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ORIGINAL ARTICLE

Wood properties and their among-family variations in 10 open-pollinated families of *Picea jezoensis*

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Abstract This study aimed to evaluate radial and among-family variations of wood properties in *Picea jezoensis*. A total of 174 trees were randomly selected from 10 open-pollinated families in a progeny trial for measuring stem diameter, dynamic Young's modulus of log ($DMOE_{log}$), annual ring width (ARW), air-dry density (AD), modulus of elasticity (MOE), and modulus of rupture (MOR). Mean values of $DMOE_{log}$, AD, MOE, and MOR were 9.60 GPa, 0.41 g/cm^3, 9.44 GPa, and 76.6 MPa, respectively. Significant differences among families were observed in all properties. *F* values obtained by analyzing variance in wood properties were higher than those generally observed in growth traits. In addition, *F* values in wood properties remained relatively higher from the 1st to 25th annual ring from the pith, although *F* value in ARW rapidly decreased with each increase in annual ring number. These results indicate that genetic factors largely contributed to the variance in wood properties compared with the growth traits.

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Introduction

Picea jezoensis Carr., one of the most important forest species in Hokkaido, Japan, is naturally distributed in central Kamchatka, maritime Siberia, extreme northeast China, North Korea, Sakhalin, and Hokkaido Island [1]. During the past five decades, wood resources from *P. jezoensis* have decreased in Hokkaido [2]. In addition, plantation of this species is difficult to establish because of its high susceptibility to insect pests (e.g., *Adelges japonicus*), frost damage during late spring, and snow blight diseases that affect seedlings [3]. However, silvicultural techniques have recently been improved, e.g., selecting a clone with resistance to *A. japonicus* has resulted in a gradual increase in the *P. jezoensis* plantation area of Hokkaido. In the near future, wood resources in Hokkaido will be supplied from these newly established plantations. On the other hand, wood resources of *Picea* species used in Japan (e.g., *P. abies* and *P. sitchensis*) were mostly imported from outside of Japan. In addition, only a few reports are available regarding wood properties of plantation-grown trees of this species [4]. Therefore, the wood properties of *P. jezoensis* should be further explored to fully utilize the wood resources from these plantation-grown trees.

P. jezoensis is one of the target species in the tree breeding program targeted by the Forest Agency, Ministry of Agriculture, Forestry and Fishery, Japan for improving growth traits. On the basis of growth traits, a total of 148 plus trees of *P. jezoensis* have been selected to date from natural and plantation forests in Hokkaido [5]. In contrast, wood properties such as wood density and modulus of elasticity (MOE) should be considered as equally important for tree breeding programs of *P. jezoensis*, because the wood of this species is mainly used for construction lumber. However, only a few reports have focused on the wood properties of *P. jezoensis* plus trees [5], compared with other *Picea* species [6–10].

It is known that wood properties significantly vary among genotypes. Moreover, the genetic effect on wood properties differs according to radial ring position [8–10]. Therefore, evaluating the genetic factor at different radial positions leads to effective selection of age in tree breeding programs of *P. jezoensis*. In addition, one of the problems in tree breeding is the considerable amount of time required to evaluate wood properties, such as MOE. Thus, early evaluation of wood properties is also important for effective selection in a tree breeding program.

The main objective of this study was to evaluate the wood properties of 10 open-pollinated families of *P. jezoensis* trees selected by tree breeding programs in Hokkaido, Japan. In addition, radial and among-family variations of wood properties were investigated. Based on the results, the feasibility of tree breeding for wood quality in *P. jezoensis* was discussed.

Materials and methods

Materials

Open-pollinated seeds of *P. jezoensis* were collected from 10 mother trees grown in four different natural forests (Akan, Ikutora, Asyoro, and Honbetsu) in Hokkaido, Japan (Fig. 1). Six-year-old seedlings that originated from these seeds were prepared in the nursery at Hokkaido Regional Breeding Office, Forest Tree Breeding Center, Forestry and Forest Research Institute, Ebetsu, Japan. These seedlings were planted in a progeny test site at Chitose, Hokkaido, Japan (42°47′50″N, 141°28′29″E) in 1966. At this site, there were three replicate blocks based on a randomized design with each plot comprising 150 trees in each family. The initial spacing of seedlings was 1.5 by 1.2 m. No thinning treatment was applied at the site before sampling for this study. Stand density at sampling time was ~2400 trees/ha. For this study, a total of 174 trees were randomly selected in 2009 when stand age was 43 years. Before cutting, stem diameter of all trees was measured at 1.3 m above the ground. One-meter-length logs were collected from 1.3 to 2.3 m above the ground in all sampled trees to measure dynamic Young's modulus of log ($DMOE_{log}$). After measuring $DMOE_{log}$, a 3-cm-thick disk and a 50-cm-long log were collected from the log obtained from 1.3 to 1.8 m above the ground to measure annual ring width (ARW) and bending properties.

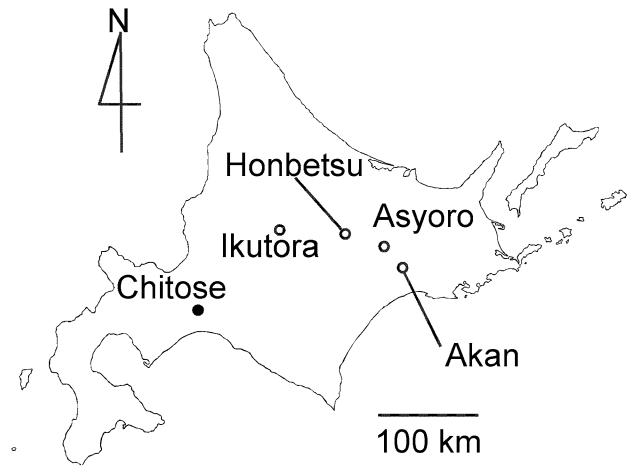

Fig. 1 Locations of progeny test site and provenances of 10 families. *Closed* and *open circles* indicate progeny test site and provenances of 10 families, respectively

Wood property

$DMOE_{log}$ was measured by a tapping method [11]. $DMOE_{log}$ was calculated using first natural frequency of longitudinal vibration obtained by a Fast Fourier Transform analyzer (Ono Sokki, CF-1200) and green density of logs.

The bark-to-bark strip with pith (2 cm thick and 3 cm wide) was randomly collected from the 3-cm-thick disk to measure ARW. ARW was measured in both directions of the prepared strip. The image data from transverse sections of these strips were imported to a personal computer equipped with a scanner (Canon, MP-650). Using the scanned images, ARW from pith to bark was measured at each annual ring using ImageJ (National Institutes of Health). ARW of each tree was expressed as a mean value of two directions.

Radial boards were collected from the logs obtained from 1.3 to 1.8 m above the ground to prepare small clear specimens [15 (R) × 15 (T) × 240 (L) mm] for the static bending test. The specimens were kept in laboratory with air conditioner (without humidity control; ca. 20 °C, 40–60 % relative humidity). After air drying, as many specimens as possible were prepared from these boards. Annual ring number from the pith was marked on the cross-section of each specimen (Fig. 2). Although each specimen included several annual rings, recorded annual ring number was defined as annual ring number from the pith. Air-dry density (AD) of each small clear specimen was measured before the static bending test. To determine MOE and modulus of rupture (MOR), the static bending

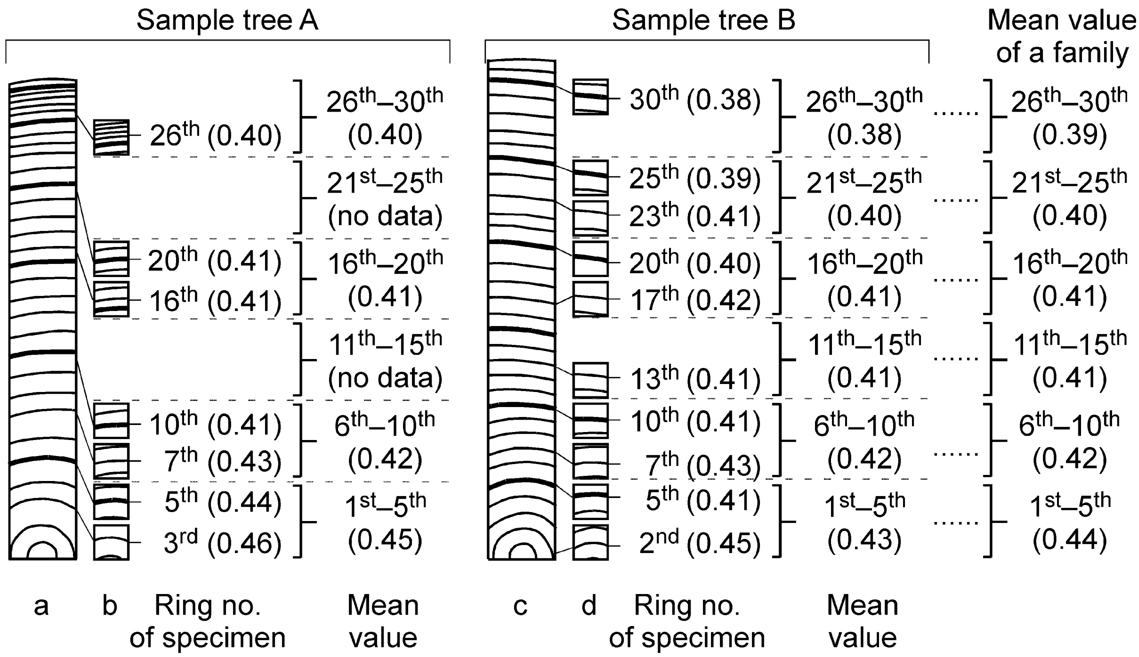

Fig. 2 Preparation of small clear specimens and calculation method of mean values for every 5 annual ring. **a** and **c** cross-sectional images of radial board in sample trees A and B, respectively; **b** and **d** cross-sectional images of small clear specimen in sample trees A and B, respectively. Due to sample tree size, specimen was not obtained from all radial positions (in this figure, specimens were not obtained from the 11th–15th annual ring and 21st–26th annual ring positions in sample tree A). Numbers in parentheses showed examples of air-dry density value (g/cm^3). For example, mean values of a family in 1st–5th (0.44 g/cm^3) were calculated by averaging of values obtained from the same positions of sample tree A (0.45 g/cm^3) sample tree B (0.43 g/cm^3) and other sample trees

test was conducted using a universal testing machine (Tokyo Testing Machine, MSC-5/500-2). Load speed was applied at the center of the specimen with 2 mm/min and 210 mm of span. After the static bending test, small blocks were collected from each specimen to measure moisture content of the small clear specimens. Moisture content values were ranged from 7.5 to 9.6 % (mean values and standard deviation were 8.6 and 0.5, respectively).

Data analysis

Number of annual rings at the position of 1.3 m above the ground varied among sample trees, although all samples were collected from the stand at the same age. Therefore, data were analyzed for each trait obtained within the 30th ring from the pith. Mean values for every five annual rings (1st–5th, 6th–10th, 11th–15th, 16th–20th, 21st–25th, and 26th–30th annual ring from the pith) were calculated to clarify radial variations of wood properties. Figure 2 shows calculation method of mean values for every 5 annual rings in wood properties. Mean values for each tree were also obtained using mean values calculated at every five annual rings. However, because of smaller stem diameter, certain sample trees did not yield any useful specimens, because their annual rings were very narrow.

One-way analysis of variance (ANOVA) was performed using the R open-source statistical package [12]. In the present study, *F* values, which are the ratios of variances within families to those among families, were used as indicators for evaluating degree of variation in wood properties among families. A larger *F* value indicates a larger variation among families. Age–age correlations were also evaluated by phenotypic correlation coefficients.

Results and discussion

Mean values

Table 1 shows statistical values of wood properties in 10 families. Mean values of stem diameter at 1.3 m above the ground in 10 families and ARW were 18.1 cm and 2.4 mm, respectively. Mean, minimum, and maximum values of $DMOE_{log}$ were 9.60, 8.78 (Asyoro 101), and 10.52 (Asyoro 102) GPa, respectively. In 31-year-old *P. glehnii* plus-tree clones planted in Hokkaido, Japan, $DMOE_{log}$ mean value of 10 families was reported as 9.58 GPa [7]. $DMOE_{log}$ mean value of standing trees calculated from stress wave velocity was 7.22 GPa (range 6.09–9.50 GPa) for *P. sitchensis* grown at 64 stands with

Table 1 Mean values and coefficient of variations of each family and F values obtained by ANOVA in wood properties

Family name	*n*	Stem diameter (cm)		ARW (mm)		$DMOE_{log}$ (GPa)		AD (g/cm^3)		MOE (GPa)		MOR (MPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Akan 101	20	19.0	3.1	2.6	0.4	9.25	1.0	0.40	0.03	9.03	1.14	72.5	11.0
Ikutora 102	27	17.0	3.5	2.1	0.5	10.04	1.2	0.43	0.03	10.18	1.12	82.2	8.3
Ikutora 103	16	18.2	4.4	2.4	0.6	9.94	0.9	0.41	0.03	9.47	1.04	77.1	9.8
Asyoro 101	15	21.6	5.0	2.9	0.6	8.78	0.8	0.38	0.02	8.50	0.78	70.0	6.6
Asyoro 102	18	16.8	4.7	2.2	0.6	10.52	1.4	0.43	0.04	10.32	1.47	83.4	10.1
Asyoro 103	14	16.0	3.9	2.1	0.5	9.53	1.4	0.43	0.03	9.39	0.98	76.2	7.5
Asyoro 104	12	18.6	4.6	2.5	0.7	9.90	1.3	0.42	0.04	9.40	0.99	77.6	11.0
Honbetsu 104	18	18.6	3.9	2.6	0.6	9.03	0.8	0.41	0.02	8.92	0.69	71.4	6.8
Honbetsu 106	23	17.5	4.7	2.4	0.6	9.55	1.0	0.42	0.03	9.42	0.95	77.7	8.6
Honbetsu 110	11	18.8	6.2	2.5	0.9	9.13	0.7	0.41	0.02	9.15	0.99	72.6	7.4
Mean/total	174	18.1	4.4	2.4	0.6	9.60	1.2	0.41	0.03	9.44	1.15	76.6	9.7
F value		2.021*		2.581**		4.260**		4.127**		5.216**		4.719**	

ARW annual ring width, $DMOE_{log}$ dynamic Young's modulus of log, *AD* air-dry density, *MOE* modulus of elasticity, *MOR* modulus of rupture, *SD* standard deviation. Mean values of each family were calculated by averaging the values of all individual trees within the family. *F* values were obtained by ANOVA

* and ** indicates significant among-family differences at 5 and 1 % levels, respectively

different stand ages (35–50 years) in the United Kingdom [13]. $DMOE_{log}$ values obtained from 10 families of *P. jezoensis* were similar to those of *P. glehnii* and relatively larger than those of *P. sitchensis*. Although moisture content of specimens for AD (7.5–9.6 %) was relatively lower than standard condition (12–15 %), AD of 10 families in *P. jezoensis* varied from 0.38 to 0.43 g/cm^3 (Table 1). AD mean value of *P. jezoensis* naturally grown in Hokkaido from small clear specimens was 0.45 g/cm^3 [14]. In *P. jezoensis* grown in Russia, Fujita et al. [15] reported that AD mean value was 0.45 g/cm^3, with minimal and maximal values at 0.38 and 0.52 g/cm^3, respectively. AD obtained in the present study was relatively smaller than that reported previously [14, 15]. In the present study, MOE and MOR mean values of 10 families were 9.44 GPa and 76.6 MPa, respectively (Table 1). Whereas, MOE and MOR mean values for *P. jezoensis* naturally grown in Russia and Hokkaido were 9.90 GPa and 87.7 MPa, and 10.33 GPa and 74.8 MPa, respectively [14, 15]. Moreover, Raiskila et al. [16] reported that MOE and MOR mean values were 9.88 GPa and 67.5 MPa, respectively, in 26-year-old *P. abies* cutting clones planted in Finland. Our results were similar to MOE of *P. jezoensis* grown in Russia and MOR of *P. jezoensis* grown in Hokkaido, and were in the range of naturally grown *P. jezoensis*, and *P. abies*, *P. glehnii* and *P. sitchensis* reported by other researchers [7, 13–16]. Based on these results, plantation-grown *P. jezoensis* was found to share wood properties similar to those of naturally grown *P. jezoensis*, as well as other *Picea* species, e.g., *P. abies* [7, 13–16]. Therefore, in the wood industry, wood resources of *P. jezoensis* from plantations can be regarded as useful as those from the naturally grown *P. jezoensis* and other *Picea* species imported from outside Japan.

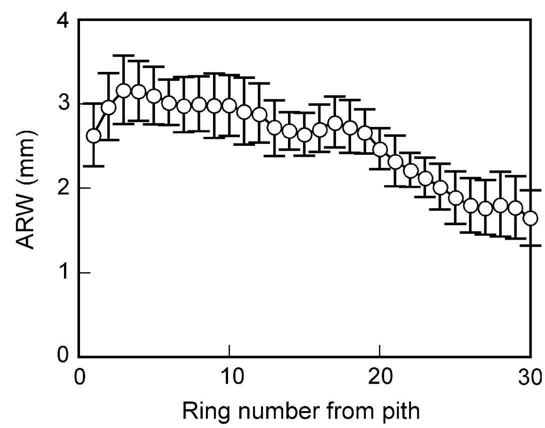

Fig. 3 Radial variation of annual ring width (ARW) in mean values of 10 families. *Circles* indicate mean values of 10 families. *Bar* indicates standard deviation

Radial variation patterns

Radial variation of ARW is shown in Fig. 3. ARW mean value in 10 families increased up to the third annual ring from the pith, then gradually decreased from the fourth annual ring toward the bark (<2 mm in mean value among the 10 families). ARW mean values in each family also tended to decrease from pith to bark, except for Asyoro 104, which showed nearly constant ARW values from the pith to the 30th annual ring (Table 2).

AD mean values also decreased from the pith to the 30th annual ring from pith in four families (Akan 101, Ikutora 102, Honbetsu 104, and Honbetsu 106) (Table 3). However, AD in the remaining six families showed almost the same radial variation patterns from the pith to the 30th annual ring from the pith (Table 3). According to Panshin and de

Table 2 Radial variation of annual ring width (mm) in each family

Family	Ring number from pith					
	1–5	6–10	11–15	16–20	21–25	26–30
Akan 101	3.5[a]	3.4[a]	3.0[ab]	2.7[bc]	2.2 [cd]	1.6[d]
Ikutora 102	2.6[a]	2.6[a]	2.4[ab]	2.6[a]	2.0[bc]	1.5[c]
Ikutora 103	3.4[a]	3.1[a]	2.8[a]	2.6[ab]	1.9[bc]	1.7[c]
Asyoro 101	3.0[ab]	3.4[a]	3.3[a]	3.3[a]	2.5[ab]	2.3[b]
Asyoro 102	2.7[a]	2.5[ab]	2.4[ab]	2.5[ab]	2.0[ab]	1.8[b]
Asyoro 103	2.7[a]	2.8[a]	2.4[ab]	2.3[ab]	1.8[bc]	1.4[c]
Asyoro 104	3.0[a]	2.9[a]	2.6[a]	2.7[a]	2.3[a]	2.0[a]
Honbetsu 104	2.9[ab]	3.1[a]	2.8[ab]	2.8[ab]	2.5[b]	2.1[b]
Honbetsu 106	2.8[a]	3.0[a]	2.9[a]	2.7[ab]	2.0[bc]	1.5[c]
Honbetsu 110	3.6[a]	3.2[a]	2.9[ab]	2.6[abc]	1.9[bc]	1.5[c]

Same alphabet letters followed by mean values indicate no significant difference at 5 % level among radial ring positions in a family by Tukey–Kramer test

Table 3 Radial variation of air-dry density (g/cm^3) in each family

Family	Ring number from pith					
	1–5	6–10	11–15	16–20	21–25	26–30
Akan 101	0.42[a]	0.40[ab]	0.39[ab]	0.40[ab]	0.39[b]	0.40[ab]
Ikutora 102	0.45[a]	0.44[ab]	0.43[ab]	0.42[b]	0.42[b]	0.41[b]
Ikutora 103	0.43[a]	0.42[a]	0.41[a]	0.40[a]	0.41[a]	0.41[a]
Asyoro 101	0.41[a]	0.40[a]	0.38[a]	0.38[a]	0.38[a]	0.38[a]
Asyoro 102	0.45[a]	0.44[a]	0.44[a]	0.43[a]	0.42[a]	0.41[a]
Asyoro 103	0.43[a]	0.42[a]	0.43[a]	0.41[a]	0.43[a]	0.42[a]
Asyoro 104	0.42[a]	0.42[a]	0.41[a]	0.40[a]	0.42[a]	0.40[a]
Honbetsu 104	0.43[a]	0.42[a]	0.41[ab]	0.39[b]	0.39[b]	0.39[b]
Honbetsu 106	0.45[a]	0.43[ab]	0.42[b]	0.41[b]	0.40[b]	0.41[b]
Honbetsu 110	0.42[a]	0.41[a]	0.40[a]	0.41[a]	0.41[a]	0.42[a]

Alphabet letters followed by mean values, refer to Table 2

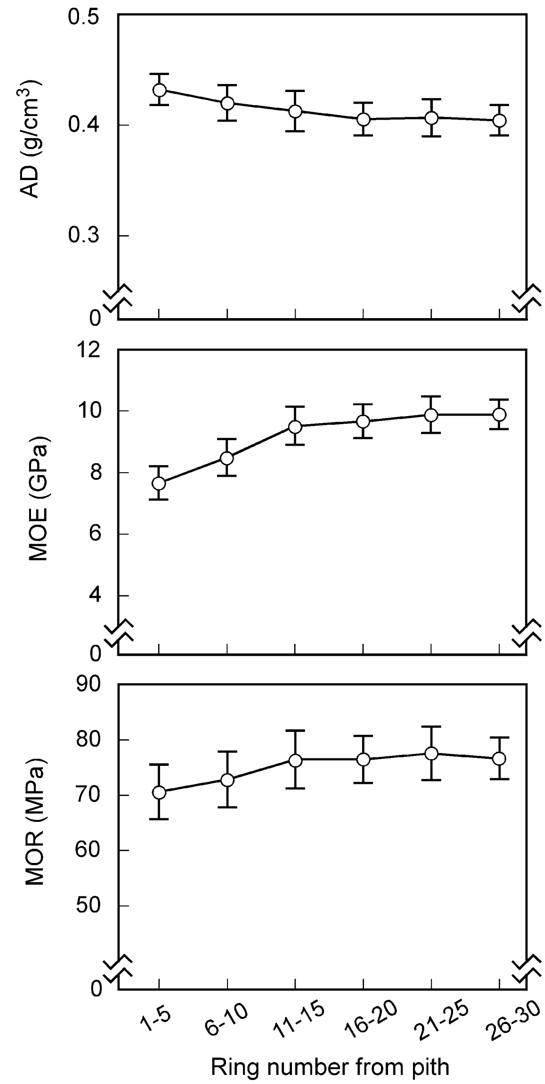

Fig. 4 Radial variations of air-dry density (AD), modulus of elasticity (MOE), and modulus of rupture (MOR) in mean values of 10 families. *Circle* and *bars* refer to Fig. 3

Zeeuw [17], radial variation patterns of wood density could be classified into two types for *P. abies* and *P. sitchensis*: wood density increases from pith to bark (Type I); wood density decreases outward from the pith, and then increases to the bark (Type II). Koubaa et al. [18] reported that radial variation patterns of wood density in *P. mariana* reflected Type II. In the present study, AD did not increase from pith to bark in mean values of 10 families (Fig. 4). Therefore, the radial variation pattern of *P. jezoensis* may differ from *P. abies*, *P. mariana*, and *P. sitchensis* reported by other researchers [17, 18]; the wood of *P. jezoensis* after the 20th annual ring from the pith may show relatively uniform wood density compared with other *Picea* species i.e., *P. abies*, *P. mariana*, and *P. sitchensis* [17, 18].

MOE gradually increased up to the 10th or 15th annual ring from the pith, and thereafter the mean value for individual trees remained almost constant at 10 GPa in mean values of 10 families (Fig. 4). This tendency was also true for MOE mean value in each family (Table 4). These results indicate that no remarkable differences were found in radial variation patterns of MOE among the 10 families. In *Picea* species, mechanical properties, such as MOE and MOR, in juvenile wood show lower values than those in mature wood [19, 20]. Alteyrac et al. [19] reported that, in 80-year-old *P. mariana*, MOE increased up to the 25th annual ring from the pith and then remained fairly constant. In addition, MOE rapidly increased from the 10th to 15th annual ring from the pith in 42- and 72-year-old *P. glauca* grown in Canada [20]. Therefore, it can be said that radial variation patterns of *P. jezoensis* were almost similar to those in *P. glauca* and *P. mariana*, whereas annual ring number, in which MOE showed a near constancy in the present study, differed in *P. mariana*.

Table 4 Radial variation of modulus of elasticity (GPa) in each family

Family	Ring number from pith					
	1–5	6–10	11–15	16–20	21–25	26–30
Akan 101	7.17[a]	8.36[ab]	9.12[b]	9.54[b]	9.60[b]	9.67[b]
Ikutora 102	8.39[a]	9.69[b]	10.43[b]	10.47[b]	10.68[b]	10.22[b]
Ikutora 103	7.79[a]	8.65[ab]	9.75[b]	9.61[b]	9.99[b]	9.93[b]
Asyoro 101	6.95[a]	7.69[a]	8.47[ab]	8.84[b]	8.81[b]	9.06[b]
Asyoro 102	8.44[a]	9.22[ab]	10.40[b]	10.58[b]	10.62[b]	10.55[b]
Asyoro 103	7.18[a]	7.86[a]	9.55[b]	9.84[b]	10.02[b]	10.41[ab]
Asyoro 104	7.69[a]	8.17[ab]	9.47[c]	9.57[bc]	10.29[bc]	9.73[bc]
Honbetsu 104	7.55[a]	8.33[ab]	9.38[c]	9.02[bc]	9.21[bc]	9.35[bc]
Honbetsu 106	8.22[a]	8.60[ab]	9.75[c]	9.45[bc]	9.56[bc]	9.67[bc]
Honbetsu 110	7.25[a]	8.36[ab]	8.89[bc]	9.75[c]	10.06[c]	10.33[c]

Alphabet letters followed by mean values, refer to Table 2

Table 5 Radial variation of modulus of rupture (MPa) in each family

Family	Ring number from pith					
	1–5	6–10	11–15	16–20	21–25	26–30
Akan 101	65.2[a]	69.1[a]	72.3[a]	75.3[a]	73.7[a]	76.3[a]
Ikutora 102	76.1[a]	81.9[ab]	84.2[b]	82.2[ab]	82.9[ab]	80.1[ab]
Ikutora 103	71.2[a]	73.9[a]	78.7[a]	75.7[a]	78.7[a]	77.1[a]
Asyoro 101	64.8[a]	67.7[a]	69.2[a]	71.2[a]	71.7[a]	73.3[a]
Asyoro 102	76.7[a]	80.9[a]	84.3[a]	84.2[a]	84.4[a]	82.3[ab]
Asyoro 103	66.7[a]	69.5[ab]	76.5[ab]	76.1[ab]	80.2[b]	79.2[b]
Asyoro 104	70.0[a]	71.9[a]	75.9[a]	78.7[a]	81.9[a]	72.8[a]
Honbetsu 104	69.2[a]	71.0[a]	74.2[a]	70.8[a]	70.4[a]	69.8[a]
Honbetsu 106	78.5[a]	74.6[a]	78.9[a]	75.5[a]	76.3[a]	78.5[a]
Honbetsu 110	68.0[a]	68.4[a]	70.5[a]	74.9[a]	75.4[a]	77.1[a]

Alphabet letters followed by mean values, refer to Table 2

In 80-year-old *P. mariana*, MOR increased up to the 25th annual ring from the pith, and then stabilized toward the bark [19]. In another study, Akutsu [21] reported that MOR in 43-year-old *P. glehnii* showed an almost constant value from pith to bark, although MOE increased then stabilized toward the bark. These results established the existence of two radial variation patterns of MOR for *Picea* species. In the present study, MOR mean value in 10 families gradually increased from the 5th annual ring toward the bark (Fig. 4). However, radial variation patterns of MOR differed among the 10 families. MOR ratios at the 21st–25th annual ring to the 1st–5th annual ring ranged from 1.0 to 1.2 in each family (Table 5). These results indicate that two radial variation patterns of MOR existed in *P. jezoensis*: MOR gradually increased up to the 15th annual ring from the pith and then became constant (Ikutora 102 and Asyoro 103); MOR radial variation showed an almost constant value from the pith to the 30th annual ring from the pith (Akan 101, Ikutora 103, Asyoro 101, Asyoro 102, Asyoro 104, Honbetsu 104, Honbetsu 106, and Honbetsu 110). Therefore, radial variation patterns of MOR in *P. jezoensis* appear to differ among families. The families showing smaller radial variations in MOR may be favorable for improving juvenile wood properties in tree breeding for *P. jezoensis*.

Among-family variations

ANOVA showed significant differences among families in all wood properties tested here (Table 1). The *F* values observed in wood properties exceeded those in growth traits (Table 1), indicating that wood properties are more genetically controlled compared with growth traits in *P. jezoensis*. In *Picea glauca*, Lenz et al. [10] reported that wood properties are genetically controlled, whereas the influence of genetic factor on growth traits is low. This tendency was also true in *P. abies* [6, 8, 9]. Based on results of the present study, it is concluded that wood properties, including wood density and mechanical properties, can be improved by tree breeding programs in *P. jezoensis*.

Table 6 shows the results of ANOVA for every five annual rings from the pith to the 30th annual ring. In ARW, significant differences among families were found from the 1st to 15th annual ring and also in other wood properties in the 1st–25th annual ring from the pith. *F* value in ARW dramatically decreased with an increase in ring number from the pith and then became <2 (no significant difference) after the 16th–20th annual ring. Although the *F* values in other wood properties decreased as annual ring number increased from the pith, *F* value from the 1st to 25th annual ring showed significant difference of at least 5 % level. A relatively smaller *F* value in the 26th–30th annual ring from the pith may be due to a lower number of samples; from 174 trees, 56 could not be measured. As *F* value is a ratio of variance within families to among families, when several families were planted under the same environmental conditions, the higher *F* values reflected different properties among families, as well as contributions of genetic factors. Radial trends demonstrating the degree of contribution of genetic factors on wood properties have been reported by several researchers [6, 8, 9, 22]. Kumar et al. [22] reported decreasing variations among families of MOE with increasing annual ring numbers in *Pinus radiata*. In contrast, Lenz et al. [10] reported that MOE heritability estimates were almost constant from pith to bark in half-sib families of *P. glauca*. In the present study, significant differences of wood properties among families were observed in all examined radial positions, except for the 26th–30th annual ring from the pith, suggesting that genetic factors affect

Table 6 *F*-values along each radial position for wood properties

Ring number from pith	ARW	AD	MOE	MOR
1–5	7.580**	3.791**	2.957**	4.554**
6–10	3.610**	4.518**	4.229**	5.784**
11–15	2.852**	4.533**	4.434**	4.425**
16–20	1.880ns	3.225**	4.039**	3.406**
21–25	1.351ns	3.263**	3.402**	3.205**
26–30	1.839ns	1.872ns	1.899ns	1.714ns

For abbreviations refer to Table 1

wood properties in both juvenile and mature woods. Therefore, it appears that wood properties in these species can be genetically improved in both juvenile and mature woods. To evaluate the age that demonstrates the highest differences in wood properties among families, *F* values were compared for five annual ring positions. Relatively higher *F* values of AD and MOE were recognized at the 11th–15th annual ring. Although the highest MOR *F* value was observed at the 6th–10th annual ring from the pith, the MOR *F* value at the 11th–15th annual ring from the pith demonstrated higher *F* values of AD and MOE. Therefore, the greatest among-family variation of wood properties could be observed at the 11th–15th annual ring from the pith, suggesting that selecting the family with the most promising wood properties is most effective at the tree age of 15.

Age–age correlations

In a tree breeding program, evaluating mean values from pith to bark by the values of each radial position is important for deciding the desirable sampling age for testing the genotype for early selection. In the present study, the correlation coefficient for wood properties was calculated using mean values from pith to the 30th annual ring from the pith and at every five annual rings (Table 7). Significant correlation coefficients were found in all wood properties, except for ARW at the 1st–5th annual ring from the pith. For evaluating the merits of early selection in 31-year-old *P. glehnii* clones, Iizuka et al. [7] examined the relationships between core wood (up to the 15th annual ring from the pith) and outer wood (after the 15th annual ring toward the bark). They reported that significant phenotypic correlation coefficients were found between core and outer woods in basic density and ring width, suggesting that selection for these traits before the 15th annual ring from the pith is possible. In the present study, the highest correlation coefficients were obtained at the 11th–15th annual ring from the pith in all traits investigated (Table 7). In addition, relatively higher *F* values of wood properties were recognized at the 11th–15th annual ring from the pith (Table 6). Therefore, mean values of wood properties from

Table 7 Correlation coefficient for age trend between mean values and their radial positions in each property

Ring number from pith	ARW	AD	MOE	MOR
1–5	0.508ns	0.823**	0.860**	0.813**
6–10	0.803**	0.855**	0.854**	0.914**
11–15	0.922**	0.976**	0.946**	0.955**
16–20	0.891**	0.929**	0.943**	0.937**
21–25	0.811**	0.918**	0.905**	0.921**
26–30	0.757**	0.796**	0.769**	0.739*

For abbreviations refer to Table 1

pith to bark can be evaluated at the 15th annual ring from the pith, indicating that early selection around the 15th annual ring is also possible for *P. jezoensis*. These results are in agreement with those of previous studies of other *Picea* species [7–9].

Conclusions

This study examined wood properties of plantation-grown trees and among-family variations of wood properties in 10 open-pollinated families of *P. jezoensis* grown at a progeny test site in Hokkaido, Japan. Wood property values, including $DMOE_{log}$, MOE, and MOR were in the range of those reported in *P. jezoensis* from natural forests or other *Picea* species. Higher *F* values in wood properties than those in growth traits indicate that the genetic contribution to wood properties may be greater than those to growth traits. In addition, significant differences among families were found from the 1st–25th annual ring from the pith in AD, MOE, and MOR, although as annual ring numbers increased *F* values decreased. These results suggested that genetic factors play a larger role from pith to bark for these properties. Phenotypic correlation coefficients between the 11th–15th annual ring from pith and tree mean value were >0.9. In addition, the highest *F* values in AD and MOE were recognized at the 11th–15th annual ring from pith. These results indicated that selection at this age may be ideal for these properties. In conclusion, this study demonstrated that wood properties of *P. jezoensis* could be improved by tree breeding programs that emphasize on wood quality.

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