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# Comprehensive assessment of growth traits and wood properties in half-sib *Pinus koraiensis* families

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**Abstract** Rapid growth and high quality have always been important goals pursued for timber forests. Therefore, growth traits and wood properties are the basis of superior materials to select and breed new cultivars. In this study, 42 half-sib families of 31-year-old *P. koraiensis* trees were used as materials. Nine growth traits (tree height, diameter at breast height, volume, basal diameter, average annual growth of the tree height, under branch height, stem straightness degree, form quotient, and branching angle) and eight wood properties (cellulose contents, hemicellulose contents, holocellulose contents, lignin contents, ash contents, wood density, fiber length and fiber width) were measured and analyzed. The results of an analysis of variance showed that there were extremely significant differences among the families in their growth and wood properties with the exception of the form quotient and wood density; that there were significant differences among block by family for growth traits except for the tree height, basal diameter, under branch height and branching angle; and that there was no significant difference for each growth trait among the blocks. The phenotypic coefficient of variation and heritability of the growth traits ranged from 7.17 to 42.35% and from 0.13 to 0.62, respectively. The phenotypic coefficient of variation and heritability of the wood properties ranged from 10.21 to 50.26% and from 0.67 to 0.92, respectively. There were extremely significantly positive correlations between the tree height, basal diameter, diameter at breast height, volume, under branch height, average annual growth of tree height and form quotient. However, there was no significant correlation between growth traits and wood properties. The result of the principal component analysis indicated that the tree height, diameter at breast height, volume, basal diameter, and cellulose contents, holocellulose contents, and lignin contents could be selected as comprehensive evaluation indices of growth and wood properties, respectively. According to a comprehensive evaluation, when the selection rate was 10%, four families (PK 40, PK 80, PK 42, and PK 71) were selected as elite families based on growth performance; another four families (PK 70, PK 62, PK 52, and PK 44) were selected as elite families based on their wood quality; and finally, four elite families (PK 70, PK 62, PK 61, and PK 40) were selected due to a combination of growth traits and wood properties. This study will provide a theoretical basis for the genetic improvement of fast-growing and high-quality *P. koraiensis* families.

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## Introduction

*Pinus koraiensis* Sieb. et Zucc. occurs naturally in a reduced space at the intersection of the northeastern part of China, the northern region of North Korea, the central region of Japan and the southern part of the far-east of Russia (Xu and Yan 2001) and is considered to be the second nationally protected timber species in China (Feng et al. 2009). The natural distribution area of *P. koraiensis* has decreased dramatically due to the overexploitation of forests (Tang et al. 2010). Thus, recommendations for *P. koraiensis* plantations were adopted to restore broadleaf conifer forests in northeast China to maintain its ecological and economic significance (Zhang et al. 2014). However, large amounts of superior materials with high genetic properties are still desired for successful afforestation. For this purpose, several seed orchards of *P. koraiensis* were established in the 1960s in northeastern China (Wang et al. 2000). So far, these seed orchards have blossomed and produced seeds; a large number of half-sib and full-sib progeny assay forests have been established, and some elite families have been selected (Feng et al. 2010).

Rapid growth and high quality have always been important goals pursued in timber forests. Therefore, growth traits and wood properties are the basis of superior materials used for selection and breeding (Wu and Luo 2000). Previous studies have shown that there was a significant negative correlation between the growth traits and wood properties, so it was necessary to select growth traits and wood properties, respectively, during the process of evaluation and selection (Yin et al. 2017). However, some other studies have shown that there was no significant correlation between growth traits and wood properties, which provided some basis for combination selection (Mo et al. 2011).

Several comprehensive evaluation methods were reported with different advantages and disadvantages (Luo et al. 2010). Multiple-trait comprehensive evaluation is an important method to select improved varieties, and it is considered to be an improvement strategy that can accelerate the selection process of the trees planted (Duan et al. 2017). The method can combine the advantages of multiple traits and was more stable, and the selected materials exhibit a genetic gain for different indicators. Multiple-trait selection for growth and wood property traits will lead to more productive populations (Hung et al. 2015).

According to previous studies on *Larix olgensis* and other conifers, the characteristics of tree height, the diameter at breast height, and the stem straightness degree, had a direct effect on volume, and the wood properties, including lignin contents, cellulose contents, fiber length and fiber width, had a direct effect on the wood quality (Yin et al. 2017). In the studies on *P. koraiensis,* the tree height, diameter at breast height, straightness degree and volume have already been used to evaluate and select excellent families and clones (Wang et al. 2016; Liang et al. 2018).

Since *P. koraiensis* is an important timber tree species (Li and Löfgren 2000), it is very important to explore the relationship between its growth traits and wood properties, and the comprehensive evaluation of growth traits and wood properties is more important (Liang et al. 2016). However, there have been no related studies to date. Therefore, this study used 42 half-sib families of *P. koraiensis* from the Sanchazi Seed Orchard in the Jilin Province as materials, and nine growth traits and eight wood properties were measured and analyzed. The purposes of this study were to (1) investigate the genetic variation of each trait among different families; (2) explore the relationship between the growth traits and wood properties; (3) select optimum evaluation indices of growth traits and wood properties according to the analysis of principle components, and (4) select elite families according to their growth traits and wood properties, which could provide a theoretical basis for the genetic improvement of fast-growing and high-quality *P. koraiensis*.

## Materials and methods

### Experimental site

The experiment was conducted at the Sanchazi Seed Orchard located at Baishan City in Jilin Province (E126°45′, N42°36′). The area belongs to the temperate continental monsoon climate zone. The mean annual precipitation and temperature are 725.5 mm and 2.5 °C, respectively. The average temperature in January was − 19.1 °C, and the extreme temperature reached − 42.2 °C. The average frost-free period was 110 days.

## Materials

There were 42 half-sib families from the Sanchazi Seed Orchard (family PK 1, PK 2, PK 3, PK 39, PK 40, PK 41, PK 42, PK 43, PK 44, PK 45, PK 46, PK 47, PK 48, PK 49, PK 50, PK 51, PK 52, PK 53, PK 54, PK 55, PK 57, PK 58, PK 59, PK 60, PK 61, PK 62, PK 64, PK 66, PK 67, PK 68, PK 69, PK 70, PK 71, PK 72, PK 73, PK 74, PK 75, PK 76, PK 78, PK 79, PK 80, and PK 81) that were used as materials. The 42 female parents were selected by growth traits from the natural distribution area of *P. koraiensis* in Sanchazi forestry bureau, Jilin Province. The families were used to field design that consisted 5 blocks. Four-year-old seedlings of each family were planted using a randomized complete block design in row plots containing 6 trees at a spacing of 3.0 × 4.0 m in the spring of 1990.

## Methods

### Growth trait measurements

Growth traits were measured in October 2017. The tree height (H), diameter at breast height (DBH), basal diameter (BD), average annual growth of tree height (AAGH), under branch height (UBH), stem straightness degree (SSD), form quotient (FQ), and branching angle (BA) were measured for each living tree. The H and UBH were measured using a sliding staff. The DBH and BD were measured using a diameter tape. The SSD was estimated as described by Zhao et al. (2014) in which the SSD values weresquared before an analysis of variance (ANOVA) (Table 1). The BA was measured using a protractor. The AAGH was the average distance between the first wheel branch and the sixth wheel branch. The FQ was the ratio of the diameter at 3 m height to DBH.

The volume was calculated as the method of Zhang et al. (2016):

$$V = (H + 3)g_{1.3}f, \tag{1}$$

where $f$ is the experimental form factor, $f = 0.33$; $g_{1.3} = \left(\pi(\mathrm{DBH})^2\right)/4$.

### Wood properties measurements

Wood properties were also measured in October 2017. Fifteen wood cores of each family (three trees per block and one wood core per tree) were collected from south to north at 1.3 m height, wrapped in paper tubes, and taken to the laboratory for analysis. The cellulose contents (CC), hemicellulose contents (HEC), holocellulose contents (HOC), lignin contents (LC), ash contents (AC), wood density (WD), fiber length (FL) and fiber width (FW) were determined. The heartwood of five wood cores (one wood core per block) of each family were used to measure the FL and FW using a stereomicroscope (SZX7; OLYMPUS Corporation, Japan) observing the materials treated by nitric acid and chromic acid (Mu et al. 2009), and each wood core could provide six FLs and six FWs. Five wood cores (one wood core per block) of each family were used to measure the WD according to drainage method as described by Cheng (1985), and each wood core was measured three times. The other wood cores were mixed using mechanical trituration to measure the CC, HEC, HOC, LC and AC using a fully automatic fiber analyzer (A2000i; ANKOM Technology, Macedon, NY, USA), according to the national standard GB/T 2677.1 93 with 15 repetitions.

**Table 1** Investigation criteria and scores of the stem straightness degree

| | Scores | | | | |
|---|---|---|---|---|---|
| Trait | 1 | 2 | 3 | 4 | 5 |
| SSD | More than two obviously bent points in the stem | More than two slightly bent points or one obviously bent point in the stem | Two slightly bent points in the stem | One slightly bent point in the stem | Straight completely in the stem |

### Statistical analysis

All the data were analyzed using Statistical Product and Service Solution (SPSS) version 19.0 (IBM Corp., Armonk, NY, USA) (Shi 2012). The significance of the fixed effects was tested using an ANOVA $F$ test. The following linear model was used for the joint analysis of families and blocks of growth traits (Shu et al. 2016):

$$X_{ijk} = \mu + \alpha_i + b_j + \alpha b_{ij} + e_{ijk} \tag{2}$$

where $X_{ijk}$ is the performance of an individual tree $k$ in family $i$ growing in block $j$; $\mu$ is the overall mean; $\alpha_i$ is the effect of family $i$; $b_j$ is the effect of block $j$; $\alpha b_{ij}$ is the interactive effect of family $i$ and block $j$, and $e_{ijk}$ is the random error.

The following linear model was used to analyze the families of wood traits:

$$X_{ij} = \mu + \alpha_i + e_{ij} \tag{3}$$

where $X_{ij}$ is the performance of an individual tree $j$ in family $i$; $\mu$ is the overall mean; $\alpha_i$ is the effect of family $i$, and $e_{ij}$ is the random error.

The coefficient of phenotypic variation (PCV) was calculated using the formula (Hai et al. 2008):

$$PCVPCV = \mathrm{SD}/\bar{X} \times 100\% \tag{4}$$

where $\bar{X}$ and $SD$ are the phenotypic mean and standard deviation of the trait, respectively.

Heritability ($h^2$) of the growth traits and wood properties was calculated as described by Shu et al. (2016) using the following Eqs. (5) and (6):

$$h^2 \text{ of growth traits} \quad h^2 = \sigma_f^2 / \left( \sigma_e^2/BR + \sigma_{fb}^2/R + \sigma_f^2 \right) \tag{5}$$

$$h^2 \text{of wood properties} \quad h^2 = \sigma_f^2 / \left( \sigma_e^2/N + \sigma_f^2 \right) \tag{6}$$

where $\sigma_f^2$, $\sigma_{fb}^2$ and $\sigma_e^2$ represent the variance components of family, family by block interaction and residual error, respectively. B, R and N represent the number of blocks, the number of plots and the number of values per family, respectively.

The phenotypic correlation between trait $x$ and $y$ was calculated as described by Bi et al. (2000):

$$r_{p12} = \frac{Cov_{p12}}{\sqrt{\sigma_{p1}^2 \cdot \sigma_{p2}^2}}, \tag{7}$$

where $Cov_{p12}$ is the covariance between trait $x$ and $y$, and $\sigma_{p1}^2$ and $\sigma_{p2}^2$ are the variance components for traits $x$ and $y$, respectively.

Principal component analysis was calculated as described by Gonzálezmartínez et al. (2007).

Comprehensive evaluations of different families were calculated as described by Zhao et al. (2016):

$$Q_i = \sqrt{\sum_{j=1}^{n} a_i} \tag{8}$$

where $a_i = X_{ij}/X_{jmax}$; the $Qi$ value is a comprehensive evaluation value for each family; $X_{ij}$ is the average value of one trait; $X_{jmax}$ is the maximum value of the trait; and $n$ is the number of traits, and the genetic gain was estimated using the formula of Francisco et al. (2008):

$$\Delta G = Wh^2/\bar{X}, \tag{9}$$

where $W$ is the selection difference, and $\bar{X}$ and $h^2$ are the mean value and heritability of a given trait, respectively.

## Results

### ANOVA

The ANOVA results of the growth traits for the *P. koraiensis* families are shown in Table 2. All the variance sources showed extremely significant differences among the families, except for trait FQ, and significant differences among block by family, except for traits H, BD, UBH and BA. There was no significant difference for all the sources among the blocks. The ANOVA results of the wood properties for *P. koraiensis* are shown in Table 3. All the variance sources showed extremely significant differences among the families except trait WD.

### Variation parameters of different traits

The average, amplitude and variation parameters of growth traits and wood properties are shown in Table 4. The average H of all the families was 12.90 m, and the maximum value was 1.18-fold of the minimum value. The average BD and DBH were 23.71 and 18.75 cm, respectively, and both the

**Table 2** ANOVA of growth traits for *P. koraiensis*

| Traits | Sources | SS | df | F |
|---|---|---|---|---|
| H | Block | 25.79 | 4 | $2.332^{NS}$ |
| | Family | 235.72 | 41 | 2.079*** |
| | Block × family | 481.88 | 164 | $1.063^{NS}$ |
| DBH | Block | 69.2 | 4 | $1.416^{NS}$ |
| | Family | 1284.2 | 41 | 2.564*** |
| | Block × family | 2531.4 | 164 | 1.264* |
| BD | Block | 99.2 | 4 | $1.317^{NS}$ |
| | Family | 1776.5 | 41 | 2.302*** |
| | Block × family | 3590.8 | 164 | $1.163^{NS}$ |
| V | Block | 0.0246 | 4 | $1.596^{NS}$ |
| | Family | 0.415 | 41 | 2.632*** |
| | Block × family | 0.7694 | 164 | 1.220* |
| AAGH | Block | 0.00799 | 4 | $0.937^{NS}$ |
| | Family | 0.20509 | 41 | 2.348*** |
| | Block × family | 0.42685 | 164 | 1.222* |
| UBH | Block | 0.1754 | 4 | $1.897^{NS}$ |
| | Family | 1.7526 | 41 | 1.849** |
| | Block × family | 4.5827 | 164 | $1.209^{NS}$ |
| SSD | Block | 5.89 | 4 | $1.559^{NS}$ |
| | Family | 74.16 | 41 | 1.915*** |
| | Block × family | 208.3 | 164 | 1.345** |
| FQ | Block | 0.01148 | 4 | $0.853^{NS}$ |
| | Family | 0.15855 | 41 | $1.149^{NS}$ |
| | Block × family | 0.70594 | 164 | 1.280* |
| BA | Block | 584 | 4 | $0.570^{NS}$ |
| | Family | 19,701 | 41 | 1.878*** |
| | Block × family | 43,752 | 164 | $1.043^{NS}$ |

*Df*, *MS* and *F* were degrees of freedom, mean square and *F* value in the *F* test, respectively. This description also applies to the following table

***Represent extremely significant differences, **represent strongly significant differences, *represent significant differences, and NS represents no significant difference, respectively

**Table 3** ANOVA of the wood properties for *P. koraiensis*

| Traits | Sources | SS | df | F |
|---|---|---|---|---|
| CC | Family | 2100.4 | 41 | 7.327*** |
| HEC | Family | 495.1 | 41 | 6.427*** |
| HOC | Family | 2495.3 | 41 | 5.667*** |
| LC | Family | 2561.1 | 41 | 3.204*** |
| WD | Family | 432,260 | 41 | $10{,}053^{NS}$ |
| AC | Family | 19.729 | 41 | 2.9983*** |
| FL | Family | 1.70E + 07 | 41 | 8.579*** |
| FW | Family | 9655 | 41 | 6.267*** |

maximum values were approximately 1.23-fold greater than the minimum values. The amplitude of V was the largest; its average was 0.15 $m^3$, and the maximum value was greater than approximately 100% of the minimum value. FQ, SSD and BA revealed the tree shape, and their averages were 0.83, 4.06 and 151.88°, respectively. The PCVs of the growth traits ranged from 7.17 to 42.35%, and the growth trait with the highest PCV was the V (42.35%), followed by the SSD (24.99%), DBH (19.59%), BD (18.99%) and H (13.25%). The PCVs of the UBH (10.17%), AAGH (10.12%) and BA (10.74%) were similar, and the growth trait with the lowest PCV was the FQ (7.17%). The $h^2$ of the FQ (0.13) was minimal, and the other growth traits ranged from 0.46 to 0.62, which showed a high degree of repeatability. For the wood properties, the average of the HEC, CC, HOC, LC and AC were 12.46, 38.61, 51.07, 25.10 and 1.03%, respectively, which indicated that the HOC comprised the largest proportion in wood chemical composition. The family with the largest AC was 5.2-fold compared to that with the lowest AC, which showed the largest times. The next largest was the LC at 3.7-fold. The average of the WD was 480.65 $kg/m^3$, and the maximum and minimum values were 631.97 $kg/m^3$ and 389.21 $kg/m^3$, respectively. The average of the FL and FW were 1967.63 μm and 37.71 μm, respectively. The wood property with the largest PCV was the AC (50.26%), followed by the WD (24.24%), and the PCVs of the other wood properties ranged from 10.21% to 23.11%. The $h^2$ of all the wood properties ranged from 0.67 (AC) to 0.92 (WD). The result showed a high phenotypic variation coefficient and a high heritability.

## Correlation analysis

The correlation coefficients between each trait are shown in Table 5. There was an extremely significant positive correlation between the H, BD, DBH, V, UBH, AAGH and FQ, and the largest correlation coefficient was 0.977, which was found between the V and DBH, followed by 0.937 (between the BD and DBH), 0.916 (between the V and BD), 0.651(between

**Table 4** Genetic and variation parameters of growth traits and wood properties

| Traits | Mean | Max | Min | SD | PCV | $h^2$ |
|---|---|---|---|---|---|---|
| H | 12.90 | 13.76 | 11.57 | 1.710 | 13.25 | 0.52 |
| BD | 23.71 | 26.26 | 21.33 | 4.503 | 18.99 | 0.57 |
| DBH | 18.75 | 20.99 | 16.77 | 3.672 | 19.59 | 0.61 |
| V | 0.15 | 0.20 | 0.11 | 0.065 | 42.35 | 0.62 |
| UBH | 1.55 | 1.66 | 1.45 | 0.157 | 10.17 | 0.46 |
| AAGH | 0.48 | 0.52 | 0.45 | 0.048 | 10.12 | 0.57 |
| FQ | 0.83 | 0.85 | 0.80 | 0.059 | 7.17 | 0.13 |
| SSD | 4.06 | 4.56 | 3.52 | 1.015 | 24.99 | 0.48 |
| BA | 151.88 | 160.40 | 139.44 | 16.306 | 10.74 | 0.47 |
| HEC | 12.46 | 18.67 | 9.05 | 2.29 | 18.35 | 0.84 |
| CC | 38.61 | 46.43 | 28.75 | 4.64 | 12.01 | 0.86 |
| HOC | 51.07 | 60.20 | 40.57 | 5.21 | 10.21 | 0.82 |
| LC | 25.10 | 38.71 | 10.41 | 5.80 | 23.11 | 0.69 |
| AC | 1.03 | 2.14 | 0.411 | 0.52 | 50.26 | 0.67 |
| WD | 480.65 | 631.97 | 389.21 | 115.81 | 24.24 | 0.92 |
| FL | 1967.63 | 2498.14 | 1573.40 | 293.73 | 14.93 | 0.88 |
| FW | 37.71 | 50.39 | 29.87 | 7.71 | 20.44 | 0.84 |

The unit of each trait: H (m), BD (cm), DBH (cm), V ($m^3$), UBH (m), AAGH (m), BA (°), HEC (%), CC (%), HOC (%), LC (%), AC (%), WD ($kg/m^3$), FL (μm), FW (μm), PCV(%). This description also applies to the following table

the V and H), 0.596 (between the H and DBH) and 0.567 (between the H and BD). The correlation between the SSD and the FQ was extremely significantly positive, and the value was 0.182. The BA indirectly reflected the ability of the trees to photosynthesize. An extremely positive correlation was found between the BA and H (0.098), BD (0.181), DBH (0.161), V (0.123), FQ (0.122) and SSD (0.078). For the wood properties, the LC had an extremely significant negative correlative with the CC (− 0.364), HEC (− 0.705) and HOC (− 0.876), respectively. A similar pattern was observed between the HEC and CC (− 0.206), and the HOC had an extremely significant positive correlation with the CC (0.451) and HEC (0.779), respectively. In addition, the correlation analysis revealed an significant positive correlation between the FL and FW (0.123). The WD was not related to any one trait. There was no significant correlation between the growth traits and wood properties.

## Principle components analysis

The results of principle components analysis (PCA) are shown in Tables 6 and 7. Seven principal components with the eigenvalues greater than 1 or approximately equal to 1 were retained, and the cumulative contribution rate of the selected seven principle components was 76.30%. The first, second and third principle component explained 21.89, 16.84 and 8.46% of the total variation, respectively. In the first principle component (PCI), the absolute values of the H, DB, DBH and V were higher, and all four values were positive, which indicated that PCI primarily represented the growth characters (Table 7). In the second principle component (PCII), the absolute values of the CC, HOC and LC were higher, and it was notable that the value of the LC was negative, which indicated that PCII primarily represented the wood chemical composition, and when the HOC and LC increased, the LC decreased. In the third principle component (PCIII), the absolute values of the FQ and SSD were higher, and the values were all positive, indicating that PCIII primarily represented the tree shape.

## Comprehensive evaluation and genetic gain

The correlation analysis showed that there was no obvious correlation between the growth traits and wood properties, so the comprehensive evaluation of growth traits, wood properties and combining growth traits with wood properties were conducted separately. The result of the PCA showed that the H, BD, DBH, and V and the CC, HOC, and LC could be selected as comprehensive evaluation indices of growth and wood

**Table 5** Correlation coefficients between traits

| Traits | H | BD | DBH | V | UBH | AAGH | FQ | SSD | BA | CC | HEC | HOC | LC | AC | FL | FW | WD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | 1.000 | | | | | | | | | | | | | | | | |
| BD | 0.567** | 1.000 | | | | | | | | | | | | | | | |
| DBH | 0.596** | 0.937** | 1.000 | | | | | | | | | | | | | | |
| V | 0.651** | 0.916** | 0.977** | 1.000 | | | | | | | | | | | | | |
| UBH | 0.176** | 0.111** | 0.149** | 0.120** | 1.000 | | | | | | | | | | | | |
| AAGH | 0.283** | 0.236** | 0.267** | 0.252** | 0.260** | 1.000 | | | | | | | | | | | |
| FQ | 0.260** | 0.266** | 0.258** | 0.240** | 0.195** | 0.245** | 1.000 | | | | | | | | | | |
| SSD | 0.056 | – 0.152** | – 0.162** | – 0.142** | 0.012 | 0.047 | 0.182** | 1.000 | | | | | | | | | |
| BA | 0.098** | 0.181** | 0.161** | 0.123** | 0.019 | 0.040 | 0.122** | 0.078* | 1.000 | | | | | | | | |
| CC | – 0.047 | – 0.096 | – 0.054 | – 0.057 | – 0.069 | 0.014 | 0.013 | 0.024 | 0.035 | 1.000 | | | | | | | |
| HEC | – 0.077 | 0.052 | – 0.017 | – 0.029 | – 0.072 | 0.099 | 0.076 | 0.047 | 0.031 | – 0.206* | 1.000 | | | | | | |
| HOC | – 0.101 | – 0.017 | – 0.052 | – 0.064 | – 0.111 | 0.098 | 0.076 | 0.063 | 0.048 | 0.451** | 0.779** | 1.000 | | | | | |
| LC | 0.123 | 0.035 | 0.059 | 0.077 | 0.115 | – 0.020 | – 0.016 | 0.052 | – 0.043 | – 0.364** | – 0.705** | – 0.876** | 1.000 | | | | |
| AC | – 0.064 | 0.118 | 0.096 | 0.077 | – 0.105 | – 0.015 | – 0.070 | – 0.032 | – 0.017 | – 0.135 | 0.255** | 0.142 | – 0.168 | 1.000 | | | |
| FL | – 0.009 | – 0.051 | – 0.084 | – 0.082 | – 0.016 | 0.047 | – 0.031 | 0.023 | – 0.032 | – 0.063 | – 0.003 | – 0.044 | 0.097 | 0.122 | 1.000 | | |
| FW | 0.047 | 0.064 | 0.072 | 0.075 | 0.071 | – 0.001 | – 0.108* | 0.062 | 0.001 | 0.001 | 0.015 | 0.017 | 0.010 | – 0.077 | 0.123* | 1.000 | |
| WD | 0.007 | – 0.163 | – 0.156 | – 0.145 | – 0.046 | 0.030 | – 0.167 | – 0.002 | – 0.030 | 0.158 | – 0.149 | – 0.037 | 0.065 | – 0.085 | 0.079 | 0.032 | 1.000 |

*H*, *BD* and *DBH* were tree height, basal diameter and diameter at breast height, respectively

**Indicated extremely significant correlation at the 0.01 level (2-tailed), *indicated significant correlation at 0.05 level (2-tailed)

**Table 6** Results of the principle components statistics

| Component | Initial eigenvalues | | | Rotate the sum of squares and load | | |
|---|---|---|---|---|---|---|
| | Total | Variance% | Accumulate% | Total | Variance% | Accumulate% |
| 1 | 4.11 | 24.19 | 24.19 | 3.72 | 21.89 | 21.89 |
| 2 | 2.64 | 15.52 | 39.70 | 2.86 | 16.84 | 38.73 |
| 3 | 1.61 | 9.50 | 49.20 | 1.44 | 8.46 | 47.19 |
| 4 | 1.39 | 8.15 | 57.35 | 1.42 | 8.38 | 55.56 |
| 5 | 1.16 | 6.79 | 64.14 | 1.38 | 8.09 | 63.65 |
| 6 | 1.11 | 6.51 | 70.65 | 1.12 | 6.57 | 70.22 |
| 7 | 0.96 | 5.65 | 76.30 | 1.03 | 6.08 | 76.30 |
| 8 | 0.83 | 4.90 | 81.20 | | | |
| 9 | 0.81 | 4.77 | 85.96 | | | |
| 10 | 0.69 | 4.03 | 89.99 | | | |
| 11 | 0.60 | 3.55 | 93.55 | | | |
| 12 | 0.51 | 2.98 | 96.52 | | | |
| 13 | 0.38 | 2.26 | 98.78 | | | |
| 14 | 0.15 | 0.88 | 99.66 | | | |
| 15 | 0.05 | 0.29 | 99.95 | | | |
| 16 | 0.01 | 0.05 | 99.999 | | | |
| 17 | 0.001 | 0.001 | 100.000 | | | |

**Table 7** Factor load matrix

| Traits | Component | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| H | 0.809 | 0.032 | 0.198 | 0.071 | − 0.124 | − 0.007 | − 0.069 |
| BD | 0.942 | − 0.101 | − 0.062 | − 0.041 | 0.059 | − 0.024 | 0.128 |
| DBH | 0.953 | − 0.090 | − 0.104 | − 0.067 | 0.069 | 0.063 | 0.092 |
| V | 0.960 | − 0.107 | − 0.063 | − 0.051 | 0.060 | 0.086 | 0.065 |
| UBH | 0.119 | − .006 | 0.195 | 0.086 | 0.598 | − 0.338 | 0.151 |
| AAGH | 0.397 | 0.007 | 0.232 | 0.275 | 0.533 | − 0.098 | − 0.108 |
| FQ | 0.199 | − 0.095 | 0.726 | − 0.226 | 0.234 | 0.065 | − 0.049 |
| SSD | − 0.178 | 0.117 | 0.809 | 0.189 | − 0.118 | − 0.039 | 0.029 |
| BA | 0.196 | − 0.030 | − 0.020 | − 0.016 | − 0.059 | 0.008 | 0.903 |
| WD | 0.107 | − 0.004 | 0.157 | 0.129 | − 0.738 | − 0.209 | 0.111 |
| HEC | 0.000 | 0.364 | 0.024 | − 0.728 | 0.047 | − 0.093 | 0.166 |
| CC | − 0.117 | 0.909 | 0.007 | 0.192 | − 0.020 | 0.044 | − 0.063 |
| HOC | − 0.104 | 0.968 | 0.017 | − 0.148 | 0.003 | − 0.002 | 0.017 |
| LC | 0.042 | − 0.929 | − 0.004 | 0.149 | − 0.013 | − 0.013 | − 0.007 |
| AC | − 0.166 | 0.199 | − 0.250 | 0.497 | − 0.198 | − 0.423 | − 0.096 |
| FL | 0.077 | 0.069 | − 0.006 | 0.157 | − 0.048 | 0.830 | 0.014 |
| FW | − 0.007 | 0.070 | 0.132 | 0.584 | 0.213 | 0.231 | 0.305 |

properties, respectively. The Qi values of different families based on growth traits, wood properties and the combination of growth and wood properties are shown in Table 8. When the selection rate was 10%, four families (PK 40, PK 80, PK 42 and PK 71) were selected as elite families based on their growth traits. The Qi values of the four families were 1.999, 1.984, 1.978 and 1.947, and the genetic gains (Table 9) of the

**Table 8** Comprehensive evaluation

| Comprehensive evaluation based on growth traits | | | | Comprehensive evaluation based on wood properties | | | | Comprehensive evaluation based on growth and wood properties | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Family | Qi | Family | Qi | Family | Qi | Family | Qi | Family | Qi | Family | Qi |
| PK 40 | 1.999 | PK 76 | 1.887 | PK 70 | 1.238 | PK 68 | 0.981 | PK 70 | 2.283 | PK 72 | 2.112 |
| PK 80 | 1.984 | PK 79 | 1.886 | PK 62 | 1.227 | PK 60 | 0.968 | PK 62 | 2.260 | PK 41 | 2.106 |
| PK 42 | 1.978 | PK 78 | 1.881 | PK 52 | 1.205 | PK 3 | 0.962 | PK 61 | 2.242 | PK 47 | 2.102 |
| PK 71 | 1.947 | PK 41 | 1.880 | PK 44 | 1.138 | PK 40 | 0.959 | PK 40 | 2.217 | PK 60 | 2.099 |
| PK 61 | 1.944 | PK 68 | 1.875 | PK 72 | 1.124 | PK 73 | 0.953 | PK 52 | 2.197 | PK 58 | 2.092 |
| PK 39 | 1.939 | PK 60 | 1.863 | PK 61 | 1.118 | PK 41 | 0.950 | PK 49 | 2.191 | PK 50 | 2.083 |
| PK 67 | 1.934 | PK 1 | 1.862 | PK 53 | 1.099 | PK 59 | 0.936 | PK 57 | 2.188 | PK 79 | 2.080 |
| PK 66 | 1.920 | PK 2 | 1.857 | PK 57 | 1.093 | PK 46 | 0.917 | PK 69 | 2.181 | PK 80 | 2.074 |
| PK 81 | 1.920 | PK 52 | 1.837 | PK 76 | 1.086 | PK 1 | 0.906 | PK 76 | 2.177 | PK 1 | 2.070 |
| PK 70 | 1.918 | PK 54 | 1.828 | PK 49 | 1.070 | PK 66 | 0.894 | PK 39 | 2.177 | PK 55 | 2.070 |
| PK 69 | 1.912 | PK 55 | 1.819 | PK 47 | 1.058 | PK 79 | 0.877 | PK 81 | 2.175 | PK 43 | 2.069 |
| PK 59 | 1.912 | PK 47 | 1.816 | PK 50 | 1.052 | PK 58 | 0.869 | PK 67 | 2.175 | PK 78 | 2.057 |
| PK 49 | 1.911 | PK 53 | 1.815 | PK 43 | 1.050 | PK 71 | 0.865 | PK 51 | 2.141 | PK 45 | 2.057 |
| PK 74 | 1.905 | PK 48 | 1.808 | PK 69 | 1.048 | PK 54 | 0.849 | PK 71 | 2.131 | PK 42 | 2.055 |
| PK 75 | 1.903 | PK 50 | 1.798 | PK 45 | 1.028 | PK 78 | 0.832 | PK 59 | 2.129 | PK 75 | 2.046 |
| PK 58 | 1.903 | PK 72 | 1.788 | PK 64 | 1.023 | PK 48 | 0.784 | PK 53 | 2.122 | PK 74 | 2.028 |
| PK 62 | 1.899 | PK 44 | 1.784 | PK 81 | 1.022 | PK 75 | 0.752 | PK 3 | 2.121 | PK 64 | 2.020 |
| PK 57 | 1.895 | PK 46 | 1.784 | PK 51 | 1.009 | PK 74 | 0.695 | PK 73 | 2.119 | PK 54 | 2.015 |
| PK 73 | 1.893 | PK 43 | 1.782 | PK 67 | 0.994 | PK 2 | 0.666 | PK 66 | 2.118 | PK 46 | 2.006 |
| PK 3 | 1.890 | PK 45 | 1.782 | PK 39 | 0.989 | PK 80 | 0.604 | PK 44 | 2.117 | PK 2 | 1.973 |
| PK 51 | 1.889 | PK 64 | 1.743 | PK 55 | 0.988 | PK 42 | 0.558 | PK 68 | 2.116 | PK 48 | 1.971 |

**Table 9** Genetic gains

| The elite families with good growth performance | | The elite families with good wood properties | | The elite families with good growth performance and wood quality | |
|---|---|---|---|---|---|
| Traits | Genetic gains (%) | Traits | Genetic gains (%) | Traits | Genetic gains (%) |
| H | 1.98 | CC | 10.99 | H | 1.83 |
| BD | 4.72 | HOC | 12.47 | BD | 2.70 |
| BDH | 6.39 | LC | − 31.29 | BDH | 3.93 |
| V | 14.39 | | | V | 8.60 |
| | | | | CC | 7.85 |
| | | | | HOC | 8.71 |
| | | | | LC | − 22.25 |

H, BD, DBH and V of these families were 1.98%, 4.72%, 6.39% and 14.39%, respectively. Four families (PK 70, PK 62, PK 52 and PK 44) were selected as elite families according to wood properties; the Qi values of the four families were 1.238, 1.227, 1.205 and 1.138, and the genetic gains of the CC, HOC and

LC were 10.99%, 12.47% and − 31.29%, respectively. Four families (PK 70, PK 62, PK 61 and PK 40) were selected as elite families based on the combination of growth traits and wood properties. The Qi values of the four families were 2.283, 2.260, 2.242 and 2.217, respectively, and the genetic gains of the H, BD, DBH, V, CC, HOC and LC of the corresponding elite families were 1.83%, 2.70%, 3.93%, 8.60%, 7.85%, 8.71% and − 22.25%, respectively.

## Discussion

### ANOVA

Studies of heredity and variation are critical to efficiently select excellent materials for forest tree breeding (Medrano et al. 2018). An ANOVA has been applied in many researches on trees (Nanson 2004; Zhao et al. 2016). The superior clones and families were selected based on an ANOVA for *Larix olgensis* (Xia et al. 2016) and *Pinus koraiensis* (Liang et al. 2016). In this study, all the sources of variance showed extremely significant differences among families, except for the FQ and WD, and insignificant differences among the blocks, which indicated that the geographical environment conditions of the different blocks were similar, and the variation was primarily caused by the genotype. The result was more conducive to the evaluation and selection of elite families.

### Genetic variation parameters

Phenotype is determined by the interaction of genotype and environmental conditions (Jones et al. 2010). The average H, DBH and V of 42 *P. koraiensis* half-sib families in this study were 12.90 m, 18.75 cm and 0.15 $m^3$, respectively, which were higher than those determined in the research of Liang et al. (2016). The results predicted that these could be caused by higher rainfall or fertile soil in this research. The annual rainfall was 493.9 mm and 725.5 mm in Longjing (the location of the experimental materials in Liang's research) and Sanchazi (the location of the study materials), respectively. The different contents values of the wood properties resulted in a specific purpose for any particular tree species. Yunnan pine has a significantly higher holocellulose contents than masson pine (Bao et al. 2001), so Yunnan pine is better for building materials with strong toughness. *Betula platyphylla*, *Larix gmelinii*, and *Populus tremula* had longer FL and lower LC, so the materials are suitable for pulpwood (Zhu et al. 2009; Yin et al. 2017; Zhang et al. 2003). In this study, the proper ratio of the HOC to LC led to the strong toughness and hardness of the *P. koraiensis* wood, which was appropriate to produce good furniture and use in building construction. In addition, it was also used to produce high-grade paper.

The coefficient of variation primarily reflected the degree of date dispersion, and it is the primary genetic parameter of tree growth traits and wood properties in forest tree breeding programs (He et al. 2011). In this study, the range of PCVs ranged from 7.17% to 42.35% for the growth traits, which was lower than that of the other species (Yin et al. 2017; Zhao et al. 2017). The PCVs of the wood properties ranged from 10.21% to 24.24%, with the exception of the AC, which was higher than that in the research of *Eucalyptus* hybrid clones (Wu et al. 2011). In the same tree species, research by Liang et al. (2016) on the growth traits and wood properties of *P. koraiensis* resulted in PCVs that were lower than those found in this study, which indicated that the variation was higher among the families in this study.

Heritability reflects the ratio of genetic variables to phenotypic variables, and it is an important parameter in selection breeding and genetic gain estimation (Chen and Shen 2005). In this study, the range of family heritability of growth traits and wood properties was from 0.52 to 0.62 and from 0.67 to 0.92, respectively, which was lower than that for the heritability of growth traits (H and DBH), similar to the values of the FL and HEC and higher than the values of the WD, CC and HOC for the wood properties in Yin's research of *Larix olgensis* (2017). All the heritability values were greater than 0.5, which showed higher heritability. High heritability and coefficients of variation are beneficial for elite families selection (Xia et al. 2016).

### Correlation analysis

Correlation analysis reflects the relationship between the traits (Cja and Rcb 1979), and it is important for the forest tree improvement (Sumida et al. 2013; Fukatsu et al. 2015). In this study, extremely significant positive correlation was found between the H, DBH and V, which was similar to many other studies (Zhao et al. 2016; Yin et al. 2017; Zhao et al. 2017). Volume growth has been typically used as a selection trait of prime importance in forest tree breeding (Gerendiain et al. 2007). In this study, the V was extremely significantly positively correlated with the BD, UBH, AAGH and FQ, which indicated that V could be predicted by the this indices (Yin et al. 2017).

For the wood properties, the significant negative correlations between the LC and cellulosics (CC, HEC and HOC) may be considered a competition for C allocation to lignin versus the cellulosics, because these two classes of molecules are the primary C sinks in the formation of the wood cell wall (Novaes et al. 2010). The correlation pattern was also examined in other tree species (Du et al. 2014; Novaes et al. 2010; Hu et al. 1999). Holocellulose is the general term for cellulose (a glucan polymer) and hemicellulose (mixtures of polysaccharides) (Sebio-Puñal et al. 2012; Pettersen 1984), which could explain the extremely significant positive correlation between the cellulosics (HOC and CC, and HOC and HEC) and the negative correlation between the CC and HEC (Liang et al. 2016; Yin et al. 2017). Wood density is an important indicator of the nature of wood (Zanne et al. 2009). It is very important to reveal the variation law of wood attribution and improve the efficiency of forest tree improvement (Doran et al. 2012). Negative correlations between growth traits and wood density have been observed in a number of tree species (Enquist et al. 1999; Burslem & Whitmore 2003; Muller-Landau 2004; Hong et al. 2014; Missanjo and Matsumura 2017), and some other studies also reported that the correlations were positive (Fukatsu et al. 2015). However, in this study, no significant correlations were found between the wood density and any trait in the growth and wood properties. The result could be due to genetic backgrounds and diverse environments (Novaes et al. 2010). Wood ash comes directly or indirectly from the soil minerals, so it is also called mineral elements (Guo and Hou 2014). An ANOVA of the AC indicated that different families of *P. koraiensis* had different abilities to absorb minerals from the soil (Lin et al. 2000), and all the traits was not significantly correlated with the AC, except for the HEC, which indicated that the intake of soil inorganic matter by the trees might be not closely related to growth traits and wood properties (Yin et al. 2017). Weak correlations between growth traits and wood properties (Markussen et al. 2003) made it feasible and necessary to combine growth traits with wood properties to select families with both excellent growth and wood properties or to separate growth traits and wood properties to select families with single major traits (Yin et al. 2017). Clearly, correlation analysis could be interpreted as representative of the correlated response of traits to selection (Cheverud 1988).

## Principal component analysis

Principal component analysis (PCA) is a statistical approach, which aims to replace the original related indicators with a new set of independent comprehensive indicators (Roweis 1997). It is useful to determine which combination of traits contributes to the growth of trees and wood quality (Brewer and Knaap 2007). In this study, the accumulating contribution of the seven principle components (PC) reached 76.30%, which was lower than the result of Denton and Nwangburuka (2011). This phenomenon could have been caused by a large number of indicators and the lack of a close correlation between these indicators. PCI represented the growth traits; PCII represented the wood traits, and PCIII represented the trunk form traits. A similar result was found in the research of Zhao et al. (2012) and Li et al. (2014). Ma et al. (2013) used PCA to explore the correlation between the quality traits and the primary factors influencing the quality of rice for the cultivars of japonica rice in Ningxia, China, and the result was stable. Therefore, it was very significant and feasible to use PCI and PCII to comprehensively evaluate the growth traits and wood properties.

## Comprehensive assessment

Comprehensive evaluation has been developed to breed multiple characteristics to cultivate materials with strong integrated ability (Yin et al. 2017). There are many different methods to evaluate families, including index selection (Jiang et al. 1996), the optimal linear breeding value prediction method (White and Hodge 1988), and so on. Different comprehensive evaluation methods have distinct advantages and disadvantages, and therefore, an appropriate comprehensive evaluation method need to be developed for research (Luo et al. 2000). Multiple-trait comprehensive evaluation is more stable and accurate using the Qi values. However, it would reduce the genetic gain when so many traits were taken into consideration to evaluate and select elite materials (Guan et al. 2005). Therefore, it is necessary to select an appropriate number of traits. According to the results of the correlation analysis and PCA, four growth traits (H, DBH, BD and V) and three wood properties (CC, HOC and LC) were utilized to evaluate and select the elite families in this study. Four elite families (PK 40, PK 80, PK 42 and PK 71) with excellent growth traits; four elite families (PK 70, PK 62, PK 52 and PK 44) with excellent wood properties and four elite families (PK 70, PK 62, PK 61 and PK 40) with excellent growth traits and wood properties were elected based on preliminary studies. The genetic gain of the H, BD, DBH and V (families PK40, PK 80, PK 42 and PK 71, which were selected by growth traits) reached 1.98, 4.72, 6.39 and 14.39%, respectively. It was at a low level compared to the research of Du et al. (2010), Liang et al. (2016) and Yin et al. (2017), which was likely due to the different tree species, environment, age and density. The genetic gain of the CC, HOC and LC (families PK 70, PK 62, PK 52 and PK 44, which were selected by wood properties) was 10.99%, 12.47% and − 31.29%, respectively, and the values were lager than those of the growth traits. It emerged that the wood properties had greater potential for improvement. The reduction of the lignin contents and the increase of cellulose can enhance the toughness of wood and is also conducive to papermaking (Novaes et al. 2010); therefore, the genetic gain of lignin was negative (Yin et al. 2016). The elite families with excellent growth traits or wood properties can provide materials to select special target improved varieties. The families (PK 70, PK 62, PK 61 and PK 40) had both superior growth traits and excellent wood properties, and the comprehensive ability was strong. All the families selected can serve as the basis to select and breed improved families, and the method can provide references to select improved varieties of other tree species.

### Economic benefit analysis

Calculating economic gains resulting from breeding is of great importance to determine whether investments in tree breeding can be justified (Haapanen et al. 2015). Currently, the price of *P. koraiensis* logs is approximately 145.31 American dollars per cubic meter in Jilin Province. Because the genetic gain of V for the elite families with excellent growth traits was 14.39%, and the average V of the elite families was 0.19 $m^3$, the price of a single log will be increased by 3.97 dollars, and the price of *P. koraiensis* per hectare will be increased by 3308.33 dollars when the planting density is maintained at $3.0 \times 4.0$ m. Thus, the economic benefits will be enormous. In this study, we also selected elite families with excellent wood properties. If these elite families with excellent wood properties are used to produce high-grade furniture, paper, and so on, the economic benefits will be even greater than expected.

## Conclusion

Growth traits and wood properties are very important indices for timber tree species. In this study, high variable coefficients and heritabilities of different characters were identified, which indicated that elite family selection was feasible. Weak correlation coefficients between the growth traits and wood properties suggested that the evaluation of different families using growth traits and wood properties separately or in combination were significative. Based on principal component analysis, four growth traits and three wood properties were selected as evaluation indicators, and 12 *P. koraiensis* families were selected as elite families with a selection rate of 10% according to different evaluation indices at last, respectively, which could provide materials to select and breed improved families for *P. koraiensis*. The evaluation method that combines correlation analysis, principal components analysis and multiple-trait comprehensive evaluation could also provide references to selected improved varieties of other tree species. In addition, the seeds of *P. koraiensis* also have high economic value, which is also a breeding target worthy of attention.

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