; Hai et al. 2008; Hidayati et al. 2013). However, moderate to high repeatability values for SWV in hardwood species have been reported. For example, Hidayati et al. (2013) reported that the repeatability of the SWV in 12-year-old *T. grandis* trees from 15 clones was 0.27. In addition, Wu et al. (2011) reported that the repeatability value of SWV in *Eucalyptus* hybrid clones was 0.77. Our results for the repeatability of *D*, TH, and SWV are in the range of those obtained by other researchers (Volker et al. 1990; Hai et al. 2008; Wu et al. 2011; Hidayati et al. 2013).

The variance components for spacing of *D*, TH, and SWV were 51.4%, 14.3%, and 46.5%, respectively (Fig. 1). The spacing variance components of *D* and SWV accounted for approximately half of the total variance, suggesting that these characteristics are largely influenced by the initial spacing. The variance component for spacing of TH was smaller (14.3%) than the other two characteristics, while the interaction variance component of TH was 24.1%, which is approximately two times as high as the other characteristics. These results indicate that a genotype and initial spacing interaction largely affects the TH. Several researchers have discussed the effects of initial spacing on the wood properties or SWV of hardwood species (Zobel and van Buijtenen 1989; Warren et al. 2009). In three *Eucalyptus* species (*E. dunnii*, *E. cloeziana*, and *E. pilularis*), Warren et al. (2009) found that trees grown at a narrow initial spacing produced wood with a higher SWV value than those grown at a wide initial spacing. In general, the existence of large knots and a high volume ratio of juvenile wood in trees planted at a wide initial spacing result in lower values of the overall wood properties (Zobel and van Buijtenen 1989). However, Kollmann and Côté (1984) pointed out that in ring-porous wood, wide annual rings result in a high wood density because of an increase in the amount of late wood. In the present study, the mean family values of SWV in *Z. serrata* tended to decrease with increas-

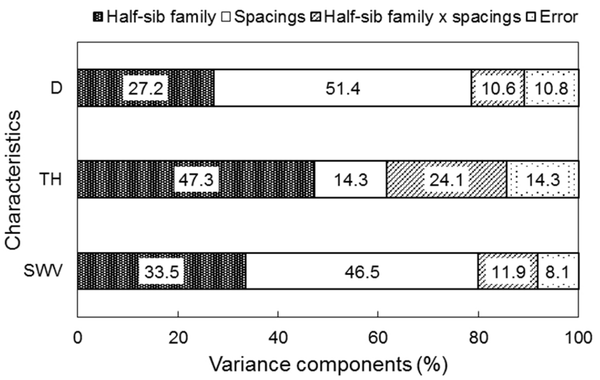

Fig. 1. Distribution of variance components for each characteristics in *Zelkova serrata*. *D*, stem diameter; TH, tree height; SWV, stress-wave velocity.

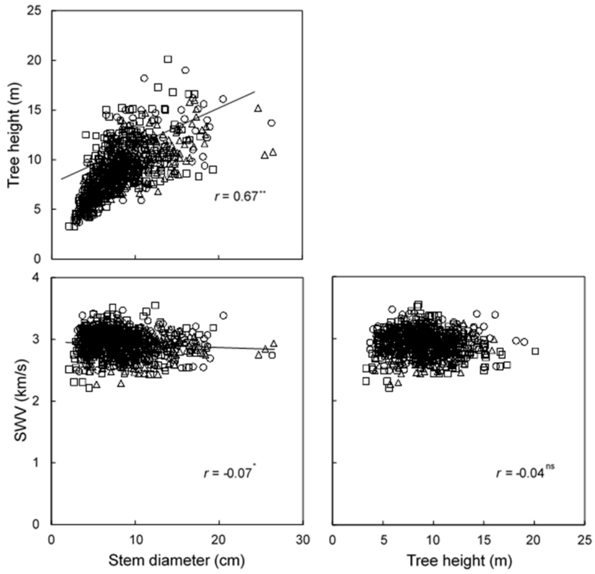

Fig. 2. Relationships between growth characteristics and the stress-wave velocity (SWV) in *Zelkova serrrata*. Circles, squares, and triangles indicate the data from the trees in initial spacings A, B, and C, respectively; *r*, correlation coefficient; **, significance at the 1% level; *, significance at the 5% level; ns, no significance. *n*=771. (A) 1.2x1.2 m, (B) 1.4x1.4 m, (C) 1.8x1.8 m initial spacings.

ing initial spacing (Table 1). Our results for SWV showed the same trend as that demonstrated in previous studies (Zobel and van Buijtenen 1989; Warren et al. 2009). However, further research is needed to evaluate the variation in the proportion of latewood in *Z. serrata* planted at different initial spacings.

Relationships between growth characteristics and SWV

Only weakly significant or nonsignificant relationships, have been found between growth characteristics and SWV in *Paraserianthes falcataria* (Ishiguri et al. 2007), *E. dunnii* (Dickson et al. 2003), and *T. grandis* (Hidayati et al. 2013). In the present study, a highly significant positive correlation (r=0.67) was found between D and TH (Fig. 2). However, only low correlation coefficients were obtained between growth characteristics and SWV (Fig. 2), suggesting that selection based on SWV does not always lead to a reduction in stem yield volume.

Implications of breeding for wood quality

Selection of superior trees based on wood quality, without any reduction in growth characteristics, is key to breeding trees for the quality of their wood. In the present study, considering the selection target into three important characteristics (D, TH, and SWV), mean values of D, TH, and SWV were significantly higher in the families A and H compared to the other families, while family G exhibited significantly lower mean values than the other families for all the measured characteristics in all the initial spacings (Table 1). Therefore, the use of superior families, such as families A and H, is recommended, whereas inferior families, such as family G, should be eliminated from *Z. serrata* tree breeding programs.

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