Wood Density and Fiber Dimensions of Root, Stem, and Branch Wood of *Populus ussuriensis* Kom. Trees

Xiping Zhao, Pingping Guo, Zhaolin Zhang, Xingchang Wang, Haixin Peng, and Mengke Wang

In order to determine the possibility of whole-tree wood utilization of a native tree species in Northeast China (*P. ussuriensis*), this study investigated the air-dried wood density and fiber dimensions for each ring in the branch, stem, and root wood of the tree species. The results showed significant differences in wood densities and fiber dimensions among tree positions (*p* < 0.05). The root had the highest average density (0.596 g/cm³), and branch had the lowest average density (0.506 g/cm³). The root and branch wood exhibited larger fibers than that of the stem wood. The root wood had the highest average fiber wall (6.038 µm). The fiber wall of branch wood appeared thinner than the stem wood, although the difference was not statistically significant. The radial pattern of wood density and fiber dimensions indicated that branches and roots did not have juvenile wood such as was found in the stems. The study concludes that the use of branch or root wood of *P. ussuriensis* would be favorable for papermaking or wood-based panels.

**Keywords**: Branch; Fiber dimension; *Populus ussuriensis* Kom.; Root; Stem; Wood density

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**INTRODUCTION**

Wood is a renewable natural resource and has always played an important role in human civilization. However, the dwindling natural forest resources on earth have led to shortages of timber to supply the furniture, construction, and other wood related industries. China is a country with low natural forest coverage (Fan and Dong 2001), and timber is largely dependent on imports (Liu and Xie 2016). Large plantations that exist are still not enough to meet the rise in timber demand (Lin 2000). One method of solving the problem is whole-tree utilization (Danielsson 1982; Leitch and Miller 2017). In most forest areas, only 65% of the total wood of the tree is harvested, while the remaining 35% of the wood consisting of branches and roots are thrown away (Nilsson and Wernius 1976). Researchers have been exploring the use of branch and root wood as supplements to stem wood (Stokke and Manwiller 1994; Dadzie and Amoah 2015). However, the prerequisite to achieve this goal is to know and understand the wood characteristics of branches and roots.

Wood characteristics vary between different parts of the tree, including wood of stems, branches, and roots. These include anatomical features (Stokke and Manwiller 1994; Zhao 2015; Dadzie *et al.* 2018), chemical composition (Guo *et al.* 2014; Nakagawa *et al.* 2016), physical properties (Dadzie and Amoah 2015; Kotowska *et al.* 2015; Dadzie *et al.* 2018), and mechanical properties (Okai *et al.* 2004).
Generally, branches have smaller wood elements than the stems and roots (Zhao 2015; Longui et al. 2017). Stem wood has a higher density than corresponding branch wood (Sarmiento and Baraloto 2011). However, variation of wood properties among some tree species is not consistent with the tendencies mentioned above. For example, branch wood is shown to have a higher density than the corresponding stem wood for six tropical tree species from Cacao agroforestry (Kotowska et al. 2015). Roots of Betula platyphyllla (L.) Rothm. have a smaller vessel diameter than tree stumps (Zhao 2015).

P. ussuriensis is a native tree species in Northeast China (Su et al. 2001), and is one of the fastest growing and shortest rotation industrial timber species. Wood from P. ussuriensis has light and soft texture, is durable (Liang 1991), and is an excellent raw material for papermaking and plywoods (Wang et al. 2009; Li et al. 2013). P. ussuriensis branches and root wood may be suitable for commercial utilization in the wood industry. However, variations in the anatomical features and physical properties of the branch and root wood of P. ussuriensis tree species have not been studied. Therefore, the objectives of this study were to determine the physical properties (wood density and ring width) and fiber dimensions (fiber length, fiber width, and fiber wall thickness), to compare the physical properties and fiber dimensions of the root, branch, and stem wood, and to determine the relationship between the physical properties and fiber dimensions.

**EXPERIMENTAL**

**Materials**

Ten mature trees were sampled from the Maoershan Forest Ecosystem Research Station (Heilongjiang, China) (127°30’–34’E, 45°20’–25’N, elevation 300 m). One standard primary branch was chosen from the upper, middle, and lower canopy of each sample tree. Three horizontally oriented proximal woody roots near the soil surface were excavated from each sample tree.

The characteristics of the sample trees are summarized in Table 1. Disc samples (5 cm thick) were moved from the stem at abrest height of 1.3 m. Disc samples were also removed from the branch or root just above the basal swelling.

A 1 cm×5 cm strip (from pith to bark) was sawed from each disc. The strip was then separated into strip A and strip B. Strip A (approximately 7.0 mm wide ×1.5 mm) was used to assess the wood density and ring width after air-drying in the laboratory to an equilibrium moisture content (12%). Strip B (approximately1.0 cm× 4.5 cm) was used to measure the fiber size.

**Table 1. Characteristics of the Sampled Trees**

<table>
<thead>
<tr>
<th></th>
<th>Tree Height (m)</th>
<th>DBH (cm)</th>
<th>Tree Age (a)</th>
<th>Branch Length (m)</th>
<th>Branch Diameter (cm)</th>
<th>Root Diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>21.3</td>
<td>25.8</td>
<td>44.5</td>
<td>8.2</td>
<td>10.7</td>
<td>9.6</td>
</tr>
<tr>
<td>Range</td>
<td>20.3 to 22.8</td>
<td>20.2 to 34.1</td>
<td>42 to 47</td>
<td>5.2 to 12.4</td>
<td>7.2 to 17.9</td>
<td>6.6 to 13.9</td>
</tr>
</tbody>
</table>

DBH represents the tree diameter at breast height position. The branch and root diameter were taken from the branch or root just above the basal swelling.
Methods

Wood density and ring width measurement
An X-ray diffractometer (D/max2200, Rigaku, Tokyo, Japan) was used to scan the sanded strip A for measuring the air-dried wood density within and between the growth rings. Combined with the scan step size of 15 µm, the measured density values were used to set the ring boundaries, and thereby determine the width of each ring.

Fiber dimensions measurement
Using a razor blade, strip A was divided into small chips, ring by ring. Each ring chip was placed into an individual test tube and macerated by a 1:1 10% chromic acid:10% nitric acid solution (Jeffrey 1917). The test tubes were then placed in a water bath at 60 °C for several hours to hasten the maceration process. The macerated material from each growth ring was rinsed and then placed on the microscopic slides for measurement. Digital images of the microscopic slides were taken using a digital microscope (Mshot-MD50, Micro-shot Technology Co., Ltd., Guangzhou, China). The fiber size was measured with an image computer analysis system (TDY-5.2, Tianyu Science and Technology Co., Ltd., Beijing, China) as previously described (Yu et al. 2009). An average of 60 fibers was measured per tree ring.

Statistical analysis
All of the statistical analyses were performed using IBM SPSS Statistics software version 24.0 (Armonk, NY, USA). Differences among the tree compartments were evaluated by analyses of variance, followed by separation of means by the least significant difference. Correlations among variables were calculated from pith to bark in the same compartment. An ANOVA test was done with significance assessed at the p<0.05 level.

RESULTS AND DISCUSSION

Wood Density and Ring Width
Different positions of the P. ussuriensis tree showed variations in the wood density and ring width. The root wood had the highest average density (0.596 g/cm³), while branch wood had the lowest (0.506 g/cm³) (Fig. 1A). For the ring width, the root wood had the widest ring (3.01 mm), while stem wood had the narrowest (1.72 mm) (Fig. 1B). The differences of wood densities and ring width between different tree positions were statistically significant at the 5% level.

![Fig. 1.](image.png)

Fig. 1. Multiple comparisons of wood densities (A) and ring widths (B) from different positions on *Populus ussuriensis* Kom. Mean values with the different lower-case letters indicate significant differences at 95% confidence level.
The findings showed that the differences of wood densities between root wood and stem wood were consistent with studies in other tree species of *Theobroma cacao* and *Durio zibethinus* (Kotowska et al. 2015). However, not all types of trees are similar. Some tree species show less density in root wood than in stem wood or similar density (Dunham et al. 2007; Kotowska et al. 2015; Nakagawa et al. 2016). Generally, trees with faster growth will produce wider rings and form wood with lower density. Otherwise, a high-density wood will form (Molteberg et al. 2006; Kiaei et al. 2016). However, many results, sometimes contradictory, have been reported about the relationship between ring width and wood density (Sousa et al. 2018; Adamopoulos et al. 2010). The present correlation analysis also confirmed this point. There were significant positive relations between the wood density and ring width in the stem and branch wood, but not in the root wood (Table 2). This result suggested that growth rate is not the only factor affecting the relationship between the wood density and ring width. In addition to growth rate, growth period (Dutilleul et al. 1998) and even latewood proportion (Adamopoulos et al. 2010) should be included in the factors. The radial variation in wood density and ring width showed that branch and stem wood of *P. ussuriensis* produced high density with wide rings under early stages of growth (Fig. 2), suggesting the possibility of forestry management for both fast tree growth and high wood density (Sousa et al. 2018).

**Table 2.** Correlation Analysis on Ring Width, Wood Density, and Fiber Dimensions in Wood of *Populus ussuriensis* Kom.

<table>
<thead>
<tr>
<th>Tree Position</th>
<th>Character</th>
<th>Wood Density (0.506 g/cm³)</th>
<th>Fiber Length (µm)</th>
<th>Fiber Width (µm)</th>
<th>Fiber Wall Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root Wood</td>
<td>Ring width (mm)</td>
<td>-0.195</td>
<td>-0.084</td>
<td>0.026</td>
<td>-0.254</td>
</tr>
<tr>
<td></td>
<td>Wood density (0.506 g/cm³)</td>
<td>-</td>
<td>0.160</td>
<td>0.178</td>
<td>0.436*</td>
</tr>
<tr>
<td></td>
<td>Fiber length (µm)</td>
<td>-</td>
<td>-</td>
<td>0.410*</td>
<td>0.444*</td>
</tr>
<tr>
<td></td>
<td>Fiber width (µm)</td>
<td>-</td>
<td>-</td>
<td>0.509*</td>
<td></td>
</tr>
<tr>
<td>Stem Wood</td>
<td>Ring width (mm)</td>
<td>0.589**</td>
<td>-0.365*</td>
<td>-0.180</td>
<td>0.392*</td>
</tr>
<tr>
<td></td>
<td>Wood density (0.506 g/cm³)</td>
<td>-</td>
<td>-0.821**</td>
<td>-0.675**</td>
<td>0.280</td>
</tr>
<tr>
<td></td>
<td>Fiber length (µm)</td>
<td>-</td>
<td>-</td>
<td>0.821**</td>
<td>0.137</td>
</tr>
<tr>
<td></td>
<td>Fiber width (µm)</td>
<td>-</td>
<td>-</td>
<td>0.201</td>
<td></td>
</tr>
<tr>
<td>Branch Wood</td>
<td>Ring width (mm)</td>
<td>0.550**</td>
<td>-0.378*</td>
<td>0.199</td>
<td>0.372*</td>
</tr>
<tr>
<td></td>
<td>Wood density (0.506 g/cm³)</td>
<td>-</td>
<td>-0.561**</td>
<td>-0.158</td>
<td>0.889**</td>
</tr>
<tr>
<td></td>
<td>Fiber length (µm)</td>
<td>-</td>
<td>-</td>
<td>0.226</td>
<td>-0.566**</td>
</tr>
<tr>
<td></td>
<td>Fiber width (µm)</td>
<td>-</td>
<td>-</td>
<td>-0.146</td>
<td></td>
</tr>
</tbody>
</table>

*Significant at p<0.05, **Significant at p<0.01
The difference in density between the ground and the underground may be due to a longer period of cambial activity that occurs in roots compared to aboveground components (Thibeault-Martel et al. 2008). This can be confirmed from the radial growth pattern of *P. ussuriensis* (Fig. 2A). The radial pattern of wood density in roots was particularly different in the stems or branches, and there was almost no change from pith to bark. Wood density in the branches had a similar radial pattern as in the stems. Stem and branch density were high during early stages of growth, then declined, and then increased gradually toward a value where the densities appeared to level off (Fig. 2A). The significant relationship between branch and stemwood density is confirmed by Sarmiento and Baraloto (2011). This has prompted some scientists to try using branches to replace the whole tree for studies (Williams 1989; Burgess and Dawson 2008; Mokochinski et al. 2017). However, there are some differences between branches and stems (He and Deane 2016; Dadzie et al. 2018). The results showed that the rates of change were different in the stems and branches. Density declined most steeply in the stem and less steeply in the branches (Fig. 2A).

The radial pattern of the ring width was very similar to the radial pattern of the wood density in the roots and branches, respectively (Fig. 2). In contrast, the curve of the ring width had a particularly different shape for the stems. The first several formed rings were narrow in the stem, which was similar to previous studies (Liang 1991; Boruszewski et al. 2017). This part of the wood is defined as juvenile wood, which is sometimes regarded as a type of wood defect in timbers (Zobel and Sprague 1998). Juvenile wood was also found in branches of some tree species (Pramod and Rao 2012). Based on the radial pattern of the ring width, no juvenile wood was found in the branches or roots of *P. ussuriensis* (Fig. 2B). The result confirmed that juvenile wood in the stem is an adaptive feature rather than an unavoidable developmental consequence (Lenz et al. 2010).

![Fig. 2. Radial variation in wood density (A) and ring width (B) of *Populus ussuriensis* Kom.](image)

**Fibers Dimensions**

Fibers dimensions have an important influence on the quality of pulp and paper products (Larsson et al. 2018; Przybysz et al. 2018), wood products, and wood composites (Wan et al. 2018). Mean fiber lengths and mean fiber widths were greatest in the branches, followed by the roots and the stems (Figs. 3A and 3B). The ANOVA test showed significant differences in the mean fiber length and width among the three positions of *P. ussuriensis* (p<0.05). The longer fibers were also wider. The results confirmed that there were positive relations between the fiber length and width, and the relations were even
significant in the stem and root wood (Table 2). Large fibers are more flexible and conformable than small fibers (Ek et al. 2009). The result showed that the root and branch wood of the tree can be used to make paper.

![Graph showing fiber measurements](https://via.placeholder.com/150)

**Fig. 3.** Multiple comparison of fiber dimension in different positions of *Populus ussuriensis* Kom. Mean values with the different lower-case letters indicate significant difference at 95% confidence level.

The root wood had the thickest fiber wall (6.038 µm), while the branch wood had the thinnest (0.508 µm) (Fig. 3C). The differences of the fiber wall thickness between the root wood and aboveground wood were statistically significant. High levels of mechanical strength for wood are positively associated with increases in the fiber wall thickness (Santini et al. 2013), which are linked to external loading forces in root systems (Stokes and Mattheck 1996). Although the fiber wall thickness in the branch wood was thinner than the fiber wall thickness in the stem wood, the difference was not statistically significant. The fiber wall thickness closely relates to the wood density (Mitchell and Denne 1997), hygroexpansivity (Lindner 2018), and tear strength for sheets (Molteberg and Høibø 2006). The study showed that the fiber wall thickness had significant positive relations with the density of wood except for the stem wood (Table 2).

The shapes of the fiber length curves were similar for roots, stems, and branches, with a gradual increase toward a value at which they leveled off (Fig. 4A). Interestingly, fibers in stem wood were very short near the pith and showed a rapid increase in the initial-stage of the growth year at approximately 10 years. This pattern is the check-shaped pattern often reported for most species (Honjo et al. 2005; Dafni et al. 2018). Unlike the fiber length, the radial pattern of the fiber width differed among the three positions (Fig. 4B). Fiber width appeared to level off in the root wood, and it linearly decreased in the branch wood. The first several values of the fiber width in stem wood were small and then increased rapidly before leveling off. Similar to the fiber length or width, the fiber wall thickness also appeared to level off in the root wood from the pith to the bark (Fig. 4C). The radial pattern of the fiber wall thickness showed similar trends in the stems and branches during their common growth period, with a gradual decrease toward a value at which they leveled off. However, fibers in the stem wood were very thick near the pith and showed a rapid increase in the initial-stage of the growth year at approximately 10 years.

The stem samples had a small fiber-dimension wood in the initial stage of the growth year, exhibiting the juvenile wood pattern again. The cambial age has a major influence on wood properties, particularly in the juvenile stage (Lenz et al. 2010; Ištok et al. 2017; Dafni et al. 2018). Juvenile wood tends to have distinct properties compared to mature wood, with smaller cells in the thinner walls (Cato et al. 2006; Boruszewski et al.
2017; Dafni et al. 2018), worse physical-mechanical properties (Tong et al. 2013; Olarescu et al. 2014), and higher content of extractives (Cobas et al. 2013; Knapic et al. 2018). These properties affect the processing technology of solid wood (Mazán et al. 2017) and restrains the production and quality of paper and compound materials (Zobel and Sprague 1998). The branches and roots of *P. ussuriensis* did not have juvenile wood, a finding that is favorable in papermaking or wood-based panels using branch or root wood.

![Fig. 4](image.png)

**Fig. 4.** Radial variation in fiber length (A), fiber width (B) and fiber wall thickness (C) of *Populus ussuriensis* Kom.

**CONCLUSIONS**

1. The root wood of *P. ussuriensis* exhibited higher density and larger fibers than the aboveground wood. The differences were statistically significant at the 5% level.

2. The branch wood exhibited lower density, and thinner, longer, and wider fibers than the stem wood. The differences were statistically significant at the 5% level but not for fiber wall thickness.

3. The correlation analysis confirmed there were relations between wood density, ring width, and fiber dimensions in wood. The significance of correlations was influenced by sampling positions in the trees.

4. The radial pattern of wood density, ring width, and fiber dimensions indicated that there was not any juvenile wood found in the branches or roots.
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