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Modeling of radial variations of wood properties in naturally regenerated trees of *Betula platyphylla* grown in Selenge, Mongolia

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Abstract

Wood properties, such as annual ring width, wood fiber length, vessel element length, basic density, air-dry density, dynamic Young's modulus, modulus of elasticity (MOE), modulus of rupture (MOR), absorbed energy in impact bending, compressive strength parallel to grain, and shearing strength, were investigated for wood from 10 naturally regenerated trees of *Betula platyphylla* Sukaczew in Mandal, Selenge, Mongolia. Mixed-effects models were used to evaluate the radial variations in the wood properties. The mean values of wood properties obtained in the present study were in almost the same range, with a few exceptions, as those reported by other researchers for other *Betula* species. The radial variations of wood properties in *B. platyphylla* were well-fitted to a nonlinear mixed-effects model (logarithmic formula); all examined wood properties increased from the pith and then became constant toward the bark side. The wood properties significantly differed between the core and outer wood. Basic density, air-dry density, and dynamic Young's modulus were significantly correlated with MOE, MOR, and compressive strength. It is concluded that when the wood of *B. platyphylla* is utilized as raw materials for solid wood products, the differences between the core wood and outer wood should be considered. In addition, the selection of wood with higher strength properties can be achieved using the wood density and dynamic Young's modulus as indicators.

Keywords: *Betula platyphylla*, Core wood, Outer wood, Wood properties

Introduction

The *Betula* species is distributed in the temperate to sub-arctic zones of northeast Asia, including western and northern China, Japan, Korea, and Mongolia [1–6]. The basic wood properties of the *Betula* species have been investigated by several researchers for efficient utilization of the wood from this species (e.g., [1, 7–9]).

Understanding the radial variation of wood properties is important for utilizing wood resources. In

general, wood properties in hardwoods vary within the tree: unstable wood properties are found in core wood near the pith, while stable properties are found in the outer wood near the bark or cambium [10–14]. The radial variations in cell length are usually used to determine the boundary between these two regions in hardwood species [9, 14, 15]. In *Betula platyphylla* Sukaczew var. *japonica* (Miq.) H. Hara naturally grown in Japan, we recently reported that the boundary determined by radial variations of fiber length was around 1.5 to 4.2 cm from the pith or the 10th to 17th annual ring from the pith [9]. Similar results in terms of radial variations of the density and mechanical properties have been obtained in other *Betula* species (e.g., *B.*

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ermanii Cham., *B. maximowicziana* Regel, *B. pendula* Roth, and *B. platyphylla*), where the region around 5 to 8 cm from the pith has been clearly marked as a low-density and low-strength properties region [16–18]. These radial variations of wood properties might be related to the xylem maturation process [9, 11–15, 18]. Therefore, further research is needed to clarify the xylem maturation process for *B. platyphylla* trees grown in Mongolia to understand the core wood and outer wood properties.

The relationships between growth characteristics and wood properties have been investigated for both softwoods and hardwoods [10, 11, 19]. Several researchers have investigated these relationships in *Betula* species specifically (e.g., [2, 3, 8, 9, 20]). Heräjärvi [20] reported significant positive correlations between wood density and static bending properties, such as the modulus of elasticity (MOE) and modulus of rupture (MOR), in 60–90-year-old *B. pendula* and *B. pubescens* Ehrh. trees grown on a plantation in Finland. When correlations were investigated between growth rate with cell length, specific gravity, and mechanical properties for *B. pendula*, *B. platyphylla*, *B. pubescens*, and *B. utilis*, growth rate had very little correlation with the wood properties in these *Betula* species [1, 2]. However, relationships among the growth characteristics and/or wood

properties are still unclear for *B. platyphylla* trees grown in Mongolia.

The objectives of this study are to investigate the wood properties of *B. platyphylla* trees naturally grown in Mandal, Selenge, Mongolia to establish the sustainable forestry and effectively utilize the wood resources. Radial variations of wood properties were evaluated by developing linear or nonlinear mixed-effects models. In addition, the differences in wood properties between core wood and outer wood. Furthermore, the relationships among measured wood properties were also investigated.

Materials and methods

Materials

Figure 1 shows the experimental procedures followed in the present study. Ten *Betula platyphylla* Sukaczew trees were collected from a natural forest in Mandal, Selenge, Mongolia (36° 47' N, 139° 29' E; approximately 1100 m above the sea level). Although tree age was unknown, because these were naturally regenerated trees, the number of annual rings ranged from 33 to 70 at 1.8 m above the ground level (Fig. 1). The stem diameter measured at 1.3 m above the ground by a tape measure (F10-020DM, KDS, Kyoto, Japan) ranged from 13.2 to 23.0 cm (mean = 15.4 cm) (Fig. 1). After harvesting the trees, two disks (1 cm in thickness) and logs (ca. 50 cm in length)

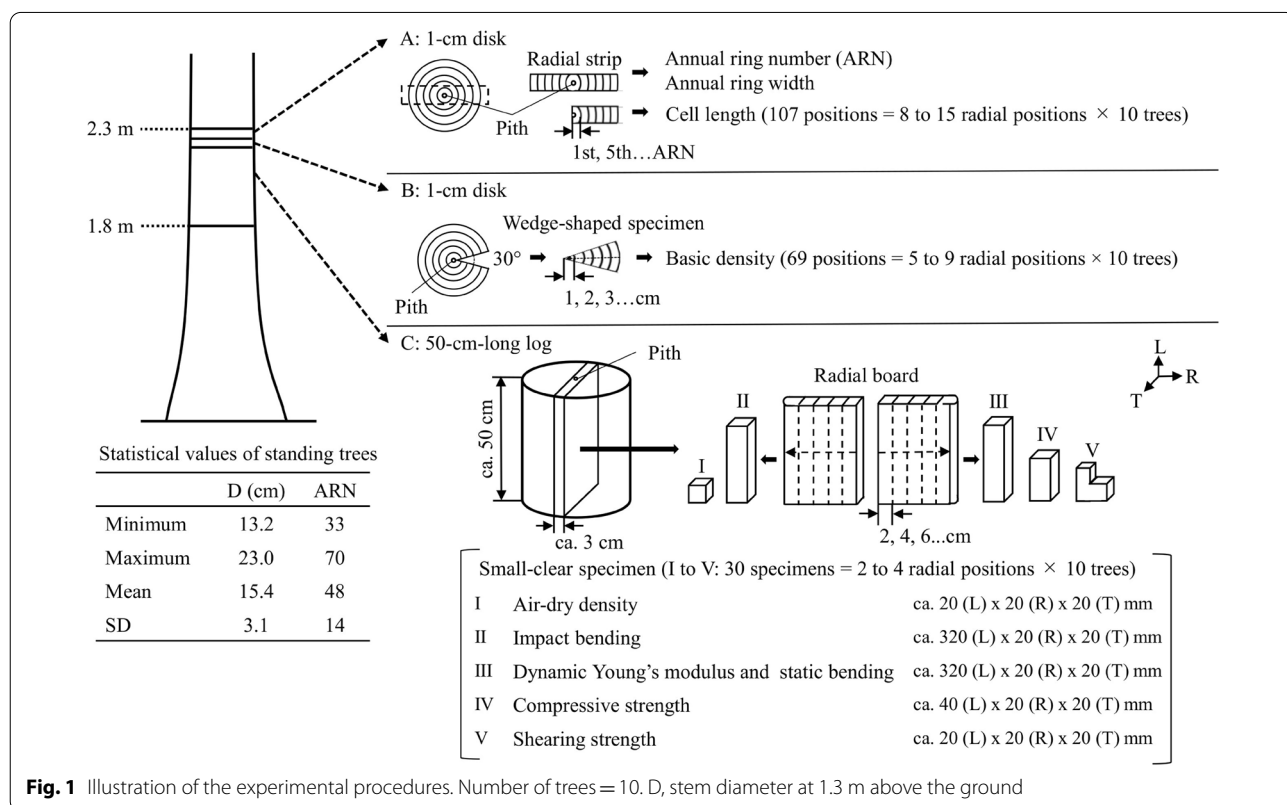


Fig. 1 Illustration of the experimental procedures. Number of trees = 10. D, stem diameter at 1.3 m above the ground

were obtained for each tree from 1.8 to 2.3 m above the ground (Fig. 1).

Annual ring width and cell length

Bark-to-bark radial strips, 10 mm in thickness, were obtained from 1-cm disks to measure the annual ring number and width (Fig. 1). The transverse sectional images (600 dpi) of radial strips in one direction from the pith to bark were captured using a scanner (GT-9300UF, Epson, Nagano, Japan). The annual ring width was measured using ImageJ (National Institutes of Health, Bethesda, MD, USA).

To determine the length of the wood fiber and vessel element, pith-to-bark radial strips (10 mm in thickness) were also obtained from the 1-cm disks (Fig. 1). Small stick specimens were obtained at 5-year intervals from the pith-to-bark radial strips. The stick specimens were collected from a total of 107 radial positions (eight to 15 radial positions \times 10 trees). The stick specimens were macerated with Schultze's solution (6 g of potassium chlorate in 100 mL of 35% nitric acid). A total of 50 wood fibers and 30 vessel elements at each radial position were measured using a micro projector (V-12, Nikon, Tokyo, Japan) and a digital caliper (CD-15CP, Mitutoyo, Tokyo, Japan).

Physical and mechanical properties

In the present study, the following physical and mechanical properties were determined: basic density, air-dry density, dynamic Young's modulus, static bending, impact bending, compressive strength, and shearing strength (Fig. 1).

To determine the basic density, wedge-shaped specimens (30° at the central angle) were prepared from the disk (Fig. 1). The wedge-shaped specimens were then cut again into smaller specimens at 1-cm intervals from the pith. The basic density was calculated by dividing the oven-dried weight by the green volume measured using the water displacement method.

Physical and mechanical properties, except for basic density and air-dry density, were measured according to Japanese Industrial Standard Z 2101:2009 [21]. Radial boards about 3 cm in thickness were obtained from approximately 50-cm-long logs (Fig. 1). The boards were dried in the laboratory at 22 °C and 65% relative humidity for 3 months. After air drying, the boards were planed to a thickness of 20 mm in the tangential direction, and then stick specimens were obtained at 20-mm intervals from the pith. The following specimens were prepared: air-dry density specimens of approximately 20 (L) by 20 (R) by 20 (T) mm; dynamic Young's modulus, static, and impact bending specimens of approximately 320 (L) by 20 (R) by 20 (T) mm; compressive strength specimens of

approximately 40 (L) by 20 (R) by 20 (T) mm; and shearing strength specimens (chair shape) of approximately 20 (L) by 20 (R) by 20 (T) mm. A total of 30 specimens (two to four radial positions \times 10 trees) were obtained from 10 sample logs.

To determine the air-dry density, small clear specimens were dried in the laboratory at 22 °C and 65% relative humidity for 2 weeks. Air-dried density was calculated by dividing the weight by the volume for the three measured dimensions. Moisture content at testing was also determined by the oven-dry method.

The dynamic Young's modulus of small-clear specimens was measured by the lateral vibrational method [22]. A fast Fourier transform comparator (CF-4500, Ono Sokki, Yokohama, Japan) with a sound level meter (LA-4440, Ono Sokki, Yokohama, Japan) and microphone (MI-3110, Ono Sokki, Yokohama, Japan) were used to measure the first natural frequency of lateral vibration due to sound emitted by hitting the radial section of a specimen with a small steel hammer.

The static bending test was conducted using a universal testing machine (MSC-5/500-2, Tokyo Testing Machine, Tokyo, Japan). The load was applied to the radial surface at the center of the span (280 mm) at a rate of 5 mm/min. The MOE and MOR were calculated from the load and deflection data. The moisture content of the specimens at testing was $10.7 \pm 0.2\%$.

The impact bending test was conducted using a Charpy impact testing machine with 98-J capacity at maximum pendulum height (162°; MC-10W, Maekawa Testing Machine MFG, Tokyo, Japan). The load was applied to the radial surface at the center of the specimens. The impact work in joules was obtained by the machine's indicator. The absorbed energy during impact bending was calculated by dividing the impact work by the cross-sectional area of the specimen. The moisture content of the specimens at testing was $9.9 \pm 0.3\%$.

The compressive strength test was conducted using a universal testing machine (RTF-2350, A&D, Tokyo, Japan) at a load speed of 0.5 mm/min. The compressive strength parallel to the grain was calculated by dividing the maximum load by the cross-sectional area of the specimen. The moisture content was $10.7 \pm 0.2\%$ at testing.

The shearing strength test was conducted using a universal testing machine (MSC-5/500-2) with a load rate of 0.5 mm/min. The shearing strength was determined by dividing the maximum load by the plane area. The moisture content of the specimens was $10.1 \pm 0.2\%$ at testing.

Statistical analyses

Statistical analyses were conducted using R software [23]. To evaluate the radial variations, data of the physical and

mechanical properties determined at 1- or 2-cm intervals from the pith were converted to cambial age by the radial variation in the annual ring width. The annual ring number from the pith in a specimen was regarded as the annual ring number from the pith at the middle position of the 1- or 2-cm specimens.

To estimate the distance from the pith in relation to the annual ring number, a nonlinear mixed-effects model was developed using the nlme function in the nlme package [24]. The following model was developed:

$$y_{ij} = \alpha_0 / \{1 + (\alpha_1 + a_j) \cdot \exp(-\alpha_2 \cdot x_{ij})\} + e_{ij}$$

where y_{ij} is the estimated distance from the pith in relation to the i th annual ring number of the j th individual tree; x_{ij} is the i th annual ring number from the pith of the j th individual tree; α_0 , α_1 , and α_2 are fixed-effect parameters; a_j is a random effect parameter for the individual tree; e_{ij} is residual.

Linear and nonlinear mixed-effects models with random effects at the tree level were developed to determine radial variation in the wood properties in relation to the annual ring number from the pith using the lmer function in the lme4 packages [25] and the nlme function in the nlme package [24], respectively. The following models were developed:

$$\text{Model I : } y_{ij} = \beta_0 x_{ij} + \beta_1 + u_j + e_{ij}$$

$$\text{Model II : } y_{ij} = \beta_0 \ln(x_{ij}) + \beta_1 + u_j + e_{ij}$$

$$\text{Model III : } y_{ij} = \beta_0 x_{ij}^2 + \beta_1 x_{ij} + \beta_2 + u_j + e_{ij}$$

where y_{ij} is the measured value for the i th annual ring number from the pith of the j th individual tree; x_{ij} is the i th annual ring number from the pith of the j th individual tree; α_0 , α_1 , and α_2 are fixed effect parameters; u_j is random effect parameter of the j th individual tree; e_{ij} is residual.

Model selection was performed using the Akaike Information Criterion (AIC) [26]. The best model (smallest AIC value) was selected from the developed models.

To evaluate the boundary between the core wood and outer wood, wood fiber length at each annual ring number was estimated using the regression formula based on the best model (selected by AIC value). The boundary was defined as the increase ratio of wood fiber length in the present year to one previous year reached 1.0% [9, 15]. In addition, each wood property was estimated at the annual ring number from the pith to the 70th annual ring number from the pith in each tree by the regression formula based on the best model. Mean values of each wood property in each tree were calculated for the core

wood (from first to boundary annual ring number determined by the annual increment of wood fiber length) and outer wood (from boundary annual ring number to 70th annual ring). A significant difference in estimated wood properties between the core wood and outer wood was detected by conducting a paired t test for the mean values of 10 trees. The relationships among the examined wood properties of the small clear specimens were determined using Pearson’s correlation coefficient.

Results and discussion

Annual ring width

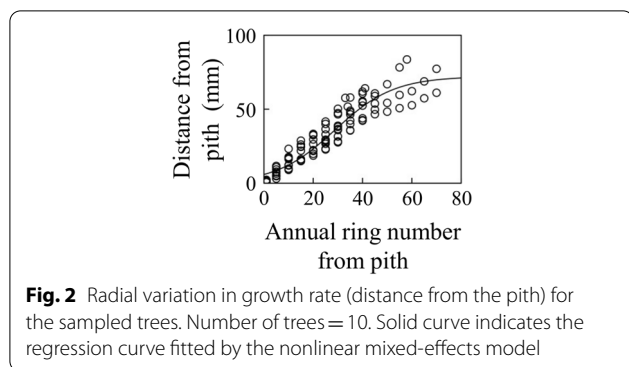
The mean value of the annual ring width (1.37 mm; Table 1) was similar to those of *Betula* species grown in Mongolia, Japan [8, 9], and Finland [27]. Figure 2 shows the distance from the pith in relation to the annual ring number from the pith. The distance from the pith in relation to the annual ring number was well-adapted to logistic functions based on the random effects of individual trees. Lee et al. [28] reported that the coefficient α_0 in the logistic formula used in the present study represents an upper limit of growth determined by environmental conditions, and its derivative $\alpha_0/2$ gives the possible maximum growth rate of y . In the present study, the coefficient α_0 was 72.086, suggesting that the y value showing the maximum growth rate was 36.043. Thus, the annual ring

Table 1 Statistical values of wood properties for the sampled trees

Property	Minimum	Maximum	Mean	SD
Annual ring width (mm)	0.87	1.75	1.37	0.25
WFL (mm)	0.93	1.21	1.03	0.09
VEL (mm)	0.55	0.71	0.61	0.05
BD (g/cm ³)	0.45	0.61	0.55	0.05
AD (g/cm ³)	0.58	0.75	0.64	0.05
DMOE (GPa)	7.84	13.50	11.20	1.95
MOE (GPa)	6.14	10.56	8.75	1.44
MOR (MPa)	63.2	109.8	85.8	14.6
U (kJ/m ²)	49.0	92.2	72.3	16.8
CS (MPa)	36.9	50.3	43.5	4.7
SS (MPa)	7.7	11.8	9.4	1.3

Number of trees = 10. SD, standard deviation; WFL, wood fiber length; VEL, vessel element length; BD, basic density; AD, air-dry density after drying at around 22 °C and 65% relative humidity for 2 weeks (11.3 ± 0.5% of moisture content); DMOE, dynamic Young’s modulus; MOE, modulus of elasticity; MOR, modulus of rupture; U, absorbed energy in impact bending; CS, compressive strength parallel to grain; SS, shearing strength of small clear specimens. Mean values of moisture content of specimens were 10.7 ± 0.2%, 9.9 ± 0.3%, 10.7 ± 0.2%, and 10.1 ± 0.2% for static bending, impact bending, compressive strength, and shearing strength specimens, respectively

number from the pith showing the maximum growth rate was 28.8. In addition, the radial growth stabilized around



the 60th annual ring number from the pith (Fig. 2). Thus, the optimum harvesting age for *B. platyphylla* grown in Mongolia is between 30 and 60 years according to the diameter growth rate.

Mean values of wood properties

Table 1 shows the mean values of the wood properties of *B. platyphylla* naturally grown in Mongolia. Wood fiber length and vessel element length ranged from 0.93 to 1.21 mm and from 0.55 to 0.71 mm, respectively. Mean values of basic density and air-dry density were 0.55 and 0.64 g/cm³, respectively. In addition, the mean value of dynamic Young's modulus was 11.20 GPa, MOE was 8.75 GPa, MOR was 85.8 MPa, absorbed energy in impact bending was 72.3 kJ/m², compressive strength was 43.5 MPa, and shearing strength was 9.4 MPa. The mean values for cell length were similar to those obtained by previous researchers for the same species or genus (Table 2) [1, 9]. Although MOE and MOR showed similar values with those of the same species [3, 9, 17], these values were relatively low compared to those in the same genus [17, 20, 29–32].

Modeling of radial variations of wood properties

In the present study, radial variations of wood properties were fitted to three different mixed-effects models: linear, logarithmic, and quadratic formula. Table 3 shows AIC values in developed models for each wood property. For all properties, Model II (the logarithmic formula) showed the smallest AIC values among the three developed models. The regression curves for the fixed effects in the selected logarithmic formula are shown in Fig. 3. All wood properties increased from the pith to the bark and then became constant toward the bark side. The radial variations in the wood properties in the present study were similar to those obtained for the same species or the same genus in other studies [1, 8–10, 16, 17, 20, 30].

Erdene-Ochir et al. [9] reported that the wood properties of *B. platyphylla* naturally grown in Mongolia

differed between the core wood and outer wood; the boundary determined by radial variations in the basic density and compressive strength was around 2 cm from the pith or the 10th to 20th annual ring from the pith. In *B. platyphylla* naturally grown in Japan, the boundary determined by fiber length was 1.5 to 4.2 cm or the 10th to 17th annual ring from the pith. In the present study, the boundary between the core wood and outer wood was determined by the annual increment in wood fiber length at each annual ring number estimated by Model II (Table 3). Table 4 shows the boundary annual ring number for each tree. The annual ring number from the pith at the boundary between the core wood and outer wood ranged from the 15th to 17th annual ring number from the pith. The obtained boundary annual ring number in the present study was in accordance with the *B. platyphylla* trees grown in Mongolia and Japan [8, 9].

To compare the wood properties between the core wood and outer wood, all examined properties were estimated using the best models for evaluating the radial variations of wood properties (Model II; Table 3). Significant differences were found between the core wood and outer wood for all examined wood properties (Table 5). Compared with the core wood, wood with a longer cell length, higher density, and higher strength could be obtained from the outer wood (outside the 20th annual ring from the pith). These differences in wood properties may affect wood utilization of this species; outer wood can be used as high-quality wood for structural products, furniture, and other uses.

Figure 4 shows the relationship between the mean annual ring width until the boundary annual ring number (cambial age) between the core wood and outer wood and annual ring number from the pith at the boundary. No significant negative correlation coefficient was found between annual ring width until the boundary ring number and the annual ring number from the pith at the boundary ($r = -0.17$, $p < 0.645$), indicating that the radial growth rate at the early growth stage did not affect the xylem maturation age in *B. platyphylla* trees grown in Mongolia.

Relationships among measured wood properties

Table 6 shows the correlation coefficients among all examined wood properties of the sampled trees. A significant correlation coefficient ($r = 0.89$, $p < 0.001$) was found between the wood fiber length and vessel element length, suggesting that the length of wood fibers and vessel elements is closely linked to each other for this species. A similar tendency was also observed in the studies by [1] and [9].

Previous studies investigating the correlation of radial growth rate with cell length, wood density, and

Table 2 Comparison of wood properties of *B. platyphylla* grown in Mongolia with other *Betula* species

Species	Country	Tree age	WFL (mm)	VEL (mm)	BD (mm)	BD (g/cm ³)	AD (g/cm ³)	DMOE (GPa)	MOE (GPa)	MOR (MPa)	U (kJ/m ²)	CS (MPa)	SS (MPa)	References
<i>B. platyphylla</i>	Mongolia	33–70	1.03	0.61	0.55	0.64	11.20	8.75	85.8	72.3	43.5	9.4	9.4	Present study
	Japan	44			0.59			10.9	92.8	52.7				[17]
<i>B. utilic</i>	China	49–60	1.20	0.70	0.48	0.58	12.40	9.89	97.8	75.9–128.2	45.1			[9]
	UK	UK						9.25	90.9	41.8				[3]
<i>B. grossa</i>	China	UK						9.55	102.4	44.4				[3]
	Japan	UK	0.5–2.1	0.6–1.2		0.72		13.7	107.9	49.0	137.1	9.8–18.6		[29]
<i>B. maximowicziana</i>	Japan	49				0.64		12.7	117.4	58.9				[17]
	Japan	UK	0.5–2.1	0.6–1.2		0.67		12.7	102.9	47.1	98.1	8.8–18.6		[29]
<i>B. ermanii</i>	Japan	UK				0.60		12.3	105.1	45.7	93.7			[31]
	Japan	43				0.70		13.7	119.3	61.2				[17]
<i>B. pendula</i>	Finland	45–56	1.17	0.76	0.48									[1]
	UK	UK				0.51		14.5	113.9					[20]
<i>B. pubescens</i>	Finland	45–56	1.11	0.78	0.44									[1]
	UK	UK				0.48		13.2	104.1					[20]
<i>B. alleghaniensis</i>	U.S.A	UK									89.0			[32]
<i>B. papyrifera</i>	U.S.A	UK									48.5			[32]

WFL, wood fiber length; VEL, vessel element length; BD, basic density; AD, air-dry density; DMOE, dynamic Young's modulus; MOE, modulus of elasticity; MOR, modulus of rupture; U, absorbed energy in impact bending; CS, compressive strength; SS, shearing strength; UK, unknown

Table 3 Comparison of AIC values in the linear and nonlinear mixed-effects models for radial variations in the wood properties in relation to cambial age

Property	Model I	Model II	Model III
WFL	-138.98	-224.91	-192.38
VEL	-315.07	-325.41	-320.24
BD	-209.97	-239.75	-209.04
AD	-62.67	-71.25	-45.98
DMOE	123.38	110.54	128.95
MOE	113.46	103.43	123.21
MOR	258.10	252.49	266.34
U	248.73	242.57	253.86
CS	184.71	175.35	193.46
SS	112.06	98.46	123.28

Number of trees = 10. AIC, Akaike Information Criterion; WFL, wood fiber length; VEL, vessel element length; BD, basic density; AD, air-dry density after drying at around 22 °C and 65% relative humidity for 2 weeks (11.3 ± 0.5% of moisture content); DMOE, dynamic Young’s modulus; MOE, modulus of elasticity; MOR, modulus of rupture; U, absorbed energy in impact bending; CS, compressive strength parallel to grain; SS, shearing strength of small clear specimens. Formulae for the models are listed in Table 2. Bold indicates the smallest AIC among the developed models for each of the examined wood properties

mechanical properties (MOE, MOR, and compressive strength) in *B. pendula*, *B. platyphylla*, *B. pubescens*, and *B. utilis* concluded that radial growth rate had no significant influence on cell length, wood density, or the mechanical properties for *Betula* species [1, 3, 9]. In addition, there is little correlation between ring width and wood density in diffuse-porous wood [11]. In the present study, stem diameter/annual ring width was not found to be significantly correlated with cell length, basic density, or most mechanical properties. The exceptions were negative correlations found for annual ring width with air-dry density, MOR, and compressive strength (Table 6). These results indicated that cell length, basic density, and most of the mechanical properties of *B. platyphylla* are independent from growth characteristics.

It is well-known that wood density is closely related to mechanical properties [3, 10, 11, 19]. As shown in Table 6, basic density or air-dry density was positively correlated with dynamic Young’s modulus, MOE, MOR, and compressive strength but not with absorbed energy in impact bending or shearing strength. These results indicate that wood density is a good indicator for predicting the strength properties of *B. platyphylla* wood. Dynamic Young’s modulus was found to be positively significantly correlated with MOE, MOR, and compressive strength (Table 6), suggesting that the mechanical properties of *B. platyphylla* (except for absorbed energy in impact bending and shearing strength) can be predicted by dynamic Young’s modulus.

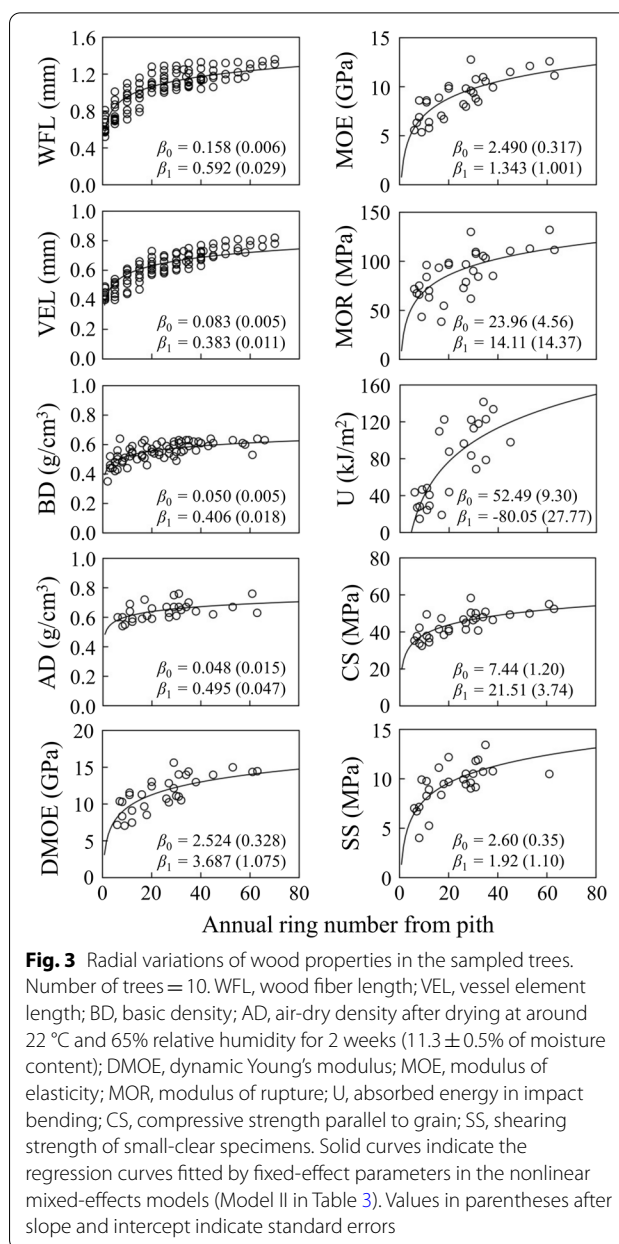


Fig. 3 Radial variations of wood properties in the sampled trees. Number of trees = 10. WFL, wood fiber length; VEL, vessel element length; BD, basic density; AD, air-dry density after drying at around 22 °C and 65% relative humidity for 2 weeks (11.3 ± 0.5% of moisture content); DMOE, dynamic Young’s modulus; MOE, modulus of elasticity; MOR, modulus of rupture; U, absorbed energy in impact bending; CS, compressive strength parallel to grain; SS, shearing strength of small-clear specimens. Solid curves indicate the regression curves fitted by fixed-effect parameters in the nonlinear mixed-effects models (Model II in Table 3). Values in parentheses after slope and intercept indicate standard errors

Implications of sustainable forestry and wood utilization in Mongolia

In the present study, result of radial growth rate indicated that optimum harvesting age in respect to radial growth rate was 30–60 years for *B. platyphylla* grown in Mongolia (Fig. 2). Even in climatic conditions are severe in Mongolia, *B. platyphylla* trees can grow well and wood resources of *B. platyphylla* can be sustainably obtained from 30 to 60 year rotation, suggesting that sustainable forestry might be established in Mongolia.

Based on the regression models for radial variations of cell length, physical and mechanical properties (Fig. 3

Table 4 Annual ring number at the boundary between the core wood and outer wood as determined by the regression formula based on the best model for wood fiber length in each tree

Tree number	u_i	Boundary annual ring number
1	0.133	15
2	-0.010	16
3	0.106	15
4	0.032	15
5	-0.019	16
6	-0.082	17
7	-0.053	17
8	-0.070	17
9	0.006	16
10	0.042	16

u_i , random effect parameter at individual tree level. Wood fiber length at every annual ring was estimated by Model II ($y_{ij} = \beta_0 \ln(x_{ij}) + \beta_1 + u_i + e_{ij}$; $\beta_0 = 0.158$, $\beta_1 = 0.592$) listed in Table 2. Annual ring number at the boundary was regarded as the annual ring number at which the annual increment of wood fiber length became less than 1%

Table 5 Estimations of wood properties of the core wood and outer wood using the best model for comparison between core wood and outer wood

Property	Core wood		Outer wood		t value (p value)
	Mean	SD	Mean	SD	
WFL (mm)	0.89	0.07	1.17	0.07	-0.281 (<0.001)
VEL (mm)	0.54	0.01	0.69	0.01	-0.146 (<0.001)
BD (g/cm ³)	0.50	0.03	0.59	0.03	-0.089 (<0.001)
AD (g/cm ³)	0.59	0.00	0.67	0.00	-0.085 (<0.001)
DMOE (GPa)	8.52	1.08	13.02	1.09	-4.499 (<0.001)
MOE (GPa)	5.65	1.35	9.70	2.51	-4.049 (<0.001)
MOR (MPa)	60.0	6.5	102.8	6.8	-42.731 (<0.001)
U (kJ/m ²)	40.5	3.5	113.9	5.2	-73.349 (<0.001)
CS (MPa)	35.8	0.7	49.0	0.7	-13.260 (<0.001)
SS (MPa)	6.8	1.1	11.4	1.0	-4.550 (<0.001)

Number of trees = 10. WFL, wood fiber length; VEL, vessel element length; BD, basic density; AD, air-dry density after drying at around 22 °C and 65% relative humidity for 2 weeks ($11.3 \pm 0.5\%$ of moisture content); DMOE, dynamic Young's modulus; MOE, modulus of elasticity; MOR, modulus of rupture; U, absorbed energy in impact bending; CS, compressive strength parallel to grain; SS, shearing strength of small clear specimens. Wood properties were estimated from the first to 70th annual ring in each tree using the best developed model for the radial pattern (Model II, Tables 2 and 5). The means and standard deviations (SDs) of the core wood and outer wood were calculated from the first ring to boundary age (listed in Table 6) and from the boundary age to 70th annual ring, respectively. Significant differences between the core and outer wood were detected using a paired t test

and Table 3), the wood of this species can be divided into two parts, core wood and outer wood, at around 15th to 17th annual ring number from the pith (Tables 4 and 5). The core wood was characterized by unstable values

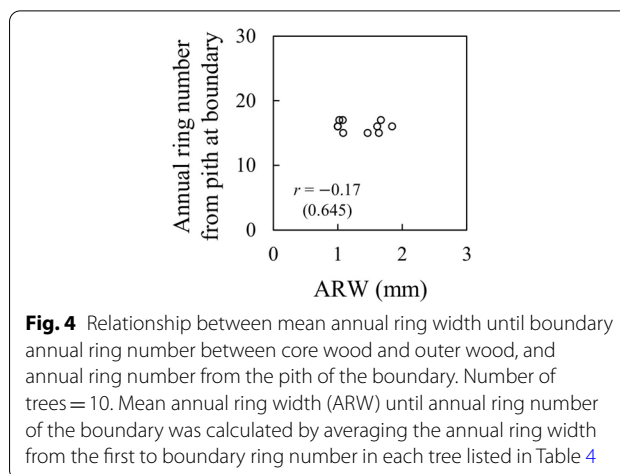


Fig. 4 Relationship between mean annual ring width until boundary annual ring number between core wood and outer wood, and annual ring number from the pith of the boundary. Number of trees = 10. Mean annual ring width (ARW) until annual ring number of the boundary was calculated by averaging the annual ring width from the first to boundary ring number in each tree listed in Table 4

of anatomical characteristics as well as cell length, and physical and mechanical properties, whereas outer wood has stable values. Therefore, it is suggested that when the wood of *B. platyphylla* is utilized, the presence of core wood and outer wood should be considered. The core wood of this species should be used for fuel wood, raw materials for charcoal, pulp and paper, and wood-based materials. On the other hand, the outer wood with stable properties can be used for furniture, interior wood, and structural lumber.

Conclusions

In the present study, wood properties were investigated for 10 naturally regenerated *B. platyphylla* trees grown in Mandal, Selenge, Mongolia to effectively utilize the wood resources. The mean values of wood properties of *B. platyphylla* grown in Mongolia were similar with those in *B. platyphylla* trees grown in Mongolia and Japan and *B. pendula* and *B. pubescens* grown in Finland. A nonlinear mixed-effects model (logarithmic formula) was well-adapted to the radial variations in the wood properties of *B. platyphylla*; all examined properties increased from the pith toward the bark side (increase in the number of annual rings) and then stabilized toward the bark. The wood properties significantly differed between the core and outer wood. In addition, the radial growth rate at the early growth stage did not affect the xylem maturation age in *B. platyphylla* trees grown in Mongolia. Based on the results of the correlation analysis, the cell length and most of the physical and mechanical properties of *B. platyphylla* were independent from growth characteristics. Significant positive correlations were obtained for basic density, air-dry density, and dynamic Young's modulus with mechanical properties (i.e., MOE, MOR, and compressive strength). When the wood of *B. platyphylla* is utilized in industrial materials, the differences between

Table 6 Correlation coefficients and significant correlations *p* values among measured wood properties of the sampled trees

Property	D	ARW	WFL	VEL	BD	AD	DMOE	MOE	MOR	U	CS	SS
D		0.701	0.765	0.858	0.459	0.471	0.214	0.230	0.946	0.348	0.066	0.670
ARW	-0.14		0.235	0.153	0.090	0.031	0.213	0.198	0.035	0.854	0.035	0.740
WFL	-0.11	-0.41		0.000	0.362	0.244	0.092	0.054	0.028	0.472	0.122	0.042
VEL	0.07	-0.49	0.89		0.167	0.062	0.010	0.005	0.009	0.303	0.013	0.144
BD	0.27	-0.56	0.32	0.47		0.209	0.031	0.038	0.030	0.899	0.027	0.581
AD	0.26	-0.68	0.41	0.61	0.43		0.046	0.064	0.089	0.407	0.008	0.672
DMOE	0.43	-0.43	0.56	0.76	0.68	0.64		0.000	0.003	0.251	0.002	0.991
MOE	0.42	-0.44	0.62	0.80	0.66	0.61	0.99		0.002	0.237	0.002	0.887
MOR	0.02	-0.67	0.69	0.77	0.68	0.57	0.83	0.85		0.100	0.024	0.977
U	0.33	-0.07	-0.26	-0.36	0.05	-0.30	-0.40	-0.41	-0.55		0.766	0.621
CS	0.60	-0.67	0.52	0.75	0.69	0.78	0.85	0.85	0.70	-0.11		0.917
SS	0.15	-0.12	-0.65	-0.50	0.20	-0.15	0.00	-0.05	-0.01	-0.18	-0.04	

Number of trees = 10. D, stem diameter at 1.3 m above the ground; ARW, annual ring width; WFL, wood fiber length; VEL, vessel element length; BD, basic density; AD, air-dry density after drying at around 22 °C and 65% relative humidity for 2 weeks ($11.3 \pm 0.5\%$ of moisture content); DMOE, dynamic Young's modulus; MOE, modulus of elasticity; MOR, modulus of rupture; U, absorbed energy in impact bending; CS, compressive strength parallel to grain; SS, shearing strength of small clear specimens. Values in left and right sides of diagonal show correlation coefficients and significant correlations *p* values. Correlation coefficients with bold style indicate correlation coefficients with *p* value less than 0.05

the core wood and outer wood should be considered. In addition, wood density and dynamic Young's modulus are suitable for predicting the higher strength properties of wood in this species.

Abbreviations

MOE: Modulus of elasticity; MOR: Modulus of rupture; AIC: Akaike information criterion.

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Authors' contributions

TE contributed to experiments, data analysis, and writing the manuscript. FI designed this study and contributed to experiments, data analysis, and writing the manuscript. IN contributed to experiments and data analysis. BT, BB and GC contributed to experiments. JO and SY contributed to discussion on the obtained results. All authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

The wood samples used in the present study were collected with the observance of Mongolian laws.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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