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Geographical variations of lumber quality of *Larix sibirica* naturally grown in five different provenances of Mongolia

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Abstract

Annual ring width, warp, dynamic Young's modulus, and static bending properties were evaluated for 2 × 4 lumber produced from *Larix sibirica* trees naturally grown in five different provenances of Mongolia. The lumber was also visually graded according to Japanese Agriculture Standard for structural lumber for wood frame construction. Mean values of dynamic Young's modulus, modulus of elasticity, and modulus of rupture for lumber in each provenance ranged from 9.89 to 14.46 GPa, 7.53 to 13.02 GPa, and 33.0 to 68.7 MPa, respectively. Significant geographic differences were found in all examined properties of lumber among the five provenances. No significant relations were found between annual ring width and other properties, suggesting that radial growth rate of *L. sibirica* trees naturally grown does not always affect reduction on mechanical properties of lumber. Knots and wane were main factors downgrading lumber among the evaluated factors. Tree height, stem shape, and juvenile wood percentage of logs more affected lumber quality of *L. sibirica* trees from natural forests.

Keywords: Geographical variation, *Larix sibirica*, Bending properties, Visual grading

Introduction

Larix species are known to have high growth rate at young age and good physical and mechanical properties of mature wood [1–3]. In addition to those characteristics, *Larix* wood shows good appearance and higher natural durability [4, 5]. By this nature, the wood of *Larix* species obtained from both natural stands and plantations is considered as valuable timber resources.

For effective wood utilization, it is important to understand variation of property and quality of woods. In *Larix* species, several researchers have been reported on geographic variations of growth characteristics and wood properties [2, 5–8]. For example, Takada et al. [6] evaluated the geographic variation of Young's modulus of stem of *Larix kaempferi* in Japan. They found that, of three test stands, only one test site showed significant differences in Young's modulus among provenances. Curnel et al. [5] also found among-provenance's differences in wood decay resistance in *Larix* species. In *Larix sibirica*, Koizumi et al. [2] reported that wood density of this species significantly differed among five natural stands in South Central Siberia, Russia. These reports suggest that interactions between provenance and environment may affect wood quality in *Larix* species.

Mongolia also use wood of *Larix*, especially for *L. sibirica*, as structural lumber construction, since over 70% of the forest area in the country is covered with this species [9]. Even though *L. sibirica* wood is used for structural lumber, available information on wood properties was still limited in this species grown in Mongolia. Recently, several researchers have tried to clarify the wood properties and drying process of *L. sibirica* naturally grown in Mongolia [10–12]. Ishiguri et al. [10] investigated the basic density, shrinkage, bending properties, compressive strength parallel to grain, decay resistance, and amounts of chemical components of 200- to 240-year-old trees of *L. sibirica* grown in Mongolia. They found that values of

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modulus of elasticity (MOE), modulus of rupture (MOR), and compressive strength were lower near the pith, and increased to 4 cm from the pith, suggesting that juvenile wood affected the results. We also investigated geographical variation in growth characteristics, dynamic Young's modulus of stem and logs, annual ring width, latewood percentage, and basic density of *L. sibirica* grown in five provenances of Mongolia [11]. The mean values of tree height, stress-wave velocity of stems, and all measured wood properties except for basic density were significantly different among the five provenances, although the stem diameter was almost the same among provenances. These results suggested that *L. sibirica* trees naturally grown in Mongolia have geographical variations in the mechanical properties in their wood. However, there is no information on lumber quality and its geographic variations of *L. sibirica* in Mongolia.

In the present study, to promote the lumber production under appropriate natural forest managements in Mongolia, 2 × 4 lumber was produced from *L. sibirica* logs collected from five different provenances where were famous *L. sibirica* forestry sites in Mongolia, and then lumber quality was evaluated. In addition, geographical variation of lumber quality was also discussed for efficient production of structural 2 × 4 lumber from *L. sibirica* trees naturally grown in Mongolia.

Materials and methods

Materials

Five natural forests of *L. sibirica* were selected from five different provenances in Mongolia: Khentii, Arkhangai, Zavkhan, Khuvsgul and Selenge [11]. Geographic information and climatic conditions of the site are listed in Table 1. In addition, a total of 25 trees (five trees in each stand) with good stem shape without any severe damages were selected to cut. Before cutting trees, stress-wave velocity of stems was measured for these selected trees. After cutting trees, logs 2 m in length were obtained from 1.3 m above the ground until the top diameter of each log became less than 14 cm. A total of 111 logs were collected from the harvested 25 trees (from 3 to 6 logs from a tree) [11]. Dynamic Young's modulus of all logs was measured by the tapping method [13]. Table 2 shows mean values of growth characteristics and stress-wave

Table 1 Geographic and climatic conditions on the sampling sites [11]

Provenance	Town	Latitude	Longitude	ASL (m)	Temperature (°C)			Precipitation (mm)		
					Mean	Min. (Jan.)	Max. (Jul.)	Mean integrated value	Min.	Max.
Khentii	Batshireet	48°51′N	110°05′E	1214	−1.6	−27.2	19.2	368	0 (Jan.)	160 (Jul.)
Arkhangai	Tsenker	47°22′N	101°43′E	1707	0.5	−19.9	17.4	377	0 (Jan.)	150 (Aug.)
Zavkhan	Tosontsengel	48°41′N	98°17′E	1878	−5.0	−36.1	17.7	242	1 (Feb.)	92 (Aug.)
Khuvsgul	Jargalant	48°31′N	99°15′E	1827	−1.8	−29.1	18.3	226	0 (Feb.)	141 (Aug.)
Selenge	Mandal	48°41′N	106°52′E	1120	0.2	−27.2	22.4	271	0 (Mar.)	157 (Aug.)

Data on temperature and precipitation were provided from Information and Research Institute of Meteorology, Hydrology and Environment, Mongolia. Mean temperature means annual temperature and was calculated by averaging monthly temperature obtained from 2012 to 2016. Mean integrated values of precipitation were calculated by integrating monthly precipitation values of 1 year (2012 to 2016), and then averaged integrated values of 5 years. Minimum and maximum values of precipitation were mean precipitation in a month

ASL: above sea level; min.: minimum; max.: maximum

Table 2 Sample trees and logs in the present study [11]

Provenance	n_1	RN	*D* (cm)		TH (m)		SWV (km/s)		n_2	$\mathrm{DMOE}_{\mathrm{log}}$ (GPa)	
			Mean	SD	Mean	SD	Mean	SD		Mean	SD
Khentii	5	68–78	25.2	0.3	19.5	1.4	3.05	0.12	27	8.01	1.14
Arkhangai	5	38–49	26.6	0.2	11.6	1.2	2.87	0.12	15	5.17	0.88
Zavkhan	5	187–200	23.6	0.2	15.9	1.0	3.27	0.29	26	7.07	1.64
Khuvsgul	5	42–55	22.5	0.3	15.1	0.7	3.24	0.14	20	7.22	0.50
Selenge	5	46–65	22.5	0.2	17.3	2.7	3.55	0.26	23	9.72	1.08
F value			–		16.978**		7.958**			38.158**	

n_1: number of harvested trees; n_2: number of logs; RN: annual ring number at 1.3 m above the ground, *D*: stem diameter at 1.3 m above the ground; TH: tree height; SWV: stress-wave velocity of stem; $\mathrm{DMOE}_{\mathrm{log}}$: dynamic Young's modulus of logs

**Significant difference among provenances ($p < 0.01$). *F* values were obtained by analysis of variance (ANOVA) test velocity of harvested trees, and dynamic Young's modulus of logs. Although the stem diameter was almost the same in all provenances, the mean values of tree height and stress-wave velocity of stems, and dynamic Young's modulus of logs were significantly different among the five provenances.

Taper and juvenile wood percentage of logs

The butt- and top-end diameters of each log were measured. Taper of log was calculated by the following equation [14]:

$$\text{Taper (cm/m)} = \frac{d_1 - d_2}{L}, \tag{1}$$

where d_1 (cm) is the butt-end diameter of log, d_2 (cm) is the top-end diameter of log, and L (m) is the length of the lumber.

Percentage of juvenile wood volume in a log was also estimated. In the previous paper [10], juvenile wood was thought to exist within 4 cm from pith in *L. sibirica* trees naturally grown in Mongolia. Juvenile wood percentage of logs was calculated as the proportion of volume of 4 cm from the pith in each log to total volume of a log calculated using mean values of butt and top diameter and length of log.

Lumber production

A total of 111 logs, 2 m in length, were used in the present study. The logs were sawn into lumber, as many as possible, with 100 × 50 mm cross section. A total of 190 pieces of lumber were obtained from the logs. The lumber was stacked by about 30 layers with wood stickers with 25 × 25 mm cross section at laboratory without air conditioner or heater in Ulaanbaatar, Mongolia. The lumber was air-dried from August 2017 to August 2018. Unfortunately, temperature and relative humidity were not recorded in the room during air-drying, but minimum, maximum, and mean monthly temperature and relative humidity of Ulaanbaatar, Mongolia, during air-drying were as follows: -22.4 (January 2018), 17.9 (June 2018), and 2.0 °C, and 30 (May 2018), 71 (December 2017), and 58%. After air-drying, the lumber was planned into 89 × 38 mm cross section.

Lumber quality

Annual ring width, moisture content, deformation of lumber (bow, crook, and twist), dynamic Young's modulus, and static bending properties were measured as lumber quality.

The bow and crook were determined as maximum deflection of lumber. Bow and crook of the lumber were calculated as the proportion at maximum deflection of bow and crook in each lumber length. To determine twist, lumber was set on a flat surface of a steel beam. After fixing three edges of a lumber, distance between remaining one edge and the flat surface was measured. Twist of the lumber was calculated as follows:

$$\text{Twist (degree)} = \sin^{-1}\left(\frac{h}{w}\right), \tag{2}$$

where h (mm) is the measuring distance and w (mm) width of the lumber.

After bending test, small-clear specimens (2.5 cm in thickness) were obtained from the lumber. The digital images (1200 dpi) of cross sections of the specimens were captured by a scanner and incorporated into a personal computer. The total number of annual rings on the cross section and total width of annual rings were measured by the image analysis software (ImageJ, National Institute of Health). Annual ring width of the lumber was determined by dividing total width by the total number of annual rings. In addition, the same specimens were also used to determine moisture content by oven-dry method.

Visual grading

All pieces of lumber were graded according to Japan Agriculture Standard for structural lumber for wood frame construction [15]. For grading, the typical visual sorting criteria, such as annual ring width, knots size, existence and size of holes, slope of grain, deformation (bow, crook, and twist), wane, and crack, were measured on surfaces of a lumber as described in Japan Agriculture Standard. Based on the measurements, the lumber was classified into the following grades: Selected, Nos. 1, 2, 3, and out grading according to Japanese Agriculture Standard for structural lumber for wood frame construction.

Dynamic Young's modulus and static bending properties of lumber

Dynamic Young's of modulus of lumber (DMOE_{lum}) was determined by tapping method [13]. To determine density at testing, weight, length and dimensions of lumber were measured by portable electric balance (SL-20K, A&D), laser measure (GLM-50C, Bosch), and digital calipers (CD-15CX, Mitutoyo), respectively. One cross end of each lumber was tapped by a small hammer, and then first resonance frequency of longitudinal vibration was obtained by a handheld fast Fourier transform (FFT) analyzer (AD-3527, A&D) with an accelerometer (PV-85, Rion) set on the other end of each lumber. DMOE_{lum} was calculated by the following equation:

$$\text{DMOE}_{\text{lum}}(\text{GPa}) = (2lf)^2\rho \times 10^{-9}, \tag{3}$$

where l (m) is the length of the lumber, f (Hz) is the first resonance frequency, and ρ (kg/m^3) is the density of the lumber at testing.

After measuring dynamic Young's modulus, four-point static bending test was conducted using a material testing machine (WDW-20E, Jinan Kason Testing Equipment). Load speed, support span, and distance between load points were 14 mm/min, 1602 mm, and 534 mm, respectively. The load was applied to edgewise direction. MOE and MOR of lumber were determined by the following equations:

$$\text{MOE (GPa)} = \frac{\Delta P\left(l - l'\right)\left[3l^2 - \left(l - l'\right)^2\right]}{8\Delta y b h^3}, \tag{4}$$

$$\text{MOR (MPa)} = \frac{3P_{\max}\left(l - l'\right)}{2bh^2}, \tag{5}$$

where ΔP (N) is the difference of load between 10 and 40% values of maximum load ($P_{\max}$), Δy is the difference of deflection corresponding to ΔP, l (mm) is the span, l' (mm) is the difference between load points, b (mm) is the width of specimen, and h (mm) is the height of specimen.

Data analysis

All data analyses were conducted using a software (Excel 2016, Microsoft). Mean values of each property were calculated by averaging values of individual trees within a provenance. An analysis of variance was applied to evaluate the differences in measured lumber properties among the provenances.

Results and discussion

Mean values of lumber properties

Mean values of the moisture content, annual ring width, air-dry density, and deformation of lumber are listed in Table 3. The mean values of annual ring width varied among five provenances. The highest and lowest mean values of annual ring width of 2 × 4 lumber were found in Arkhangai (3.4 mm) and Zavkhan (0.5 mm), respectively (Table 3). The mean values of air-dry density of lumber were 0.61, 0.63, 0.62, 0.55, and 0.59 g/cm^3 for Khentii, Arkhangai, Zavkhan, Khuvsgul, and Selenge, respectively. Compared to air-dry density of 2 × 4 lumber produced from the trees in other *Larix* species, obtained mean values of air-dry density in the present study were relatively higher than those of *L. kaempferi*, *Larix decidua*, and *Larix dahurica*, but

Table 3 Mean values and standard deviations of lumber properties

Provenance	*n*	MC (%)		ARW (mm)		AD (g/cm^3)		Bow (%)		Crook (%)		Twist (°)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Khentii	48	12.9	0.5	2.3	0.8	0.61	0.05	0.05	0.04	0.03	0.03	0.06	0.07
Arkhangai	30	13.2	0.4	3.4	0.8	0.63	0.04	0.07	0.04	0.06	0.06	0.11	0.11
Zavkhan	48	13.2	0.4	0.5	0.2	0.62	0.03	0.06	0.06	0.04	0.05	0.06	0.04
Khuvsgul	29	12.4	0.4	2.6	0.5	0.55	0.03	0.17	0.10	0.05	0.07	0.16	0.13
Selenge	35	11.6	0.2	2.0	0.4	0.59	0.04	0.13	0.05	0.07	0.05	0.11	0.08
F value		107.238**		132.780**		21.020**		26.984**		3.389*		8.773**	

n: number of lumber; MC: moisture content determined by oven-dry method; ARW: annual ring width; AD: air-dry density; SD: standard deviation

**Significant difference among provenances ($p < 0.01$); *significant difference among provenance ($p < 0.05$). *F* values were obtained by one-way ANOVA test in lumber properties

Table 4 Bending properties of 2 × 4 lumber produced from the trees of other *Larix* species

Species	Age	Country	*n*	MC (%)	Density (g/cm^3)	MOE (GPa)	MOR (MPa)
L. kaempferi [16]	31	New Brunswick, Canada	126	12.0	0.44	8.44	39.5
L. kaempferi [18]	36	Nikko, Japan	84	13.5	0.50	8.59	56.8
L. kaempferi [17]	63	Nagano, Japan	52	12.4	0.51	8.86	32.9
L. gmelinii [19]	–	Daxing'anling, China	3357	12.0	0.64	8.45–10.16	19.6–38.4
L. decidua [16]	63	Maine, United States of America	277	12.0	0.46	10.93	43.8
L. decidua [16]	17	Nova Scotia, Canada	47	12.0	0.40	5.93	27.3
L. decidua [16]	34	Prince Edward Island, Canada	76	12.0	0.46	8.98	40.5
L. dahurica [1]	–	Far East, Russia	215	15.0	0.52	11.10–14.06	45.3–67.4

n: number of lumber

almost the same with *Larix gmelinii* (Table 4). Among the five provenances, mean values of bow, crook, and twist ranged from 0.05 to 0.17%, 0.03 to 0.07%, and 0.06° to 0.16°, respectively (Table 3). The lowest values of average bow (0.05%), crook (0.03%) and twist (0.06°) were found in Khentii. The highest mean values of bow (0.17%) and twist (0.16%) were found in Khuvsgul.

Mean values of dynamic Young's modulus, MOE, and MOR of lumber ranged from 9.89 to 14.46 GPa, 7.53 to 13.02 GPa, and 33.0 to 68.7 MPa, respectively (Table 5). Bending properties of 2 × 4 lumber in *Larix* species have been reported by several researchers [1, 5, 16–19]. In *L. kaempferi*, as shown in Table 4, mean values of MOE and MOR were 8.44 GPa and 39.5 MPa for 2 × 4 lumber produced from 31-year-old trees planted in Canada [16], and 8.86 GPa and 32.9 MPa for 2 × 4 lumber produced from 63-year-old trees planted in Japan [17]. Chui and MacKinnon-Peters [16] also measured MOE and MOR of 2 × 4 lumber of *L. decidua*, and they were 10.93 GPa and 43.8 MPa for 63-year-old trees planted in United States of America, and 8.98 GPa and 40.5 MPa for 34-year-old trees planted in Canada, respectively (Table 4). In addition, Ethington et al. [1] reported that MOE and MOR of 2 × 4 lumber of *L. dahurica* ranged from 11.10 to 14.06 GPa (1.610 to 2.039 × 10^6 psi), 45.3 to 67.4 MPa (6.564 to 9.779 psi), respectively (Table 4). The mean values of MOE and MOR were similar or relatively higher than those of other *Larix* species (Table 4).

Figures 1 and 2 show longitudinal variations of MOE and MOR of lumber in each provenance. Except for Khuvsgul, MOE of lumber slightly decreased from bottom to top of trees. In Khuvsgul, it slightly decreased with increase of height positions and then increased at most upper position (Fig. 1). The similar trends were also observed in dynamic Young's modulus of logs used in the present study [11]. On the other hand, longitudinal patterns of MOR of lumber varied not only among the provenances, but also within a tree (Fig. 2).

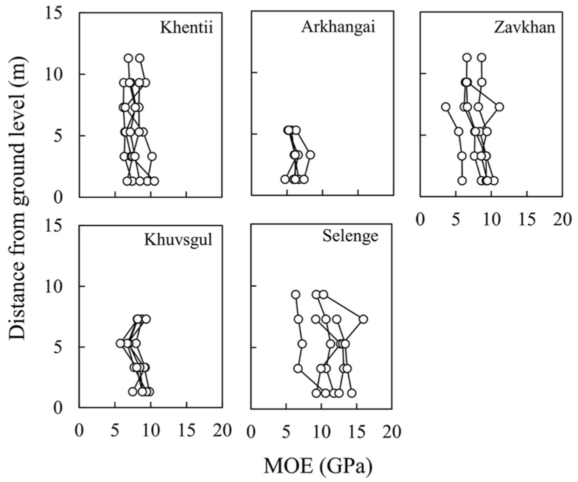

Fig. 1 Longitudinal variations of modulus of elasticity (MOE) of lumber in each provenance. Open circles indicate mean values of MOE of lumber obtained from each height. *n* number of lumber

Correlation coefficients between dynamic Young's modulus of lumber and MOE or MOR of lumber are listed in Table 6. Dynamic Young's modulus of lumber was strongly correlated with the both MOE and MOR of lumber, except for Khuvsgul, suggesting that measuring the dynamic Young's modulus of lumber is a useful indicator for predicting bending properties of *L. sibirica* lumber.

Relationships between annual ring width and mechanical properties

Miyajima [20] investigated the relationships between the annual ring width and the mechanical properties of 2 × 4 lumber of *L. kaempferi* trees planted in Japan. He reported that increasing annual ring width resulted in the decreasing values of the MOE and MOR. To clarify similar tendency with Miyajima [20], the relationships between annual ring width and lumber properties were analyzed in the present study (Table 7). No significant

Table 5 Mean values and standard deviations of dynamic Young's modulus and bending properties of the lumber

Provenance	*n*	DMOE$_{lum}$ (GPa)				MOE (GPa)				MOR (MPa)			
		Mean	SD	Max.	Min.	Mean	SD	Max.	Min.	Mean	SD	Max.	Min.
Khentii	48	12.39	2.32	17.73	8.08	10.32	2.04	15.48	6.63	50.6	19.3	98.8	14.5
Arkhangai	30	9.89	1.35	12.89	7.57	7.53	1.42	10.53	4.25	33.0	11.5	59.1	14.2
Zavkhan	48	12.35	2.16	15.83	6.39	10.28	2.49	18.18	4.35	58.4	23.8	115.5	15.9
Khuvsgul	29	10.99	0.98	13.57	9.16	9.87	1.06	12.12	7.93	52.9	14.0	94.1	33.7
Selenge	35	14.46	1.85	17.59	10.90	13.02	2.40	22.41	9.57	68.7	20.9	121.5	37.8
F value		26.579**				29.546**				15.128**			

n: number of lumber; DMOE$_{lum}$: dynamic Young's modulus of lumber; MOE: modulus of elasticity; MOR: modulus of rupture; SD: standard deviation

**Significant difference among provenances ($p < 0.01$). *F* values were obtained by one-way ANOVA test

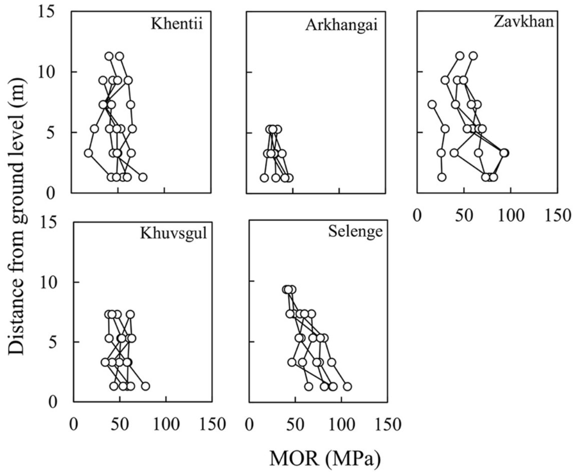

Fig. 2 Longitudinal variations of modulus of rupture (MOR) of lumber in each provenance. Open circles indicate mean values of MOR of lumber obtained from each height. *n* number of lumber

relations were found between annual ring width and lumber properties, except for the lumber from Khentii. Negative significant correlations were recognized between annual ring width and air-dry density, dynamic Young's modulus, or MOE in the lumber from Khentii. Our results in *L. sibirica* except for the lumber from Khentii were not the same with those reported by Miyajima [20] in *L. kaempferi*. Therefore, it is considered that radial growth rate of trees does not always relate to lumber quality in *L. sibirica*.

For the determination of lumber quality, effect the presence of juvenile wood on lumber quality should be considered. Ishiguri et al. [10] showed that wood with lower MOE and MOR, like juvenile wood, was present within 4 cm from the pith for *L. sibirica* naturally grown in Mongolia. In the present study, juvenile wood percentage in logs was calculated. As a result, juvenile wood percentage gradually increased from bottom to top in all provenances (Fig. 3). The longitudinal trend in juvenile wood percentage was similar to that in MOE of lumber (Fig. 1). Thus, juvenile wood of this species is considered as one of the primary factors to reduce lumber quality. If the wood with wider annual rings was found around the pith area, negative correlations will be found between annual ring width and strength properties. Further research is needed to clarify the relationships between annual ring width and formation of juvenile wood in this species.

Geographical variation of lumber properties

It is known that geographical variations are found in growth characteristics and wood properties in *Larix* species [2, 6, 11]. In *L. kaempferi*, Takada et al. [6] investigated geographic variations of Young's modulus of stems for *L. kaempferi* trees originated from 19 different seed provenances in two provenance-trial test stands in Hokkaido, Japan. As the results, they found that some better or worse provenances in Young's modulus rankings were common in two test stands, although there were no correlations between the test stands. Koizumi et al. [2] examined geographical variations of anatomical and mechanical properties of wood in *L. sibirica* grown in five natural stands of Russia. They found that the wood from Baikal site had very high density, especially due to the narrow growth rings, whereas the wood from the Altai

Table 6 Relationships between dynamic Young's modulus and MOE or MOR of lumber

Factor 1	Factor 2	Khentii (*n* = 48)	Arkhangai (*n* = 30)	Zavkhan (*n* = 48)	Khuvsgul (*n* = 29)	Selenge (*n* = 35)
DMOE_{lum}	MOE	0.861**	0.563**	0.855**	0.785**	0.584**
	MOR	0.704**	0.456*	0.808**	0.337$^{\text{ns}}$	0.602**

n: number of lumber; DMOE_{lum}: dynamic Young's modulus of lumber; MOE: modulus of elasticity; MOR: modulus of rupture; ns: no significance

*Significance at 5% level

**Significance at 1% level

Table 7 Correlation coefficients between annual ring width and lumber properties in each stand

Property	Khentii (*n* = 48)	Arkhangai (*n* = 30)	Zavkhan (*n* = 48)	Khuvsgul (*n* = 29)	Selenge (*n* = 35)
AD	− 0.360*	− 0.118$^{\text{ns}}$	− 0.118$^{\text{ns}}$	− 0.232$^{\text{ns}}$	− 0.256$^{\text{ns}}$
DMOE_{lum}	− 0.491**	− 0.234$^{\text{ns}}$	− 0.264$^{\text{ns}}$	− 0.048$^{\text{ns}}$	− 0.055$^{\text{ns}}$
MOE	− 0.345*	− 0.055$^{\text{ns}}$	− 0.198$^{\text{ns}}$	− 0.065$^{\text{ns}}$	− 0.108$^{\text{ns}}$
MOR	− 0.238$^{\text{ns}}$	− 0.175$^{\text{ns}}$	− 0.203$^{\text{ns}}$	− 0.081$^{\text{ns}}$	− 0.107$^{\text{ns}}$

n: number of lumber; AD: air-dry density; DMOE_{lum}: dynamic Young's modulus of lumber; MOE: modulus of elasticity; MOR: modulus of rupture

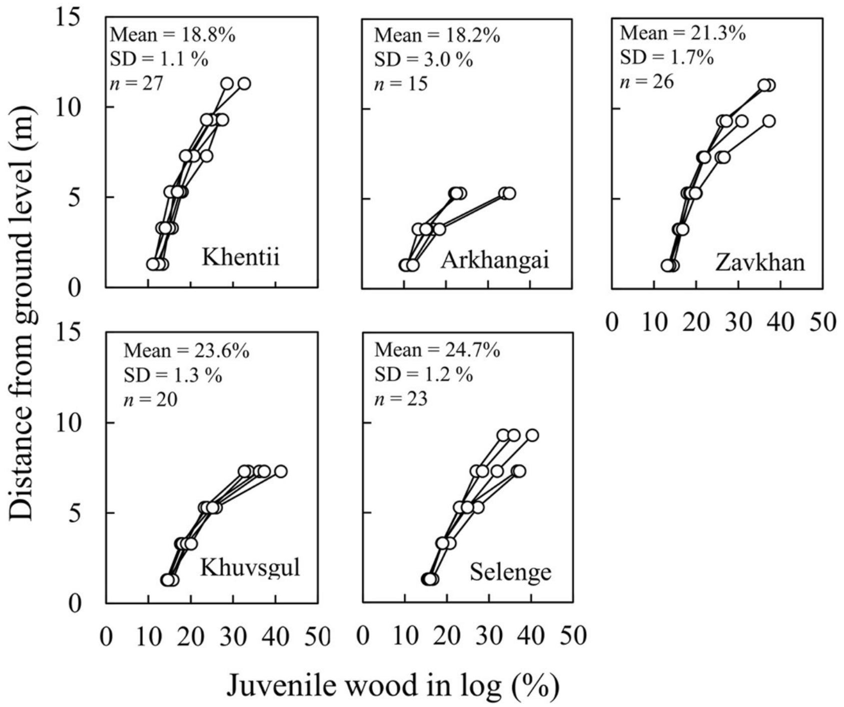

Fig. 3 Longitudinal variations of juvenile wood percentage of logs in each provenance. Open circles indicate juvenile wood percentage of log from individual tree. *SD* standard deviation; *n* number of lumber

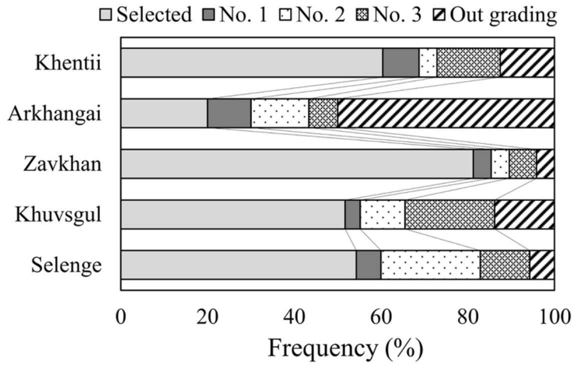

Fig. 4 Percentage of each grading class of lumber in each provenance

Table 8 Factors of lumber classified into outgrading in each provenance

Provenance	*n*	Factor	Frequency (%)
Khentii	6/48 (12.5%)	Knot	50
		Twist	17
		Wane	33
Arkhangai	15/30 (50.0%)	Knot	33
		Twist	7
		Wane	60
Zavkhan	2/48 (4.2%)	Knot	100
Khuvsgul	4/29 (13.8%)	Knot	75
		Twist	25
Selenge	2/35 (5.7%)	Knot	100

n: number of outgrading lumber/total number of lumber (percentage of outgrading lumber)

site in the mountain range had a low density. In addition, we previously reported that geographical variations were found tree height, stress-wave velocity, latewood percentage, and dynamic Young's modulus of logs in *L. sibirica* naturally grown in Mongolia [11]. In the present study, all lumber properties showed significant differences among the provenances (Tables 3 and 5). The results suggest that wood of *L. sibirica* trees naturally grown in Mongolia has geographic variation in lumber quality as well as growth characteristics and wood properties.

Figure 4 shows the results of visual grading for lumber from each provenance. Percentage of number of lumber assigned to the Selected and No. 1 in each stand showed more than 50% in all stands except for Arkhangai. In contrast, 50% of total lumber showed outgrading in Arkhangai (Fig. 4). Main reasons of downgrading lumber

Table 9 Taper values of logs at three height positions

Provenance	Height position of log (m)					
	1.3–3.3		3.3–5.3		5.3–7.3	
	Taper (cm/m)		Taper (cm/m)		Taper (cm/m)	
	Mean	SD	Mean	SD	Mean	SD
Khentii	1.1	0.4	0.8	0.2	0.9	0.4
Arkhangai	2.5	0.6	2.2	0.7	2.7	0.5
Zavkhan	1.0	0.2	1.0	0.4	0.8	0.4
Khuvsgul	1.3	0.1	1.3	0.1	1.4	0.4
Selenge	1.3	0.3	0.6	0.5	0.8	0.1

Standard deviation

from Arkhangai were knot and wane (Table 8). Among the provenances, the highest taper value of log was found in Arkhangai (Table 9); although the trees from Arkhangai used in the present study showed almost the same diameter as those other provenances at 1.3 m above the ground, tree height was quite lower than other provenances (Table 2). In addition, juvenile wood percentage of logs at 5.3–7.3 m showed the highest values in Arkhangai (Fig. 3). Based on the results, tree height, taper value and juvenile wood percentage of logs are considered to affect lumber quality considerably in *L. sibirica* trees naturally growing in Mongolia.

Conclusions

Geographical variations of 2 × 4 lumber quality were examined in *L. sibirica* trees naturally grown in Mongolia. Among five provenances, significant differences were found in all lumber properties such as air-dry density, deformation, dynamic Young's modulus, MOE and MOR. Radial growth rate of *L. sibirica* trees naturally grown did not affect decrease in mechanical properties of lumber. Knot and wane were main factors for downgrading lumber among the evaluated factors. Tree height, stem shape, and juvenile wood percentage of logs are considered to affect lumber quality considerably of *L. sibirica* trees from natural forests in Mongolia.

Abbreviations

MOE: modulus of elasticity; MOR: modulus of rupture.

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Authors' contributions

BT contributed to experiments, data analysis and writing the manuscript. FI designed this study and also contributed to experiments, data analysis and writing the manuscript. HA-S contributed to experiments and discussion on the obtained results. YT and IN contributed to experiments and data analysis. 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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Competing interests

The authors declare that they have no competing interests.

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