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Utilization potential of naturally regenerated Mongolian *Betula platyphylla* wood based on growth characteristics and wood properties

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Highlights

- Wood with high density and high compressive strength can be obtained near to the bark of *Betula platyphylla* trees.
- Basic density of *B. platyphylla* wood may be predicted by the stress-wave velocity of stems.
- Growth characteristics are positively correlated with stress-wave velocity and basic density.
- Early evaluation of basic density is possible when using the wood at 2 cm from the pith.
- A significant between-site variation was found in the basic density at the position from the 1st to the 15th annual ring from the pith.
- Wood from *B. platyphylla* trees grown in Mongolia may be used for industrial products equally to the same species in other countries.

Abstract

To preliminary evaluate the potential wood utilization of *Betula platyphylla* Sukaczew trees naturally regenerated in Mongolia, growth characteristics (stem diameter and tree height), wood properties (annual ring width, basic density, and compressive strength parallel to grain at the green condition) of core samples, and stress-wave velocity in stems were investigated for *Betula platyphylla* trees grown naturally in three different sites in Selenge, Mongolia. *Betula platyphylla* trees, naturally grown in Nikko, Japan, were also examined to compare wood properties between the two regions. The mean values of stem diameter, tree height, stress-wave velocity of stems, annual ring width, basic density, and compressive strength parallel to grain at green condition in Mongolian *B. platyphylla* were 17.6 cm, 14.1 m, 3.50 km s⁻¹, 1.27 mm, 0.51 g cm⁻³, and 20.4 MPa, respectively. Basic density and compressive strength were decreased first from the pith, and then gradually increased toward the bark. The wood properties of *B. platyphylla* trees grown naturally in Mongolia were similar to those in *B. platyphylla* trees grown in Japan. Growth characteristics, especially stem diameter, were positively correlated with the stress-wave velocity of stems and basic density. Early evaluation of basic density in *B. platyphylla* trees is possible by using wood located 2 cm from the pith. Basic density at the position from the 1st to the 15th annual ring from the pith showed significant between-site differences in Mongolian *B. platyphylla*. Based on the results, it is concluded that the wood of *B. platyphylla* trees grown in Mongolia may be used for industrial products as well as those from similar species in other countries.

Keywords basic density; compressive strength; early evaluation; stress-wave velocity

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1 Introduction

Betula platyphylla Sukaczew (later *Betula platyphylla* in this study) is a pioneer and fast-growing tree species in temperate to subarctic zones (Zhang 1997; Johnson and More 2004; Mao et al. 2010). *Betula platyphylla* is distributed in Northeast Asia, such as western and northern China, Japan, Korea, Mongolia, and Russia (eFloras 2008). In northern Europe, the other *Betula* species, *Betula pendula* Roth and *Betula pubescens* Ehrh., have been used as main hardwood species in forest regeneration and plantation (Hynynen et al. 2010). In addition, *Betula alleghaniensis* Britton, *Betula papyrifera* Marshall, and *Betula lenta* L. have been used as plantation species to produce wood for industrial utilization in the United States of America (Verkasalo 1990).

The wood properties of *Betula* species have been investigated by several researchers (for example, Hakkila 1966; Bhat 1980; Verkasalo 1990; Heräjärvi 2004a,b; Repola 2006; Luostarinen et al. 2009; Viherä-Aarnio and Velling 2017; Lachowicz et al. 2019). The wood has been used widely for charcoal, fuel, pulps, printing papers, and paperboard as well as raw materials for sawn timber, veneer, and plywood (Luostarinen and Verkasalo 2000; Heräjärvi 2002; Bekhta et al. 2009; Dubois et al. 2020). In European countries, such as in Finland, the wood of *Betula* species has been utilized for a multitude of industrial and bioenergy products (e.g., Kärhä 2011).

Stress-wave techniques are a well-known, nondestructive testing methods used to evaluate wood quality, especially density, stability and mechanical properties (Smulski 1991; Wang et al. 2001, 2004; Ishiguri et al. 2008; Yin et al. 2011). Wood density is known to strongly affect the physical and mechanical properties of wood (Kollman and Côté 1984). Therefore, the stress-wave velocity of stems and basic density are important indicators when evaluating wood properties. Shmulsky and Jones (2011) mentioned that understanding the radial variations of wood properties is important for utilizing the wood resources.

In Mongolia, *B. platyphylla* occupies approximately 10% of the total forest area, comprising about 6% of total forest stock volume, as stated by the Ministry of Environment and Tourism (2016). In contrast to the abundance of forest resources in this species, its wood is only utilized by households for firewood or small wooden artifacts. In other words, the wood utilization level of *B. platyphylla* in Mongolia is lower compared to that of similar species growing in other countries. Detailed information about the wood is required for *B. platyphylla* grown in Mongolia to promote the wood utilization of this species. However, only a few studies are available regarding this issue (Sambuu and Dolgorhuu 2009). Regarding to the utilization of wood resources of this species, basic information about wood is also needed for tree breeding programs for wood quality in the future establishment of plantations in Mongolia.

The objective of this study is to preliminarily evaluate the potential wood utilization on the basis of growth characteristics (stem diameter and tree height) and selected wood properties (annual ring width, basic density, and compressive strength parallel to the grain) of core samples, and stress-wave velocity in stems of *B. platyphylla* trees grown naturally in Mongolia. Relationships between growth characteristics, wood properties, and stress-wave velocity are investigated. To determine the possible utilization methods, the results are compared with those of the same species growing in Japan and other countries. Finally, possibility of tree breeding for wood quality is discussed.

2 Materials and methods

2.1 Experimental sites

The experimental sites were located in Selenge, Mongolia (48°34′–41′N, 106°38′–52′E, ca. 1100 m above the sea level). This province has the highest growing stock volume of *Betula* forests in Mongolia. Three different sites (Site I, II, and III) of naturally regenerated forests were selected for this study. Site I is a pure forest of *B. platyphylla*, whereas Site II and III are mixed forests with *Pinus sylvestris* L. and *Larix sibirica* Ledeb., respectively. Exact tree age was unknown because trees were growing in naturally regenerated forests. To compare wood properties, trees of naturally regenerated *B. platyphylla* (without any silvicultural treatments) were also selected in the Experimental Forest, Utsunomiya University, Nikko, Japan (36°47′N, 139°29′E, ca. 1550 m above sea level). Tree age was also unknown in Japanese *B. platyphylla*. Fig. 1 shows the basic climatic conditions of experimental sites.

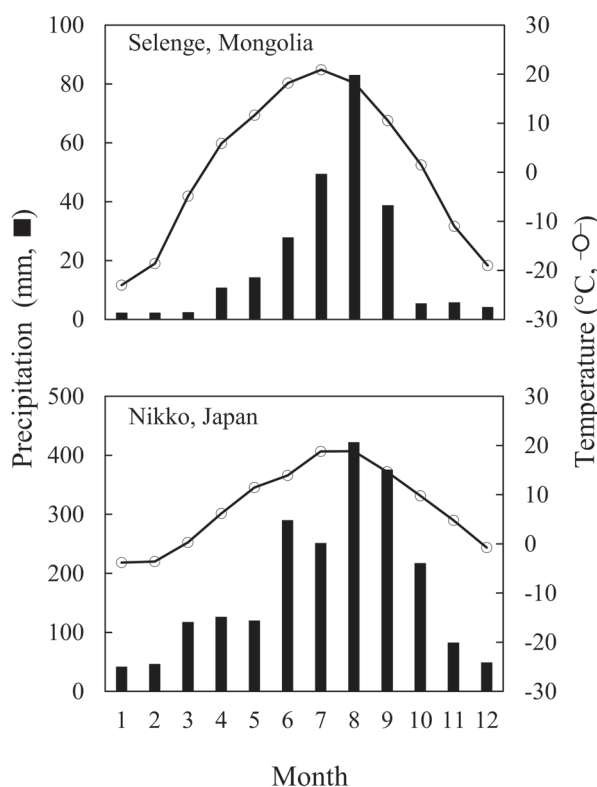


Fig. 1. Monthly mean precipitation and temperature of sampling sites in the present study.

Note: Mongolian and Japanese climate data were provided from the Information and Research Institute of Meteorology, Hydrology, and Environment, Mongolia, and Japan Meteorological Agency, respectively. Mean monthly precipitation and temperature were calculated by averaging monthly values obtained from the data for the last 5 years (2014–2018). Bars indicate mean value of precipitation, and circles and solid lines indicate mean values of temperature of average values for 5 years in each month.

2.2 Growth characteristics and stress-wave velocity of stems

Fig. 2 shows the experimental procedures in the present study. Growth characteristics (stem diameter and tree height) and the stress-wave velocity of stem were measured for a total of 110 trees from the three sites in Mongolia and 10 trees in Japan. Stem diameter was measured at 1.3 m above the ground, using a tape measure. Tree height was measured using an ultrasonic height meter (Vertex IV, Haglölf). The stress-wave velocity of stems was measured between positions at 0.5 m and 1.5 m above ground, using a commercial handheld stress-wave timer (Fakopp Microsecond Timer, Fakopp Enterprise), as described in by Ishiguri et al. (2008) and Tumenjargal et al. (2018).

2.3 Wood properties

Core samples 5 mm in diameter were obtained by a core borer (Haglölf) at 1.3 m above ground for 30 Mongolian *B. platyphylla* trees (10 trees per site and three cores per tree) to measure the wood properties (Fig. 2). Ten sample trees were selected based on the mean values of stem diameter at 1.3 m above the ground in each site. For 10 Japanese *B. platyphylla* trees, 2 cm-thick disks were obtained at around 1.3 m above the ground and radial boards with 2 cm thickness (including bark-to-bark) were obtained from the disks.

Transverse sections of pith-to-bark core samples and bark-to-bark radial strips were trimmed with a disposable knife to measure annual ring width. Next, bark-to-bark radial strips and pith-to-bark core strips were prepared. The image data (2400 dpi) of the transverse section of both the radial and core strips from pith to bark in one direction were captured using a scanner (GT-9300UF, Epson). Both the annual ring number and width were measured using the software ImageJ (National Institutes of Health, USA). The mean values were calculated every 5 years to evaluate the radial variation of annual rings.

Separate core samples with 5 mm diameters were obtained from 30 Mongolian *B. platyphylla* trees, using the same method for measuring basic density. For Japanese *B. platyphylla* trees, 2 cm-thick disks were obtained at approximately 1.3 m above the ground after felling the trees. The wedge-shaped specimens (30° in center angle) were then prepared. The basic density was measured at one-centimetre intervals from the pith to the bark, and calculated by dividing oven-dried weight (105 °C) by green volume measured by the water displacement method (Kollmann and Côté 1984).

Separate core samples with 5 mm diameters were obtained from both Mongolian and Japanese *B. platyphylla* trees by using the method described above to assess compressive strength parallel to grain at green condition. It was measured at 5-mm intervals from the pith to the bark, using strength-test equipment for core samples (Fractometer II, IML), according to our previ-

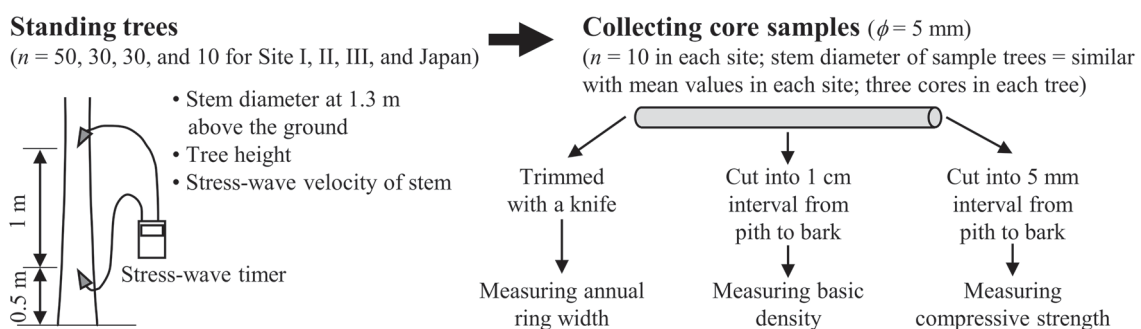


Fig. 2. Illustration of the experimental procedures in standing trees measurements of *Betula platyphylla* and core sample preparation for testing.

Note: ϕ , diameter of core samples.

ous reports (Matsumoto et al. 2008; Ishiguri et al. 2012). Matsumoto et al. (2008) reported that values of compressive strength at green condition in the core samples measured by Fractometer II had almost the same values than compressive strength parallel to the grain at green condition in small-clear specimens in Japan Industrial Standard. This suggests that the values of compressive strength measured by Fractometer II can be compared with reference values obtained by small-clear specimens at green condition.

2.4 Data analysis

The mean values of basic density and compressive strength were calculated at one-centimetre intervals from the pith to the bark to analyze their radial variations. In addition, values of basic density and compressive strength determined with respect to radial distance from the pith were converted to those with respect to tree age (annual ring number from pith) applying the method described by Makino et al. (2012). By using these results, the mean values of basic density and compressive strength were also calculated at five-year intervals from the pith to the bark.

Differences between mean values of Mongolian and Japanese sites were detected by the *t*-tests. Analysis of variance (ANOVA) was applied to evaluate the differences in measured characteristics, such as basic density among Mongolian sites. The relationship between the measured tree and wood properties was determined using Pearson's correlation. In addition, correlation coefficients of basic density were determined between the inner (within 2 or 3 cm from the pith) and the outer wood (2 or 3 cm from the bark). All statistical analyses were conducted using MS Excel (Excel 2016, Microsoft).

3 Results

3.1 Growth characteristics and stress-wave velocity of the stem

Table 1 shows mean values of growth characteristics and stress-wave velocity of stems of *B. platyphylla* trees in Mongolia and Japan. Mean values of stem diameter, tree height, and stress-wave velocity of stems in three sites in Mongolia ranged from 13.4 to 22.7 cm, 11.0 to 17.6 m, and 3.29 to 3.76 km s⁻¹, respectively. Mean values of stem diameter, tree height, and stress-wave velocity of stems were 17.6 cm, 14.1 m, and 3.50 km s⁻¹, respectively. Although stem diameter was not significantly different between Mongolian and Japanese *B. platyphylla* trees, tree height and stress-wave velocity of Mongolian trees were significantly lower than those of Japanese trees.

Table 1. Growth characteristics and stress-wave velocity in wood of *Betula platyphylla* naturally grown in Mongolia and Japan.

Site	<i>n</i>	D (cm)				TH (m)				SWV (km s ⁻¹)			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
I	50	13.4	2.8	9.0	21.0	11.0	2.0	7.7	14.8	3.29	0.20	2.87	3.65
II	30	22.7	5.1	15.4	36.7	17.6	3.3	10.3	25.8	3.76	0.48	2.62	4.44
III	30	19.4	3.2	13.8	26.9	15.9	2.0	10.5	18.7	3.61	0.33	2.76	4.14
Mean/total	110	17.6	5.4	9.0	36.7	14.1	3.8	7.7	25.8	3.50	0.39	2.62	4.44
Nikko, Japan	10	17.8	2.7	13.8	21.8	17.1	2.3	14.4	21.2	4.07	0.13	3.87	4.26
Significance				ns				*				**	

n, number of standing trees; D, stem diameter at 1.3 m above the ground; TH, tree height; SWV, stress-wave velocity of stems; SD, standard deviation; Min., minimum; Max., maximum. Significant differences were obtained by *t*-test between Mongolian trees (110 trees) and Japanese trees (10 trees). **, significant difference ($p < 0.01$); *, significant difference ($p < 0.05$); ns, no significant difference.

Table 2. Number of annual rings and annual ring width in the sample of 30 Mongolian and 10 Japanese *Betula platyphylla* trees.

Site	n	Number of annual rings			Annual ring width (mm)			
		Mean	Min.	Max.	Mean	SD	Min.	Max.
I	10	42	36	54	1.42	0.21	0.23	4.28
II	10	83	74	93	1.13	0.15	0.13	3.45
III	10	67	62	76	1.27	0.09	0.09	3.48
Mean/total	-	-	-	-	1.27	0.15	0.15	3.74
Nikko, Japan	10	54	49	60	1.46	0.21	0.44	3.92
Significance			-				ns	

n, number of sample trees; SD, standard deviation; Min., minimum; Max., maximum. Significant differences were obtained by *t*-test between Mongolian and Japanese samples. ns, no significant difference.

3.2 Wood properties

Number of annual rings and mean values of the annual ring width of Mongolian *B. platyphylla* trees ranged from 36 to 93 and 0.09 to 4.28 mm, respectively (Table 2). No significant difference was found in annual ring width between Mongolian and Japanese *B. platyphylla* trees. As shown in Fig. 3, the annual ring width of *B. platyphylla* decreased from the pith towards the bark in each Mongolian and Japanese site. The pace of decrease varied by site, and the trees of sites II and III were older than the trees of site I and in Japan.

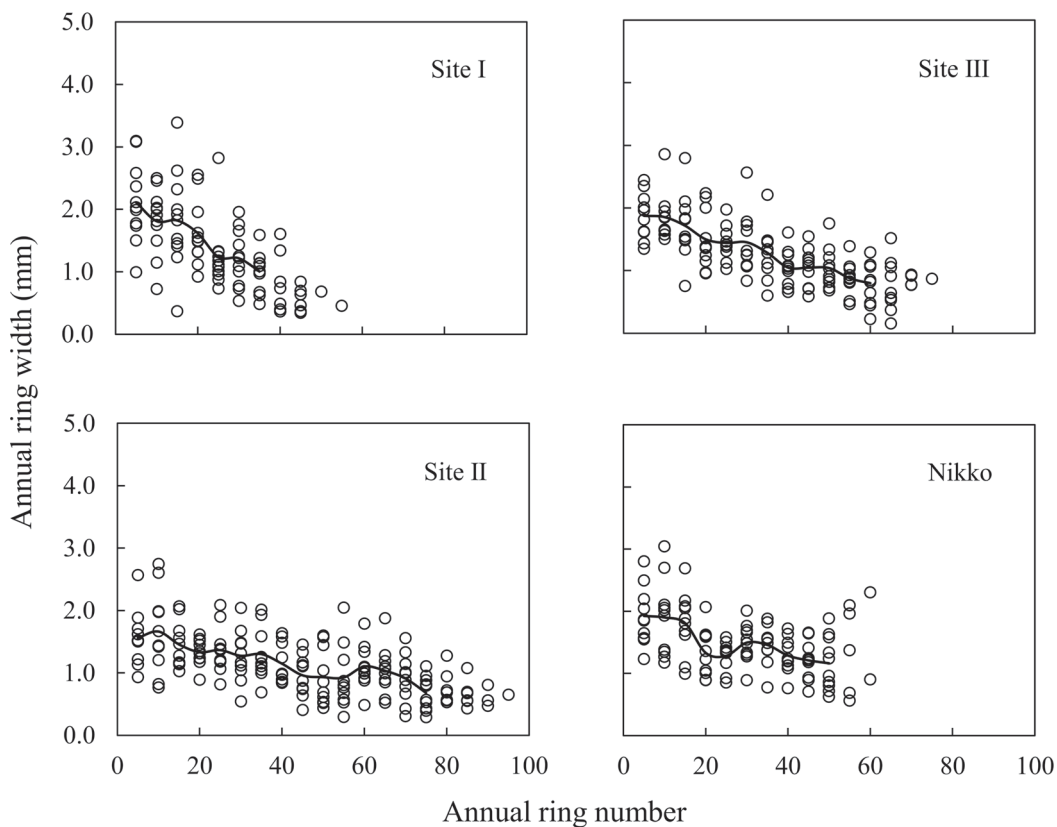


Fig. 3. Radial variations in annual ring width in Mongolian and Japanese *Betula platyphylla* trees. Note: Solid lines indicate mean values of 10 trees at each site.

Table 3. Means and standard deviations of wood properties in the sample of 30 Mongolian and 10 Japanese *Betula platyphylla* trees.

Site	<i>n</i>	BD (g cm ⁻³)				CS (MPa)			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
I	10	0.49	0.04	0.41	0.53	20.5	2.2	16.8	23.6
II	10	0.55	0.02	0.51	0.58	21.3	1.1	19.4	23.9
III	10	0.51	0.02	0.47	0.53	19.2	1.8	16.1	21.9
Mean/total	30	0.51	0.04	0.41	0.58	20.4	1.9	16.1	23.9
Nikko, Japan	10	0.49	0.02	0.45	0.52	21.3	1.5	18.8	23.6
Significance				**				ns	

n, number of sample trees; BD, basic density; CS, compression strength; SD, standard deviation; Min., minimum; Max., maximum. Significant differences were obtained by *t*-test between Mongolian and Japanese samples. **, significant difference ($p < 0.01$); ns, no significant difference.

The mean values of basic density of Mongolian *B. platyphylla* wood in each site ranged from 0.49 to 0.55 g cm⁻³ (Table 3). Basic density showed significantly higher mean values compared to those of Japanese trees (Table 3). Basic density in both Mongolian and Japanese *B. platyphylla* wood decreased down to approximately 2 cm from the pith (or 10th to 20th annual ring from the pith), and then increased towards the bark (Fig. 4). Table 4 shows mean values of basic density at 5-year intervals starting from the pith in trees of the three Mongolian sites. Significant differences in basic density at the position of annual ring numbers from 1–5, 6–10, and 11–15 were found among three sites, whereas the mean values did not differ significantly after the 20th annual ring.

The mean value of compressive strength parallel to the grain at green condition in the Mongolian *B. platyphylla* wood was 20.4 ± 1.9 MPa (Table 3). Compressive strength increased from the pith towards the bark, except for Site I (Fig. 5). In Site I, the radial variation was similar to that of basic density; compressive strength decreased to approximately 2 cm from the pith or to the 10th annual ring from the pith, and then gradually increased (Fig. 5). In other Mongolian sites, as well as in Japan, compressive strength systematically increased along with the radial position and the number of annual rings. The compressive strength became almost constant after the 40th annual ring from the pith in both Mongolia and Japan (Fig. 5). No differences were found in the compressive strengths between the Mongolian and Japanese *B. platyphylla* wood (Table 3).

Table 4. Mean values of basic density in certain radial positions in the sample trees of 30 Mongolian *Betula platyphylla* trees.

Radial position (annual ring number)	Site I (<i>n</i> = 10)		Site II (<i>n</i> = 10)		Site III (<i>n</i> = 10)		Significance among three sites
	Mean	SD	Mean	SD	Mean	SD	
1–5	0.48	0.07	0.56	0.05	0.51	0.04	**
6–10	0.46	0.06	0.53	0.05	0.49	0.03	**
11–15	0.47	0.05	0.52	0.03	0.49	0.04	*
16–20	0.48	0.05	0.52	0.03	0.49	0.03	ns
21–25	0.50	0.05	0.52	0.04	0.50	0.03	ns
26–30	0.51	0.04	0.52	0.03	0.50	0.03	ns
31–35	0.52	0.03	0.53	0.03	0.51	0.03	ns

n, number of sample trees; SD, standard deviation; *F*- and *p*-values obtained by analysis of variance (ANOVA) test among three sites. **, significant difference ($p < 0.01$); *, significant difference ($p < 0.05$); ns, no significant difference.

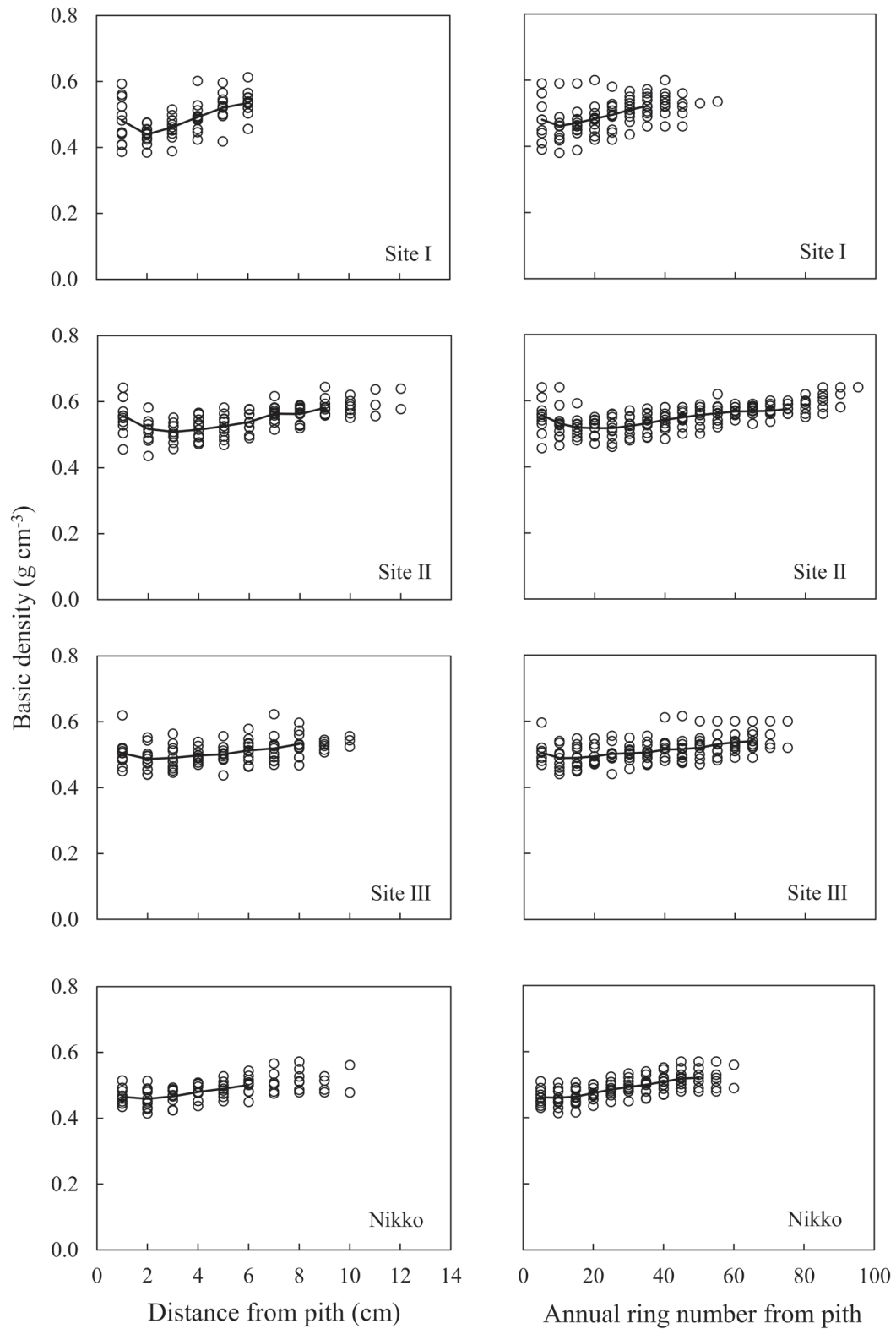


Fig. 4. Radial variations in basic density in Mongolian and Japanese *Betula platyphylla* trees. Note: Solid lines indicate mean values of 10 trees at each site.

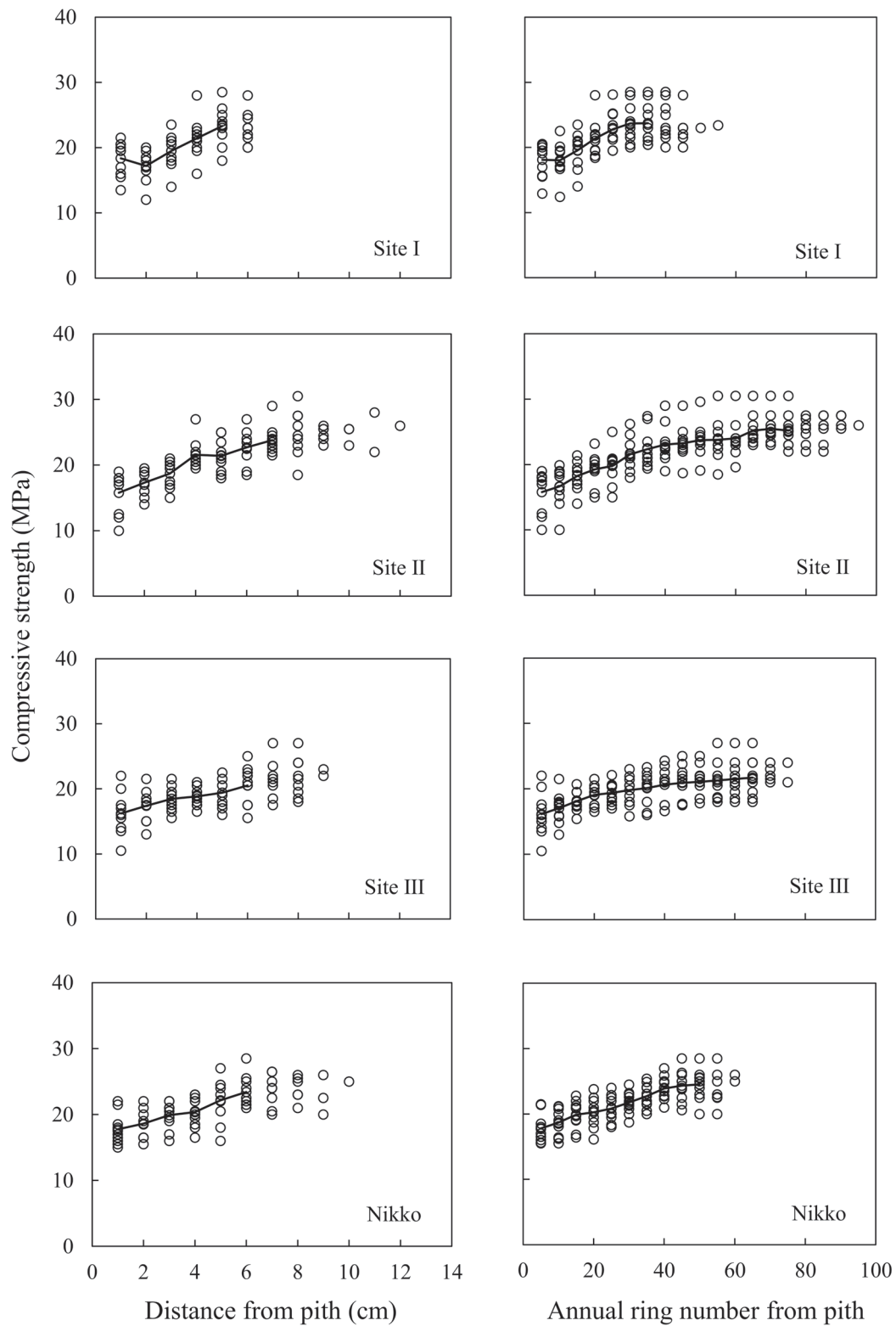


Fig. 5. Radial variations in compressive strength parallel to the grain at green condition in Mongolian and Japanese *Betula platyphylla* trees.

Note: Solid lines indicate mean values of 10 trees at each site.

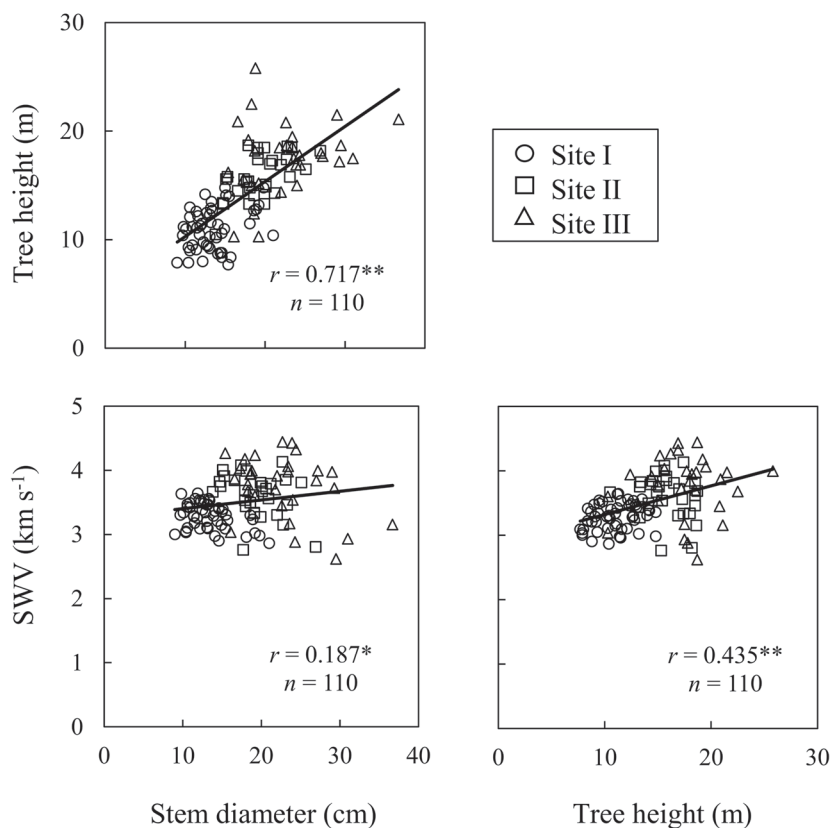


Fig. 6. Relationships between stem diameter or tree height and stress-wave velocity (SWV) of stems in 110 Mongolian *Betula platyphylla* trees. Note: Circles, triangles, and squares indicate Site I, Site II, and Site III, respectively. *n*, number of sample trees; *r*, correlation coefficient; **, significant correlation ($p < 0.01$); *, significant correlation ($p < 0.05$).

3.3 Relationships between examined tree and wood properties

A significant positive correlation was found between stem diameter and tree height for 110 Mongolian trees ($r=0.717, p<0.01$) (Fig. 6). This tendency was also true for the sampled 30 trees (Table 5, $r=0.696, p<0.01$). The results suggest that growth characteristics are closely linked to each other for this species. The stress-wave velocity of stems in the examined height intervals also correlated

Table 5. Correlation coefficients among measured characteristics in the sample of 30 Mongolian *Betula platyphylla* trees.

Property	D	TH	ARW	SWV	BD	CS
D		**	*	*	**	ns
TH	0.696		**	**	**	ns
ARW	-0.450	-0.587		**	*	ns
SWV	0.446	0.532	-0.478		**	ns
BD	0.565	0.574	-0.384	0.552		**
CS	0.101	0.151	-0.144	0.221	0.499	

D, stem diameter at 1.3 m above the ground; TH, tree height; ARW, annual ring width; SWV, stress-wave velocity of stems; BD, basic density; CS, compressive strength; **, significant correlation ($p < 0.01$); *, significant correlation ($p < 0.05$); ns, no significant.

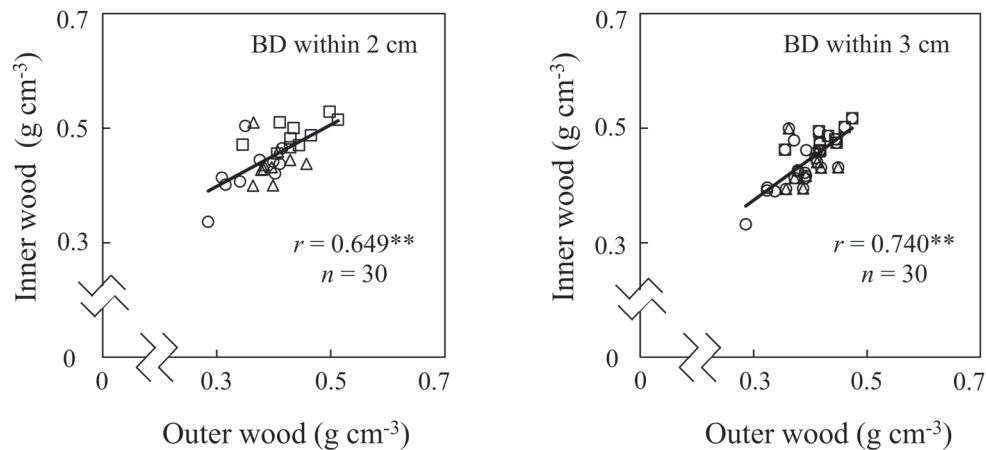


Fig. 7. Relationships of basic density (BD) between inner and outer wood in the sample of Mongolian *Betula platyphylla* trees.

Note: Circles, triangles, and squares indicate Site I, Site II, and Site III, respectively. n , number of sample trees; r , correlation coefficient; **, significant correlation ($p < 0.01$).

positively with the stem diameter ($r=0.446$, $p<0.05$), and tree height ($r=0.532$, $p<0.01$) (Table 5). Similar but much weaker tendencies were observed in all 110 trees: the correlation coefficients between stress-wave velocity and stem diameter and stress-wave velocity and tree height showed values of $r=0.187$ and $r=0.435$ ($p<0.05$ and $p<0.01$), respectively. Significant negative correlation coefficients were found between annual ring width and stress-wave velocity or basic density, but not with compressive strength (Table 5). Significant correlation coefficients were found between basic density and other examined tree and wood properties, whereas compressive strength did not correlate with growth characteristics or stress-wave velocity (Table 5). Basic density correlated positively with stem diameter ($r=0.565$, $p<0.01$) and tree height ($r=0.574$, $p<0.01$) (Table 5). Faster-growing trees had more wood volume with higher density. Strong positive correlations were found between the basic densities of inner and outer wood (Fig. 7).

4 Discussion

4.1 Stress-wave velocity of stems

The stress-wave velocity of wood in different forms (trees, logs, and small-clear specimens) have been reported in hardwood species by several researchers (Armstrong and Patterson 1991; Smulski 1991; Ilic 2003; Wang et al. 2004; Yin et al. 2011). Ilic (2003) reported that the stress-wave velocity of 45 small hardwood beams along a longitudinal direction at 12% moisture content ranged from 4180 to 5700 m s^{-1} (4.18 to 5.70 km s^{-1}). Yin et al. (2011) reported that the stress-wave velocity of green logs of *Populus × euramericana* cv. I-72/58 “San Martino” ranged from 3.05 to 3.09 km s^{-1} . The mean value of the stress-wave velocity of Mongolian *B. platyphylla* trees along a longitudinal direction at green condition was almost similar to that of green logs of *P. × euramericana* (Yin et al. 2011). Yin et al. (2011) also mentioned that stress-wave technology is a reliable method to predict the strength properties of both logs and trees in hardwood species. The results of this study indicate potential to apply stress-wave velocity measurement to *B. platyphylla*, as well.

4.2 Wood properties

The mean value of the annual ring width (1.27 mm) at three sites (Table 2) was almost similar to those of 25-year-old *B. pubescens* trees (1.35 to 1.40 mm) grown in Finland (Luostarinen et al. 2009). The radial variations in annual ring width were also examined in other *Betula* species grown in Finland (Bhat 1980; Luostarinen et al. 2009). The annual ring width of *B. pendula* trees increased up to about 25 years of age (25th annual ring) from the pith, and then dramatically decreased toward the bark (Bhat 1980). The radial patterns of annual ring width in this study (Fig. 3) were almost identical to the results obtained by Bhat (1980).

Compared to the basic density of *Betula* species, the mean values obtained in the present study (Table 3) were relatively higher than those of 22-, 30-, and 45-year-old *B. pendula* trees (0.47 to 0.48 g cm⁻³) grown in Finland (Bhat 1980; Repola 2006; Viherä-Aarnio and Velling 2017). Lachowicz et al. (2019) reported that the mean values of the basic density of *B. pendula* grown in Poland were 0.51, 0.53, and 0.54 g cm⁻³ for 30-, 50-, and 70-year-old trees, respectively. Lachowicz et al. (2019) concluded that tree age effects wood density in this species. Verkasalo (1990) reported that the mean value of wood density ranged from 480 to 550 kg m⁻³ (0.48 to 0.55 g cm⁻³) for *B. alleghaniensis* and *B. papyrifera* trees grown in the United States of America. In the present study, the mean basic density of wood gradually increased after the 6th annual ring towards the bark in all Mongolian sites (Table 4). The mean value of the basic density of three Mongolian sites (0.51 g cm⁻³) was similar to those reported for *B. pendula* grown in European countries and *B. alleghaniensis* Britton and *B. papyrifera* Marsh grown in the United States of America (Bhat 1980; Verkasalo 1990; Repola 2006; Viherä-Aarnio and Velling 2017; Lachowicz et al. 2019). The radial pattern of basic density in *B. platyphylla* in the present study (Fig. 4) was regarded as type II in the classification by Panshin and de Zeeuw (1980); basic density decreased outward from the pith, and then increased to the bark. Similar radial variations were also found in other *Betula* species (Bhat 1980; Heräjärvi 2004b).

Compressive strength has been reported to range from 41.8 to 44.8 MPa at 15% moisture content in *Betula* species (*B. platyphylla* and *Betula utilis* D. Don) (Zhang 1997). In the present study, compressive strength was measured at green condition. Thus, the values were converted into those specimens at 28% of moisture content (fiber saturation point) using the method developed by Ishimaru et al. (2017). In the results, the values at the fiber saturation point ranged from 18.7 to 20.0 MPa. Thus, it was found that mean values of compressive strength in Mongolian *B. platyphylla* (Table 3) were similar to those of the same species grown in Japan and other *Betula* species grown in other countries. The radial variations of compressive strength (Fig. 5) were similar to those of subtropical and tropical fast-growing hardwood species, such as *Casuarina equisetifolia* L. (Chowdhury et al. 2009) and *Dysoxylum mollissimum* Bl. (Ishiguri et al. 2016). Based on the results, it is considered that wood density and compressive strength of Mongolian *B. platyphylla* is suitable for industrial utilization, although the number of sample trees and tested wood properties were limited in this study.

4.3 Relationships between examined tree and wood properties

Previous studies have reported both for hardwood and softwood species that no correlation or a weak negative correlation exists between stem diameter and stress-wave velocity (Ishiguri et al. 2008, 2011, 2012; Tumenjargal et al. 2018). However, significant positive correlations were also found in tropical fast-growing hardwood species, such as *Gmelina arborea* Roxb. ex Sm. (Hidayati et al. 2017), *Eucalyptus urophylla* S.T. Blake, and *Eucalyptus grandis* W. Hill ex Maiden (Prasetyo et al. 2017). In the present study, significant positive correlations were observed between the growth

characteristics and stress-wave velocity (Fig. 6 and Table 5), which is consistent with the results obtained in the above the mentioned studies. Our results suggest that the stress-wave velocity in naturally grown Mongolian *B. platyphylla* wood is dependent on growth characteristics; trees with faster radial and height growth appear to produce wood with higher strength properties. This finding might be related to a positive relationship between stem diameter and basic density (Table 5): higher basic density values were found in higher distances from the pith (Fig. 4).

Some studies indicate a negative but not very strong correlation between growth rate and wood density in *Betula* species (Bhat 1980; Heräjärvi 2004b; Repola 2006). Bhat (1980) reported that basic density was negatively related to annual ring width in *Betula* species, which is in accordance with the results of this study (Table 5).

Wood density has been reported to be closely related to mechanical properties, such as static bending and compressive strength in both hardwood and softwood species, including *B. platyphylla* trees (Hakkila 1966; Panshin and de Zeeuw 1980; Kollman and Côté 1984; Zobel and van Buijtenen 1989; Zhang 1997; Heräjärvi 2002, 2004a,b). Our results also suggest that wood density is a good indicator for predicting mechanical properties in *B. platyphylla* trees (Table 5). However, compressive strength and other measured growth characteristics and wood properties did not correlate in this study.

4.4 Possibility of tree breeding for wood quality

Although the number of sample trees and selection of tested properties were limited, possibility for tree breeding for wood quality was evaluated on the basis of the results in order to assess the need for future plantation establishment of this species in Mongolia.

In tree breeding programs, the early selection of trees with good wood properties is an important issue to reduce the breeding period (West 2006). The relationships of basic density between inner wood and outer wood were reported by several researchers (e.g., Wiemann and Williamson 1988; Ishiguri et al. 2011). Significant correlation coefficients of wood density in tropical pioneer trees were recognized between the inner wood within 3 cm from the pith, and the outer wood (within 3 cm from the bark side) ($r^2=0.71$ to 0.88 , $r=0.843$ to 0.938 , $p<0.01$) (Wiemann and Williamson 1988). The correlation coefficients were almost similar to those obtained in this study (Fig. 7). Thus, early evaluation of basic density in *B. platyphylla* trees should be possible using wood at 2 cm from the pith.

As shown in Table 4, significant differences between the three Mongolian study sites were observed in the average basic densities of wood from the position between the 1st and 15th annual ring from the pith. The experimental sites were not far from each other (Table 1), thus the environmental conditions did not differ much between the three sites. The differences in basic densities at initial stage of growth might occur due to genetic differences. This result suggests that improvement of basic density is possible for selection of trees in tree breeding programs. However, further research is needed to clarify the effects of environmental conditions on wood properties in Mongolian *B. platyphylla* trees.

5 Conclusions

In the present study, growth characteristics and wood properties of core samples were investigated for *B. platyphylla* naturally regenerated in Selenge, Mongolia with the reference of that grown in Japan. The aim was to preliminary evaluate the potentials for wood utilization. The values for wood properties in Mongolian *B. platyphylla* were similar to those in Japanese *B. platyphylla*

and in other *Betula* species used in many countries. In addition, positive correlations were found between the growth characteristics and stress-wave velocity of stems or basic density, suggesting that trees with good growth not always produce lower quality wood. If tree breeding programs will be established for this species in Mongolia, early selection and improvement of basic density can be possible. Based on the results, it is concluded that wood from *B. platyphylla* trees grown in Mongolia has the potential to be used as a raw material for a multitude of industrial products. Further research is needed to clarify the detailed wood properties and to determine the best utilization of wood from Mongolian *B. platyphylla* trees.

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