Preliminary evaluation of anatomical characteristics of four common Mongolian softwoods

Murzabyek Sarkhada, Murzabyek Sarkhada,b,c, Futoshi Ishiguri,a Ikumi Nezu,a,b, Haruna Aiso,a Agus Ngadianto,a,b,d, Bayasa Tumenjargal,b, Bayartsetseg Baasan,a, Ganbaatar Chultem,a, Yyunichi Ohshima,a and Shinso Yokota,a

aSchool of Agriculture, Utsunomiya University, Utsunomiya, Tochigi, Japan; bUnited Graduate School of Agricultural Science, Tokyo University of Agriculture and Technology, Tokyo, Japan; cTraining and Research Institute of Forestry and Wood Industry, Mongolian University of Science and Technology, Ulaanbaatar, Mongolia; dVocational College, Universitas Gadjah Mada, Yogyakarta, Indonesia; eSchool of Industrial Technology, Mongolian University of Science and Technology, Ulaanbaatar, Mongolia

ABSTRACT
To effectively and sustainably utilize wood resources from boreal forests in Mongolia, anatomical characteristics, tracheid morphology, cell proportion, annual ring width, and latewood percentage were preliminary determined in Pinus sylvestris, Pinus sibirica, Picea obovata, and Larix sibirica trees naturally growing in Mongolia. Based on the observation, the anatomical characteristics of four common Mongolian softwoods were the same as those previously observed in the same species or the same genus species. Based on the parameters of the Gompertz functions for annual ring width, silvicultural management, such as thinning timing and harvesting age, should be considered depending on the species when the plantation is established. The results of the model selection for relationships between latewood percentage and basic density indicated that the increase ratio of basic density corresponded to an increase of latewood percentage is almost the same irrespective of species, although there are species-specific values of basic density corresponding to specific latewood percentages. The results obtained in the present study contribute effective and sustainable utilization of wood resources from Mongolian forestry.

Introduction
Natural forest of Mongolia is mainly classified into two types: boreal forests and saxaul forests (FRDC 2020). Boreal forests are distributed in northern Mongolia and occupy 84.9% (9,911,327 ha) of the total forest area (11,674,438 ha) (FRDC 2020). Saxaul forests are distributed in the deserts and steppes in southern Mongolia and occupy 15.1% (1,763,111 ha) of the total forest area (FRDC 2020). A total of 11 coniferous species, including Abies, Picea, Pinus, Larix, and Juniperus, are naturally distributed in Mongolia (Damdinsuren 2014). Among the 11 species, 4 species—Pinus sylvestris L., Pinus sibirica Du Tour., Picea obovata Ledeb., and Larix sibirica Ledeb.—are known as important forestry species in the country (Tsogbaatar 2004; Altrell 2019; Sukhbaatar et al. 2020). Stock volume of the four species reaches around 93.2% of the country’s total stock volume (FRDC 2020). In 1990, Mongolia made a dramatical change in its political and economical systems, the basic concept of which is the transition from a single–party political system to a democratic form of society (Jamsran 2004).

As the results, the annual logging volume in Mongolia decreased from 2.2 million m³ in 1980s, 0.86 million m³ in 1992, to 0.5 million m³ in 2000 (Nyamjav et al. 2007). However, in recent decades, the production of industrial roundwood has gradually increased from 49,000 m³ in 2010 to 162,000 m³ in 2019 (FAO 2014, 2019). Thus, there is some possibility of increasing demand for wood resources in Mongolia. To promote the sustainable forestry using natural resources, efficient utilization of wood resources is needed for Mongolian forestry.

In softwoods, anatomical characteristics, such as tracheid diameter, tracheid wall thickness, and latewood percentage, are closely related to the physical and mechanical properties of wood (Bendtsen and Senft 1986; Takata et al. 1992; Kang 1993; Koizumi et al. 2005; Peltola et al. 2009; Gryc et al. 2011). For example, Koizumi et al. (2005) reported that in Larix kaempferi, the effect of latewood percentage on average wood density was greatest in outer wood (mature wood). In addition, wood anatomical characteristics are also related to liquid or gas permeabilities which affect processibility in wood drying and wood preservation (Milita et al. 1995; Fujii et al. 1997; Matsumura et al. 1998; Usta and Hale 2006). Milita et al. (1995) reported that factors such as the presence of juvenile or mature wood and between-tree variability have a greater effect on permeability than does wood density in plantation grown Pinus taeda. For efficient wood utilization, anatomical characteristics concerning the
physical and mechanical properties of wood should be clarified.

A sigmoid or S-type curve resembles trends in the life cycle of trees (Salas-Eljatib et al. 2021). Current annual increment (CAI) and mean annual increment (MAI) can be determined by the sigmoid models, such as the logistic model, the Gompertz model, and others (Salas-Eljatib et al. 2021). These annual increment values are useful for determining the suitable rotation age with respect to volume yield (Guzmán et al. 2012; Resende et al. 2021). Guzmán et al. (2012) reported that the rotation length that maximized wood production (maximum sustainable yield) was 27.5 years for the best site and 33.5 years for the poorest site of Pinus radiata plantations based on the MAI value. Thus, the optimum age to apply thinning and harvesting with respect to volume yield can be estimated based on these annual increment values in radial growth.

We have investigated wood properties in Mongolian softwoods (Ishiguri et al. 2018; Tumenjargal et al. 2018, 2020; Sarkhad et al. 2020, 2022). In a previous paper, we clarified differences in wood properties between juvenile wood and mature wood using linear or nonlinear mixed-effects modeling for radial variations of wood properties in four common Mongolian softwood, P. sylvestris, P. sibirica, P. obovata, and L. sibirica (Sarkhad et al. 2022). However, basic information on anatomical characteristics and the effect of these characteristics on physical properties were still unclear for these Mongolian softwoods. Wood anatomical characteristics in relation to dendrochronology and wood properties have been researched on P. sylvestris and L. sibirica (Schweingruber 1990; Koizumi et al. 2003; Benkova and Schweingruber 2004; Pritzkow et al. 2014; Fonti and Babushkina 2016; Khansarioreh et al. 2018) because these species are naturally distributed in Europe and were utilized as plantation species (Farjon 2017). However, information about wood properties and anatomical characteristics in the other two species, P. sibirica and P. obovata are not so much, as these species are naturally distributed in limited countries, such as Russia, Mongolia, and others (Farjon 2017). Thus, additional information on anatomical characteristics and their impacts on other wood properties should be investigated for the Mongolian softwoods harvested from natural forests.

To effectively and sustainably utilize wood resources in Mongolia, anatomical characteristics (tracheid morphology, cell proportion, annual ring width, and latewood percentage) were preliminary investigated for four common Mongolia softwoods in this study, although number of sample trees were limited.

**Materials and methods**

**Materials**

Four common Mongolian softwoods—P. sylvestris, P. sibirica, P. obovata, and L. sibirica—were collected from Mandal, Selenge, Mongolia (48°49’N, 106°53’E and 48°41’N, 106°38’E; Figure 1). Figure 1 also shows the mean monthly temperature and precipitation at the nearest meteorological station located in Mandal, Selenge, Mongolia. Pinus sylvestris trees were harvested from a natural mixed forest with Betula platyphylla. Remained other three species were harvested from another mixed forest with B. platyphylla. The altitude

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Figure 1. Geographic information of sampling site (a), monthly mean temperature and precipitation of Mandal, Selenge, Mongolia (b), and tree shape of samples (c). Monthly mean temperature and precipitation were averaged values from 2014 to 2018.
of both stands was about 1120 m above sea level. Unfortunately, detailed information, such as stand density, soil conditions, and others was unknown. In each natural forest, we selected sample trees having 20 to 30 cm in stem diameter at 1.3 m above the ground, because the size is commercial harvesting size in Mongolia. Five trees in each species were harvested, and 3 cm in thickness disks were collected at 1.3 m above the ground. Table 1 shows the growth characteristics, annual ring number, basic density, and boundary cambial age between juvenile and mature wood of the sample trees (Sarkhad et al. 2020, 2022). After collecting the disks, bark-to-bark radial strips with a pith (5 cm in width) were prepared for the following experiments. To avoid the compression wood, the radial strips were collected from positions that did not include eccentric growth and dark-colored earlywood (typical appearance of compression wood in softwoods).

**Anatomical characteristics**

Generally, wood properties in softwoods can be divided into two parts: juvenile and mature wood (Bendtsen and Senft 1986; Zobel and van Buijtenen 1989; Moore and Cown 2017; Sarkhad et al. 2022). The boundary between juvenile and mature wood normally was around the 15th to 20th annual ring from the pith (Shiozawa 1982; Bendtsen and Senft 1986; Zobel and van Buijtenen 1989; Moore and Cown 2017; Sarkhad et al. 2022). In fact, the boundary between juvenile and mature wood determined by radial variation modeling of tracheid length ranged from 20th to 24th annual ring from the pith in the same sample trees for all four tree species of this study (Table 1, Sarkhad et al. 2022). Thus, in this study, cell morphology and proportion were determined at the 10th and 40th annual rings from the pith as the representatives of juvenile and mature wood, respectively. Small wood blocks were collected from the 10th and 40th annual rings from the pith of the radial strips collected at 1.3 m above the ground. Transverse sections (20 µm in thickness) were prepared using the sliding microtome (REM-710, Yamatokohki, Saitama, Japan). These transverse sections were used for the following experiments.

![Table 1](https://example.com/table1.png)

| Property       | Pinus sylvestris | Pinus sibirica | Picea obovata | Larix sibirica |
|----------------|-----------------|---------------|---------------|---------------|
|                 | Mean (SD)       | Min.–Max.     | Mean (SD)     | Min.–Max.     |
| D (cm)          | 27.1 (2.2)      | 26.5 (1.3)    | 27.9 (2.2)    | 25.6 (1.6)    |
| TH (m)          | 24.3–29.9       | 24.8–28.1     | 24.2–29.6     | 24.0–28.2     |
| ARN (2)         | 16.2 (2.2)      | 11.9 (1.5)    | 14.3 (2.3)    | 15.3 (1.3)    |
| BD (g cm⁻³)    | 72 (3)          | 67–74         | 57–67         | 49–64         |
| Boundary cambial age | 0.39 (0.01)    | 0.37 (0.01)   | 0.34 (0.02)   | 0.53 (0.05)   |

**Note:** D: stem diameter at 1.3 m above the ground; TH: tree height; ARN: annual ring number at 1.3 m above the ground; BD: basic density; Min.: minimum; Max.: maximum. Mean and standard deviation (SD) for each species were calculated from the data of five trees in each species. Boundary cambial age between juvenile and mature wood was determined by the results of nonlinear mixed-effects model for radial variations of latewood tracheid length (Sarkhad et al. 2022). The diameter and wall thickness of tracheids in earlywood and latewood were determined as tracheid morphology. The transverse sections without dehydration were put on grass slides and then mounted with 25% glycerin and cover slips. Transverse images were captured using a digital camera (DS-2210, Sato Shouji Inc., Kawasaki, Japan) and a microscope (BX51, Olympus, Tokyo, Japan). Diameters in radial and tangential directions and tangential wall thickness were measured for 20 tracheids at each annual ring position and wood type (earlywood and latewood) by ImageJ (National Institutes of Health, MD, USA). Tracheid diameter was also calculated by averaging diameters in the radial and tangential directions. The boundary between earlywood and latewood was determined according to Mork’s definition (Denne 1989).

Cell proportions were determined using the point counting method (Denne and Hale 1999). Transverse sections were stained with safranin, and dehydrated by graded ethanol. Then, the sections were then dipped into xylene and mounted by biorite (Ohken, Tokyo, Japan). Transverse images with current annual rings were taken using DS-2210 and BX51. Mesh images (100µm interval) were overlapped to the transverse images by ImageJ, and each point was counted and classified into the following cell types: tracheid, ray parenchyma, and axial intercellular (resin) canal in each earlywood and latewood. About 400 to 1000 points in a photomicrograph of each species were measured in an annual ring of each species. Cell percentage was calculated by dividing the number of grids in each cell type by the total number of grids.

**Annual ring width and latewood percentage**

Annual ring and latewood widths from the pith to bark were measured in all annual rings of both directions of the strips. The image data (1200 dpi) of the transverse sections of the strips were captured on a personal computer equipped with a scanner (GT-9300UF, EPSON, Nagano, Japan). Using the scanned images, the annual ring and latewood widths from pith to bark were measured at each annual ring using ImageJ. Annual ring and latewood widths of each tree were expressed as mean values of two directions.
Boundary between earlywood and latewood was determined by the color differences observed by naked eyes.

**Data analysis**

Statistical analysis was conducted using R software (R Core Team 2020). A paired t-test was used for detecting the differences in cell morphology and cell proportions between the 10th and 40th annual rings from pith or earlywood and latewood. Also, correlations between data up to the 20th annual ring from the pith and data of the 21st to 40th annual ring from the pith were evaluated in annual ring width and latewood percentage using Pearson’s correlation coefficients.

Radial variations of cumulative annual ring width and latewood percentage were evaluated by developing linear and nonlinear mixed-effect models using the lmee function in lmee packages (Bates et al. 2015) and the nlme function in nlme package (Pinheiro and Bates 2000).

To evaluate the radial variation of cumulative annual ring width, the model (1) was developed based on the Gompertz function (Table 2). The developed models were selected by the value of the Akaike Information Criterion (AIC, Akaike 1998). Using the estimated parameters in the selected models, MAI and CAI were calculated.

Radial variations in latewood percentage were evaluated using the following models (2 and 3): 

\[
LWP_{ij} = b_0 \times ARN_{ij} + b_1 + Tree_{ij} + e_{ij}
\]  
\[
LWP_{ij} = c_0 \ln (ARN_{ij}) + c_1 + Tree_{ij} + e_{ij}
\]

where \(LWP_{ij}\) is the latewood percentage of the \(i-th\) annual ring number from the pith of the \(j-th\) individual tree, \(ARN_{ij}\) is the \(i-th\) annual ring number from the pith of the \(j-th\) individual tree, \(b_0, b_1, c_0\), and \(c_1\) are the fixed-effect parameters, \(Tree_{ij}\) is the random-effect parameter of the \(j-th\) individual tree, and \(e_{ij}\) is the residuals. The developed models were selected by the value of the AIC.

To evaluate the differences in the relationships between basic density and latewood percentage among tree species, the following mixed-effects models (4) were developed:

\[
BD_{ij} = (d_0 + Species_{ij}) \times LWP_{ij} + d_1 + Species_{ij} + e_{ij}
\]  
\[
BD_{ij} = (d_0 + Species_{ij}) \times LWP_{ij} + d_1 + e_{ij}
\]  
\[
BD_{ij} = d_0LWP_{ij} + d_1 + Species_{ij} + e_{ij}
\]

where \(BD_{ij}\) is the basic density of the \(i-th\) individual tree of the \(j-th\) species, \(Species_{ij}\) is random-effect parameters of the \(j-th\) species, \(LWP_{ij}\) is the latewood percentage of the \(i-th\) individual tree within the \(j-th\) species, \(d_0\) and \(d_1\) are fixed-effect parameters, and \(e_{ij}\) is residuals.

The basic density was measured at 10 years intervals from the pith (Sarkhad et al. 2022). Thus, latewood percentage values were averaged at each 10 years intervals from the pith.

**Results and discussion**

**Anatomical characteristics**

Table 3 shows the tracheid morphologies at the 10th and 40th annual ring from pith. Earlywood and latewood tracheid diameters in both radial and tangential directions at the 40th annual ring from the pith exceeded those at the 10th annual ring from the pith in all species, except for latewood of L. sibirica. Tracheid wall thickness in earlywood and latewood at the 10th annual ring from the pith was almost the same as that at the 40th annual ring from the pith, except for P. obovata (Figure 2). When compared to earlywood, the tracheid diameter in both radial positions decreased in latewood, and tracheid wall thickness increased in latewood. However, no significant differences in tracheid wall thickness were found between earlywood and latewood in P. sibirica.

Transition from earlywood to latewood was gradual in P. sibirica (Figure 2). These tracheid morphological features in P. sibirica are very similar to those of other five-needle pine, such as Pinus pentaphylla grown in Japan and Pinus koraiensis grown in Korea (Wood Technological Association of Japan 1984; Kang 1993; Lee et al. 1997).

Out of the four tested species, tracheid morphologies were characterized by larger diameter and thicker wall in L. sibirica, and smaller diameter and thinner wall in P. sibirica. Also, mean values of tracheid morphologies in four Mongolian softwoods were in the range of those of the same species or the same genus species reported by other researchers (Wood Technological Association of Japan 1984; Kang 1993; Ilvessalo-Pfähfl 1995).

In the four species, cell proportions in tracheids, rays, and intercellular canals ranged from 83.6 to 90.6%, 8.8 to 15.9%, and 0.3 to 0.8%, respectively (Table 4). There were no differences between radial

| Table 2. Developed models for radial variation of cumulative annual ring width. |
| --- |
| Equation | Formula | Random effects | Pinus sylvestris | Pinus sibirica | Picea obovata | Larix sibirica |
| 1-i | \(CRW_{ij} = a_0 \exp(\frac{ARN_{ij}}{C0/C1}) + e_{ij}\) | Asymptotic value | 2564.54 | 1949.25 | 2034.83 | 1820.67 |
| 1-ii | \(CRW_{ij} = (a_0 + Tree_{ij}) \exp(\frac{ARN_{ij}}{C0/C1}) + e_{ij}\) | Start position of the curve | 2416.59 | 1845.61 | 1696.43 | 1659.11 |
| 1-iii | \(CRW_{ij} = a_0 \exp(-\exp(-(ARN_{ij}+Tree_{ij})) + e_{ij}\) | Slope | 2494.28 | 1815.98 | 1969.87 | 1793.80 |
| 1-iv | \(CRW_{ij} = a_0 \exp(-\exp(-(ARN_{ij}+Tree_{ij})) + e_{ij}\) | Positive | 2396.22 | 1841.92 | 1804.32 | 1718.63 |
| Note: Equation (1-i), fixed-effects model; Equations (1-ii) to (1-iv), mixed-effects model; CRW, cumulative annual ring number at the ith annual ring number from pith; ARNi, the ith annual ring number from pith; ARNj, the ith annual ring number from pith; ARNi, the ith individual tree; CRWi, 1-th individual tree; CRWj, the ith individual tree within the j-th species, Speciesj is random-effect parameters of the j-th species, BDij is the basic density of the j-th tree, Speciesj is random-effect parameters of the j-th species, d0 and d1 are fixed-effect parameters, and eij is residuals. Bold value indicates minimum AIC among four developed models in each species. |
models in each species (Figure 4). As a result, the pith showing maximum MAI and CAI were determined using the fixed-effect parameters in the selected models in each species (Figure 4). As a result, the smallest annual ring number showing maximum CAI was found in L. sibirica (about the 20th annual ring), followed by P. obovata, P. sibirica, and P. sylvestris (about 60 to 70th annual ring) (Table 7). Thus, appropriate silvicultural management, such as thinning timing, harvesting age, and others, should be considered depending on the species when the plantation is established.

Figure 5 shows the relationships between the mean values of the annual ring width from pith to 20th annual ring (position I in Figure 5) and the mean values from 21st to 40th (position II in Figure 5). A significant correlation coefficient was not found, suggesting that trees with faster radial growth in the relatively early stage of growth did not always show a faster radial growth rate after 20 years of growth. Takata et al. (1992) examined the annual ring width of L. kaempferi from 25 seed provenances, and they reported that a significant negative correlation ($r = -0.18$) was found between core wood (juvenile wood) and outer wood (mature wood) of annual ring width. In L. sibirica naturally growing in Mongolia, Tumenjargal et al. (2018) reported that a significant positive correlation was found between mean values of annual ring width from 1st to 10th annual rings and those from 11th to 20th annual rings, but mean values from 1st to 10th annual rings were insignificantly correlated with those from 21st to 30th, and from 31st to

### Table 3. Tracheid morphology at the 10th and 40th annual rings from the pith.

| Species        | 10th annual ring | 40th annual ring | t value (p value) |
|----------------|------------------|------------------|------------------|
|                | Morphology       | LW   | LW   | (EW-LW) | (EW-LW) | (10th-40th) | LW (10th-40th) |
| Pinus sylvestris | Dr (μm)          | 36.6 (2.6) | 21.1 (3.4) | 39.7 (3.7) | 22.3 (1.6) | 5.656 (.005) | 9.123 (.001) | -4.719 (.009) |
|                | DT (μm)          | 33.3 (1.4) | 24.4 (3.1) | 36.7 (2.6) | 26.7 (1.8) | 7.274 (.002) | 11.735 (<.001) | -4.039 (.015) |
|                | WT (μm)          | 2.4 (0.2)  | 4.4 (0.8)  | 2.4 (0.2)  | 5.1 (0.8)  | -6.680 (.003) | 9.915 (.002)  | 0.052 (.961) |
| Pinus sibirica  | Dr (μm)          | 33.6 (2.3) | 16.2 (1.0) | 40.8 (3.5) | 19.1 (1.8) | 15.281 (<.001) | 13.565 (<.001) | -14.257 (<.001) |
|                | DT (μm)          | 31.0 (0.8) | 21.8 (0.8) | 37.8 (1.3) | 25.5 (1.8) | 17.904 (<.001) | 9.835 (.001)  | -3.070 (.037) |
|                | WT (μm)          | 2.6 (0.1)  | 3.0 (0.4)  | 2.5 (0.2)  | 3.6 (1.1)  | -2.328 (.080) | -2.111 (.102) | 0.848 (.444) |
| Picea obovata   | Dr (μm)          | 31.4 (4.5) | 14.1 (1.9) | 39.8 (1.7) | 17.5 (1.4) | 11.016 (<.001) | 10.764 (<.001) | -5.793 (.004) |
|                | DT (μm)          | 28.1 (3.4) | 18.7 (1.5) | 36.4 (2.0) | 23.2 (1.0) | 14.059 (<.001) | 21.835 (<.001) | -4.989 (.008) |
|                | WT (μm)          | 2.0 (0.2)  | 3.4 (0.5)  | 2.8 (0.2)  | 4.6 (0.7)  | -5.566 (.005) | -5.075 (.007) | 9.811 (.001) |
| Larix sibirica  | Dr (μm)          | 42.8 (6.4) | 20.2 (2.0) | 52.3 (3.3) | 21.3 (1.6) | 9.633 (.001)  | 11.377 (<.001) | -2.875 (.045) |
|                | DT (μm)          | 37.0 (5.3) | 23.6 (2.6) | 43.5 (2.3) | 25.6 (1.6) | 10.725 (<.001) | 14.467 (<.001) | -3.885 (.018) |
|                | WT (μm)          | 2.6 (0.4)  | 6.8 (1.1)  | 3.0 (0.6)  | 7.4 (0.8)  | -12.202 (.002) | -7.616 (.002) | -1.725 (.160) |

Note: EW: earlywood; LW: latewood; Dr and Dt: tracheid diameter in radial direction and tangential direction, respectively; WT: radial wall thickness. Values in parentheses after mean values were standard deviation. t and p values were obtained by paired t-test (number of samples = five trees in each species). Bold indicates p values less than 0.05.

### Figure 2. Photomicrographs of transverse sections of latewood in the sample trees. Scale bar = 50 μm.

### Figure 5. Relationships between the mean values of the annual ring width from pith to 20th annual ring (position I in Figure 5) and the mean values from 21st to 40th (position II in Figure 5). A significant correlation coefficient was not found, suggesting that trees with faster radial growth in the relatively early stage of growth did not always show a faster radial growth rate after 20 years of growth. Takata et al. (1992) examined the annual ring width of L. kaempferi from 25 seed provenances, and they reported that a significant negative correlation ($r = -0.18$) was found between core wood (juvenile wood) and outer wood (mature wood) of annual ring width. In L. sibirica naturally growing in Mongolia, Tumenjargal et al. (2018) reported that a significant positive correlation was found between mean values of annual ring width from 1st to 10th annual rings and those from 11th to 20th annual rings, but mean values from 1st to 10th annual rings were insignificantly correlated with those from 21st to 30th, and from 31st to
This study’s results parallel those reported by Tumenjargal et al. (2018). Latewood percentage of *Pinus sylvestris* and *Larix sibirica* showed relatively higher latewood percentages compared to the other two species (Table 4). Compared to the same species or the same genus species, the mean values obtained in this study showed similar values (Takata et al. 1992; Koizumi et al. 2005; Peltola et al. 2009; Gryc et al. 2011; Tanabe et al. 2016) or relatively lower values (Kang 1993; Karlman et al. 2005; Gryc et al. 2011).

Figure 6 shows the radial variations of latewood percentage. While logarithmic formula (Equation (3)) was fitted on *P. sylvestris* and *L. sibirica*, linear formula (Equation (2)) was adapted to *P. sibirica* and *P. obovata*, suggesting that latewood percentage increased from pith to bark and then stabilized in *P. sylvestris* and *L. sibirica*, while it gradually increased from pith to bark side in *P. sibirica* and *P. obovata*. However, value of slope in the linear formula in *P. sibirica* showed almost zero (0.0048), indicating that latewood percentage was almost constant from pith to bark. Similar radial patterns in latewood percentages were recognized in the same genus species (Kang 1993; Karlman et al. 2005; Koizumi et al. 2005; Tanabe et al. 2016).

Figure 5 shows the relationships between mean values of latewood percentages from pith to 20th annual ring number from the pith. Solid lines with gray and black colors indicate individual trees and mean value of sample trees, respectively.
ring (position I in Figure 5) and mean values from 21st to 40th (position II in Figure 5). A significant positive correlation was found, suggesting that trees with a higher latewood percentage around the pith area have a higher latewood percentage wood after 20 years of growth. The results also indicate that the selection of trees with higher latewood percentages may be possible when tree breeding programs for wood quality are established for these four Mongolian softwood species.

Effects of tree species on relationships between latewood percentage and basic density were evaluated by a mixed-effects model. The model with random slope and intercept (Table 8, Equation (4-i)) was not converged. The AIC value in the model with random intercept (Equation (4-iii)) was higher than that in the model with random slope (Equation (4-ii)), suggesting that the best model among the three developed models was the model with only random intercept (Equation (4-iii)). The results of the model selection indicated that the increase ratio of basic density corresponded to an increase of latewood percentage is almost the same irrespective of species, although there are species-specific values of basic density corresponding to certain latewood percentages (Figure 7). If the latewood percentage was the same in four species, _L. sibirica_ showed the highest basic density, followed by _P. sibirica_, _P. sylvestris_, and _P. obovata_ (Table 8). Comparison of two _Pinus_ species, _P. sylvestris_ has a lower species-specific value of basic density (Figure 7) but has a higher latewood percentage (Table 5) rather than that in _P. sibirica_. The results might be closely related to the physiological phenomena of trees. Further research is needed to clarify the differences in the relationships

| Species         | Equation | Parameters | Estimates | SE       | t value | p value | Parameter | Variance component | Variance component ratio (%) |
|-----------------|----------|------------|-----------|----------|---------|---------|-----------|---------------------|-----------------------------|
| *Pinus sylvestris* | 1-iv     | \(a_0\)    | 234.572   | 26.382   | 8.891   | <.001   | Tree2j    | <0.001             | 0.0                          |
|                 |          | \(a_1\)    | 1.013     | 0.030    | 33.659  | <.001   | \(e_0\)   | 40.866              | 100.0                        |
|                 |          | \(a_2\)    | 0.017     | 0.002    | 10.446  | <.001   | \(e_{ij}\) | 40.866              | 100.0                        |
| *Pinus sibirica* | 1-iii    | \(a_0\)    | 149.215   | 3.759    | 39.692  | <.001   | Tree1j    | 0.007               | 0.0                          |
|                 |          | \(a_1\)    | 1.228     | 0.040    | 30.368  | <.001   | \(e_0\)   | 18.322              | 100.0                        |
|                 |          | \(a_2\)    | 0.039     | 0.001    | 31.202  | <.001   | \(e_{ij}\) | 18.322              | 100.0                        |
| *Picea obovata* | 1-ii     | \(a_0\)    | 141.251   | 6.152    | 22.960  | <.001   | Tree0j    | 169.374             | 91.9                         |
|                 |          | \(a_1\)    | 1.149     | 0.015    | 75.752  | <.001   | \(e_0\)   | 14.835              | 8.1                          |
|                 |          | \(a_2\)    | 0.049     | 0.001    | 42.585  | <.001   | \(e_{ij}\) | 14.835              | 8.1                          |
| *Larix sibirica*| 1-ii     | \(a_0\)    | 107.409   | 6.363    | 16.880  | <.001   | Tree0j    | 168.596             | 82.3                         |
|                 |          | \(a_1\)    | 1.081     | 0.033    | 32.211  | <.001   | \(e_0\)   | 36.254              | 17.7                         |
|                 |          | \(a_2\)    | 0.063     | 0.003    | 21.716  | <.001   | \(e_{ij}\) | 36.254              | 17.7                         |

Note: SE: standard error. Estimated values of the fixed- and random-effect parameters were obtained from the selected model based on the AIC value (Table 2).
between latewood percentage and basic density at the species level.

**Conclusions**

In this study, anatomical characteristics were preliminarily investigated in four common Mongolian softwoods— *P. sylvestris*, *P. sibirica*, *P. obovata*, and *L. sibirica*, although the number of samples were limited. Microscopic features of the four species paralleled those obtained in the same species or the same genus species by the previous researchers. Tracheid morphology in examined four softwoods was also similar to that in the same species or the same genus species. These results may suggest that wood from these four Mongolian softwoods can be utilized for the same purposes in the same species or the same genus species found in the other countries. Based on the Gompertz formula for annual ring width, annual ring number from pith showing the maximum values of the CAI and MAI for *P. sylvestris*, *P. sibirica*, *P. obovata*, and *L. sibirica* ranged from 59 to 68, 32 to 48, 24 to 34, and 17 to 23 years, respectively. The results suggested that appropriate silvicultural management, such as thinning timing, harvesting age, and others, should be considered depending on the species when the plantation is established. No significant correlation coefficient of mean annual ring width was found between the pith area and 21st to 40th annual ring from the pith, suggesting that trees with faster radial growth in the relatively early stage of growth did not always show a faster radial growth rate after 20 years of growth. On the other hand, a positive correlation in latewood percentage was found between two different positions. Thus, trees with a higher latewood percentage around the pith area have a higher latewood percentage wood after 20 years of growth. The results of the model selection for explaining the relationships between latewood percentage and basic density indicated that the increase ratio of basic density corresponded to an increase of latewood percentage is almost the same irrespective of species, although there are species-specific values of basic density corresponding to specific latewood percentages. The results obtained in the present study can contribute to establishing sustainable forestry using

### Table 7. Annual ring number from pith at maximum values of current annual increment (\(ARN_{\text{CAI}}\)) and mean annual increment (\(ARN_{\text{MAI}}\)).

| Species       | Tree | Random-effect parameters | \(ARN_{\text{CAI}}\) | \(ARN_{\text{MAI}}\) |
|---------------|------|--------------------------|----------------------|----------------------|
| *Pinus sylvestris* | 1    | -0.00022                 | 60                   | 69                   |
|               | 2    | 0.00077                  | 57                   | 65                   |
|               | 3    | 0.00225                  | 52                   | 60                   |
|               | 4    | -0.00284                 | 71                   | 82                   |
|               | 5    | 0.00003                  | 59                   | 68                   |
|               |      | Only fixed-effect parameters | 59                   | 68                   |
| *Pinus sibirica* | 1    | -0.04806                 | 31                   | 45                   |
|               | 2    | -0.01641                 | 31                   | 47                   |
|               | 3    | 0.16143                  | 36                   | 56                   |
|               | 4    | -0.04009                 | 31                   | 45                   |
|               | 5    | 0.05688                  | 30                   | 44                   |
|               |      | Only fixed-effect parameters | 32                   | 48                   |
| *Picea obovata* | 1    | -1.681                   | 24                   | 34                   |
|               | 2    | 20.627                   | 24                   | 34                   |
|               | 3    | -2.016                   | 24                   | 34                   |
|               | 4    | -19.824                  | 24                   | 34                   |
|               | 5    | 2.893                    | 24                   | 34                   |
|               |      | Only fixed-effect parameters | 24                   | 34                   |
| *Larix sibirica* | 1    | -15.578                  | 17                   | 23                   |
|               | 2    | -7.250                   | 17                   | 23                   |
|               | 3    | 0.861                    | 17                   | 23                   |
|               | 4    | 22.904                   | 17                   | 23                   |
|               | 5    | -0.938                   | 17                   | 23                   |
|               |      | Only fixed-effect parameters | 17                   | 23                   |

**Figure 5.** Relationships mean values of annual ring width or latewood percentage between different two radial positions. ARW: annual ring width; LWP: latewood percentage; \(r\): correlation coefficient; \(p\): \(p\) value. Each symbol indicates the mean value of individual tree. Positions I and II are pith to 20th annual ring from pith, and 21st to 40th annual ring from pith, respectively.
natural forests and plantations in boreal regions and Mongolia.

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