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

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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/cm^3), and branch had the lowest average density (0.506 g/cm^3). 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 platyphylla* (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 abreast 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

	Tree Height(m)	DBH(cm)	Tree Age (a)	Branch Length(m)	Branch Diameter (cm)	Root Diameter (cm)
Mean	21.3	25.8	44.5	8.2	10.7	9.6
Range	20.3 to 22.8	20.2 to 34.1	42 to 47	5.2 to 12.4	7.2 to 17.9	6.6 to 13.9

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 of15 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/cm^3), while branch wood had the lowest (0.506 g/cm^3) (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.

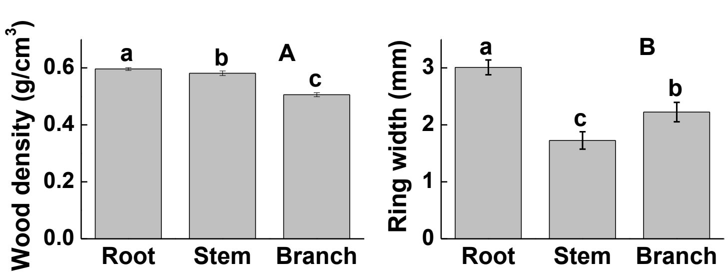

Fig. 1. Multiple comparisons of wood densities (A) and ring widths (B) from different positions on *Populus ussuriensis* Kom. Mean values with the different lower-case letters indicate significant differences at 95% confidence level.

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.

Tree Position	Character	Wood Density (0.506 g/cm^3)	Fiber Length (μm)	Fiber Width (μm)	Fiber Wall Thickness (μm)
Root Wood	Ring width (mm)	-0.195	-0.084	0.026	-0.254
	Wood density (0.506 g/cm^3)	-	0.160	0.178	0.436*
	Fiber length (μm)	-	-	0.410*	0.444*
	Fiber width (μm)	-	-		0.509*
Stem Wood	Ring width (mm)	0.589**	-0.365*	-0.180	0.392*
	Wood density (0.506 g/cm^3)	-	-0.821**	-0.675**	0.280
	Fiber length (μm)	-	-	0.821**	0.137
	Fiber width (μm)	-	-		0.201
Branch Wood	Ring width (mm)	0.550**	-0.378*	0.199	0.372*
	Wood density (0.506 g/cm^3)	-	-0.561**	-0.158	0.889**
	Fiber length (μm)	-	-	0.226	-0.566**
	Fiber width (μm)	-	-		-0.146

*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).

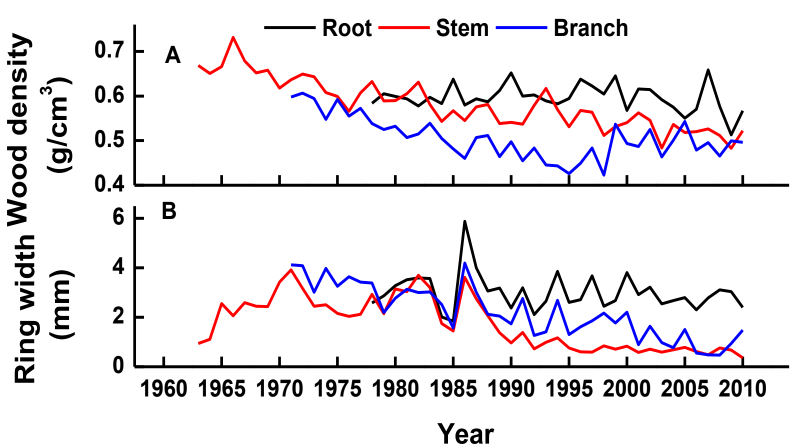

Fig. 2. Radial variation in wood density (A) and ring width (B) of *Populus ussuriensis* Kom.

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.

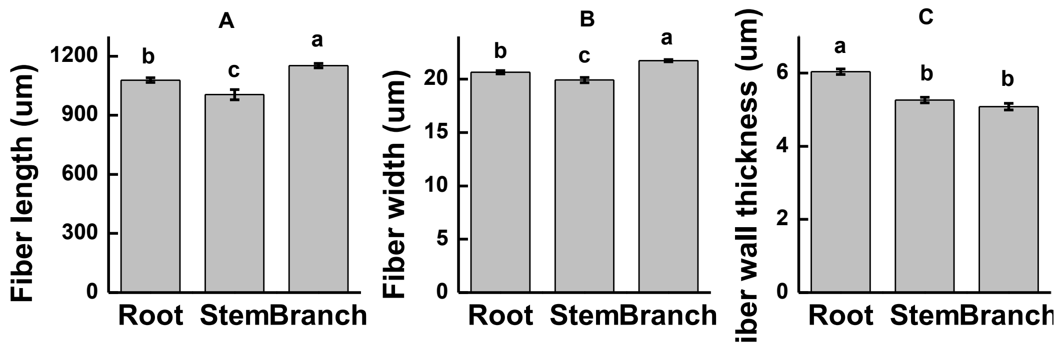

Fig. 3. Multiple comparison of fiber dimension in different positions of *Populus ussuriensis* Kom. Mean values with the different lower-case letters indicate significant difference at 95% confidence level.

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 affects 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.

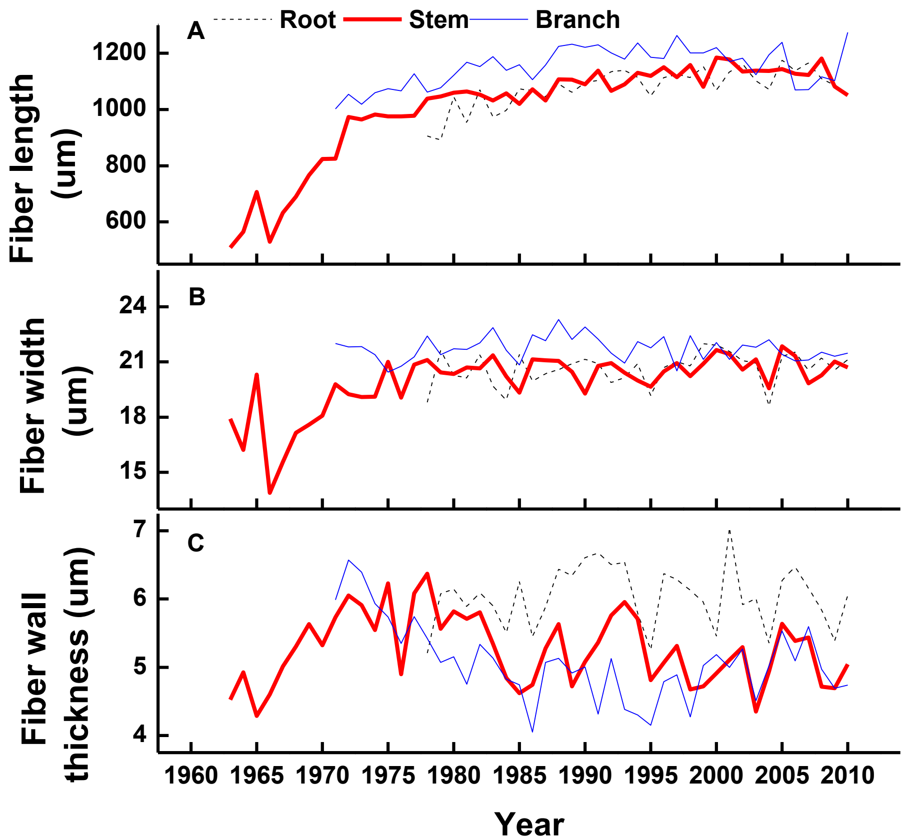

Fig. 4. Radial variation in fiber length (A), fiber width (B) and fiber wall thickness (C) of *Populus ussuriensis* Kom.

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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REFERENCES CITED

Adamopoulos, S., Passialis, C., Voulgaridis, E. (2010). "Ring width, latewood proportion and density relationships in black locust wood of different origins and clones," *Iawa J.* 31(2), 169-178. DOI: 10.1163/22941932-90000014

Boruszewski, P., Jankowska, A., and Kurowska, A. (2017). "Comparison of the structure of juvenile and mature wood of *Larix decidua* Mill. from fast-growing plantations in Poland," *BioResources* 12(1), 1813-1825. DOI:10.15376/biores.12.1.1813-1825

Burgess, S. S. O., and Dawson, T. E. (2008). "Using branch and basal trunk sap flow measurements to estimate whole-plant water capacitance: A caution," *Plant Soil* 305(1-2), 5-13. DOI:10.1007/s11104-007-9378-2

Cato, S., Mcmillan, L., Donaldson, L., Richardson, T., Echt, C., and Gardner, R. (2006). "Wood formation from the base to the crown in *Pinus radiata*: Gradients of tracheid wall thickness, wood density, radial growth rate, and gene expression," *Plant Mol. Biol.* 60(4), 565-581. DOI: 10.1007/s11104-007-9378-2

Cobas, A. C., Felissia, F. E., Monteoliva, S., and Area, M. C. (2013). "Optimization of the properties of poplar and willow chemimechanical pulps by a mixture design of juvenile and mature wood," *BioResources* 8(2), 1646-1656. DOI: 10.15376/biores.8.2.1646-1656

Dadzie, P. K., and Amoah, M. (2015). "Density, some anatomical properties, and natural durability of stem and branch wood of two tropical hardwood species for ground applications," *Eur. J. Wood Wood Prod.* 73(6), 759-773. DOI: 10.1007/s00107-015-0925-x

Dadzie, P. K., Amoah, M., Ebanyenle, E., and Frimpong-Mensah, K. (2018). "Characterization of density and selected anatomical features of stemwood and branchwood of *E. cylindricum*, *E. angolense*, and *K. ivorensis* from natural forests in Ghana," *Eur. J. Wood Wood Prod.* 76(2), 655-667. DOI: 10.1007/s00107-017-1195-6

Dafni, F., Costas, P., Elias, V., Apostolos, S., and Maria, T. (2018). "Wood density and tracheid length of Aleppo pine (*Pinus halepensis* Mill.) grafts in relation to cambium age and growth rate," *Journal of Forest Science* 64(3), 101-107. DOI: 10.17221/127/2017-jfs

Danielsson, B. O. (1982). "Tree harvesting change in Sweden due to whole tree utilization," *Energy from Forest Biomass* 29(1), 19-24. DOI: 10.1016/b978-0-12-652780-3.50008-7

Dunham, S. M., Lachenbruch, B., and Ganio, L. M. (2007). "Bayesian analysis of Douglas-fir hydraulic architecture at multiple scales," *Trees-Struct. Funct.* 21(1), 65-78. DOI: 10.1007/s00468-006-0097-8

Dutilleul, P., Herman, M., and Avellashaw, T. (1998). "Growth rate effects on correlations among ring width, wood density, and mean tracheid length in Norway spruce (*Picea abies*),” *Can. J. Forest Res.* 28(28), 56-68. DOI: 10.1139/x97-189

Ek, M., Gellerstedt, G., and Henriksson, G. (2009). “Paper products physics and technology,” in: *Pulp and Paper Chemistry and Technology*, M. Ek, G. Gellerstedt, and G. Henriksson (eds.), Walter de Gruyter, Berlin, Germany.

Fan, B., and Dong, Y. (2001). “Percentage of forest cover in different historic periods of China,” *Journal of Beijing Forestry University* 23(4), 60-65. DOI: 10.3321/j.issn:1000-1522.2001.04.013

Guo, T., Tang, X. F., Zhang, J. B., Wei, J. Q., Wang, Y., Li, Y. H., and Zhang, Z. (2014). “Chemical constituents from the root and stem of *Zanthoxylum avicennae*,” *Appl. Mech. Mater.* 618, 426-430. DOI: 10.4028/www.scientific.net/amm.618.426

He, D., and Deane, D. C. (2016). “The relationship between trunk- and twigwood density shifts with tree size and species stature,” *Forest Ecol. Manag.* 372, 137-142. DOI: 10.1016/j.foreco.2016.04.015

Honjo, K., Furukawa, I., and Sahri, M. H. (2005). “Radial variation of fiber length increment in *Acacia mangium*,” *Iawa J.* 26(3), 339-352. DOI: 10.1163/22941932-90000119

Ištok, I., Šefc, B., Hasan, M., Popović, G., and Sedlar, T. (2017). “Fiber characteristics of white poplar (*Populus alba* L.) juvenile wood along the Drava River,” *DrvnaIndustrija: Znanstveno-stručni Časopis za pitanja Drvne Tehnologije* 68(3), 241-247. DOI: 10.5552/drind.2017.1729

Jeffrey, E. C. (1917). *The Anatomy of Woody Plants*, The University of Chicago Press, Chicago, IL.

Kiaei, M., Naji, H. R., Abdul-Hamid, H., and Farsi, M. (2016). “Radial variation of fiber dimensions, annual ring width, and wood density from natural and plantation trees of alder (*Alnus glutinosa*) Wood,” *Drevarsky Vyskum/wood Research* 61(1), 55-64.

Knapic, S., Grahn, T., Lundqvist, S.-O., and Pereira, H. (2018). “Juvenile wood characterization of *Eucalyptus botryoides* and *E. maculata* by using silviScan,” *BioResources* 13(2), 2342-2355. DOI: 10.15376/biores.13.2.2342-2355

Kotowska, M. M., Hertel, D., Rajab, Y.A., Barus, H., and Schuldt, B. (2015). “Patterns in hydraulic architecture from roots to branches in six tropical tree species from cacao agroforestry and their relation to wood density and stem growth,” *Frontiers in Plant Science* 6, 1-17. DOI: 10.3389/fpls.2015.00191

Larsson, P. T., Lindström, T., Carlsson, L. A., and Fellers, C. (2018). “Fiber length and bonding effects on tensile strength and toughness of kraft paper,” *J. Mater. Sci.* 53(3), 1-10. DOI: 10.1007/s10853-017-1683-4

Leitch, M., and Miller, S. (2017). *Optimizing Wood Utilization Based on Whole Tree Inherent Property Maps*, Springer, Singapore, Malaysia.

Lenz, P., Cloutier, A., Mackay, J., and Beaulieu, J. (2010). “Genetic control of wood properties in *Piceaglauca* - An analysis of trends with cambial age,” *Can. J. Forest Res.* 40(4), 703-715. DOI: 10.1139/x10-014

Li, J., Wang, F., Li, S., Guan, C., Wang, C., and Wen, B. (2013). “Comprehensive evaluation on pulp properties for fiber timber varieties of poplar in Heilongjiang province,” *Protection Forest Science and Technology* (3), 17-20. DOI: 10.13601/j.issn.1005-5215.2013.03.034

Liang, L. J. (1991). “The preliminary study of the *Populus ussuriensis* xylotomy characteristic and density,” *Journal of Jilin Forestry University* 7(1), 75-78.

Lin, Y. (2000). “A summary of the research on industrial plantation forest development in China," *World Forestry Research* 13(5), 50-56. DOI: 10.3969/j.issn.1001-4241.2000.05.009

Lindner, M. (2018). "Factors affecting the hygroexpansion of paper," *Journal of Materials Science* 53(1), 1-26. DOI: 10.1007/s10853-017-1358-1

Liu, N. W., and Xie, M. H. (2016). "Structure analysis and suggestions of China timber imports," *China Forest Products Industry* 43(9), 10-14. DOI: 10.3969/j.issn.1001-5299.2016.09.004

Longui, E. L., Rajput, K. S., Melo, A. C. G., Alves, L. A., and Nascimento, C. B. (2017). "Root to branch wood anatomical variation and its influence on hydraulic conductivity in five Brazilian Cerrado species," *Bosque* 38(1), 183-193. DOI: 10.4067/s0717-92002017000100018

Mazán, A., Vanco, M., and Barcík, Š. (2017). "Influence of technological parameters on tool durability during machining of juvenile wood," *BioResources* 12(2), 2367-2378. DOI: 10.15376/biores.12.2.2367-2378

Mitchell, M. D., and Denne, M. P. (1997). "Variation in density of *Picea sitchensis* in relation to within-tree trends in tracheid diameter and wall thickness," *Forestry* 70(1), 47-60. DOI: 10.1093/forestry/70.1.47

Mokochinski, F. M., Watzlawick, L. F., Botelho, R. V., and Moreira, V. (2017). "Randomized branch sampling to estimate fruit production in pecan trees cv. 'Barton'," *Cienc. Rural* 47(4), 1-6. DOI: 10.1590/0103-8478cr20151591

Molteberg, D., and Høibø, O. (2006). "Development and variation of wood density, kraft pulp yield, and fibre dimensions in young Norway spruce (*Picea abies*)," *Wood Sci. Technol.* 40(3), 173-189. DOI: 10.1007/s00226-005-0020-2

Nakagawa, M., Hori, M., Umemura, M., and Ishida, T. (2016). "Relationships of wood density and wood chemical traits between stems and coarse roots across 53 Bornean tropical tree species," *J. Trop. Ecol.* 32(2), 175-178. DOI: 10.1017/s0266467416000018

Nilsson, P. O., and Wernius, S. (1976). "Whole-tree utilization: A method of increasing the wood supply," *Ecol. Bull.* 21, 131-136.

Okai, R., Frimpongmensah, K., and Yeboah, D. (2004). "Characterization of strength properties of branchwood and stemwood of some tropical hardwood species,"*Wood Sci. Technol*. 38(2), 163-171. DOI: 10.1007/s00226-004-0232-x

Olarescu, C. M., Campean, M., and Olarescu, A. (2014). "Dimensional stabilization of wood originating from small-diameter trees through heat treatment," *BioResources* 9(3), 4844-4861. DOI: 10.15376/biores.9.3.4844-4861

Pramod, S., and Rao, K. (2012). "Anatomical changes during transition from juvenile to adult wood in branch and main trunk xylem of Subabul (*Leucaena leucocephala*[Lam.] de Wit),"*Journal of Sustainable Forestry* 31(7), 661-673. DOI: 10.1080/10549811.2012.684300

Przybysz, K., Malachowska, E., Martyniak, D., Boruszewski, P., Iłowska, J., Kalinowska, H., and Przybysz, P. (2018). "Yield of pulp, dimensional properties of fibers, and properties of paper produced from fast growing trees and grasses," *BioResources* 13(1), 1372-1387. DOI: 10.15376/biores.13.1.1372-1387

Santini, N. S., Schmitz, N., Bennion, V., and Lovelock, C. E. (2013). "The anatomical basis of the link between density and mechanical strength in mangrove branches," *Funct. Plant Biol.* 40(4), 400-408. DOI: 10.1071/FP12204

Sarmiento, C., and Baraloto, C. (2011). "Within-individual variation of trunk and branch xylem density in tropical trees," *Am. J. Bot.* 98(1), 140-9. DOI: 10.3732/ajb.1000034

Sousa, V. B., Louzada, J. L., and Pereira, H. (2018). "Variation of ring width and wood density in two unmanaged stands of the Mediterranean Oak *Quercus faginea*," *Forests* 9(1), 44. DOI: 10.3390/f9010044
Stokes, A., and Mattheck, C. (1996). "Variation of wood strength in tree roots," *J. Exp.Bot.* 47(298), 693-699. DOI: 10.1093/jxb/47.5.693
Stokke, D. D., and Manwiller, F. G. (1994). "Proportions of wood elements in stem, branch, and root wood of black oak (*Quercus velutina*)," *Iawa J.* 15(3), 1507-1509. DOI: 10.13275/j.cnki.lykxyj.2001.05.002
Su, X., Huang, Q., Zhang, X., Zhang, Q., Bing, W., and Yao, S. (2001). "Study on gene resources in *Populus ussuriensis*," *Forest Research* 14(5), 472-478. DOI: 10.13275/j.cnki.lykxyj.2001.05.002
Thibeault-Martel, M., Krause, C. H., and Rossi, S. (2008). "Cambial activity and intra-annual xylem formation in roots and stems of *Abies balsamea* and *Picea mariana*," *Ann. Bot.-London* 102(5), 667-674. DOI: 10.1093/jxb/47.5.693
Tong, D., Zhang, Y., and Song, K. Y. (2013). "Comparative analysis of longitudinal compressive and bending properties of hydrothermal-treated juvenile and mature elm wood," *BioResources* 8(1), 383-394. DOI: 10.15376/biores.8.1.383-394
Wan Mohamed, W., Baharum, A., Ahmad, I., Abdullah, I., and Zakaria, N. E. (2018). "Effects of fiber size and fiber loading on mechanical properties and morphology of thermoplastic mengkuang reinforced natural rubber composites," *BioResources* 13(2), 2945-2959. DOI: 10.15376/biores.13.2.2945-2959
Wang, Y. J., Sun, W. S., Wang, Q. D., Tang, G., and Feng, G. C. (2009). "Evaluation of plus tree selection of *Populus ussuriensis* in plywood timber forest," *Jilin Forestry Science and Technology* 38(1), 10-13. DOI: 10.1109/ICINFA.2009.5204907
Williams, R. A. (1989). "Use of randomized branch and importance sampling to estimate loblolly pine biomass," *South J. Appl. For.* 13(4), 181-184.
Yu, H., Liu, Y., Han, G., and Cui, Y. (2009). "Comparison of image analysis and conventional methods for cellular tissue proportion measurement of wood," in: *2009 IEEE International Conference on Information and Automation*, Zhuhai, Macau, China, pp. 22-24.
Zhao, X. (2015). "Effects of cambial age and flow path-length on vessel characteristics in birch," *Journal of Forest Research* 20(1), 175-185. DOI: 10.1007/s10310-014-0458-x
Zobel, B. J., and Sprague, J. R. (1998). *Juvenile Wood in Forest Trees*, Springer-Verlag, Berlin, Germany.

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