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Effects of radial growth rate on juvenile wood properties of *Pinus sylvestris* planted in Mongolia

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Abstract

The establishment of forest plantations in boreal zones in Mongolia is important for wood production as well as carbon dioxide fixation. The present study aims to elucidate the juvenile wood properties (basic density, modulus of elasticity [MOE], modulus of rupture [MOR], and compressive strength parallel to grain) of plantation-grown *Pinus sylvestris* to promote the establishment of plantations. In addition, the effect of the radial growth rate on wood properties was also evaluated using a linear mixed-effects model. In the juvenile wood phase, wood properties were increased from the pith to bark side based on the results of model selections. Up to the 20th annual ring from the pith, the estimated mean values of basic density, MOE, MOR, and compressive strength were 0.40 g/cm^3, 5.35 GPa, 65.1 MPa, and 28.4 MPa, respectively. Variance component ratios of growth categories were low in wood properties, with the exception of basic density, suggesting that the radial growth rate did not affect wood properties in the juvenile wood phase in this species growing in Mongolia. Based on the results obtained in the present study, we have concluded that although basic density in the faster growth category yielded relatively lower values, appropriate radial growth promotion during the initial stage of growth in *P. sylvestris* trees planted in Mongolia exerted no negative impact on juvenile wood properties.

Keywords: annual ring width, basic density, compressive strength, modulus of elasticity, modulus of rupture

Introduction

Boreal forests cover about 15.7 × 10^8 hectares and occur only in the Northern Hemisphere (Grower et al. 2003). They are mainly natural forests consisting of coniferous species, such as *Picea*, *Abies*, and *Larix* (Grower et al. 2003, Farjon 2010). These coniferous species are regarded as valuable timber resources. However, harvesting boreal forests is challenging because the rate of vegetation regrowth is slow due to the extremely cold winters and infertile soils (Grower et al. 2003). Therefore, one of the alternative means of conducting sustainable forestry in this region involves the establishment of plantations. Furthermore, considering that younger trees have a higher capacity to serve as carbon sinks, the establishment of plantations in this region is also an important factor in combating global warming (Jörgensen et al. 2021).

A faster initial growth rate of trees is crucial for establishing plantations in this region. However, a more rapid initial growth rate also results in an increase in the volume of juvenile wood, which is inferior in relation to solid wood production (Zobel and van Buijtenen 1989, Ishiguri et al. 2009, Pollet et al. 2017). Therefore, to produce desirable high-quality wood from plantations, a balance between the initial growth rate and juvenile wood problems should be considered. For example, Pollet et al. (2017) proposed that from a purely mechanical standpoint, juvenile growth should be minimized or at least maintained at a relatively low level of about 4 mm/year in Douglas fir (*Pseudotsuga menziesii*) planted in Belgium. Thus, the relationship between the initial growth rate and juvenile wood quality must be examined for plantation trees in the boreal area for solid wood production.

The southern border between the Siberian boreal forests and the Central Asian dry steppes is located in the northern part of Mongolia (Mühlenberg et al. 2012). Forestry in Mongolia has mainly relied on natural forest resources (Tumenjargal et al. 2018, 2020, Sarkhad et al. 2022). Thus, wood properties have mainly been assessed in coniferous species found in natural forests, such as *Larix sibirica*, *Pinus sylvestris*, *Pinus sibirica*, *Picea obovata*, and others (Ishiguri et al. 2018, Tumenjargal et al. 2018, 2020, Sarkhad et al. 2022). On the other hand, efforts have also been made to establish plantations in Mongolia (Sukhbaatar et al. 2020, Ganbaatar et al. 2021). Ganbaatar et al. (2021) reported the effects of thinning on tree growth and crown development in *P. sylvestris* plantations in Mongolia. However, the available information about wood properties remains limited for planted trees in Mongolia.

The effects of radial growth rate on wood properties in coniferous species have been discussed by numerous researchers (Zobel and van Buijtenen 1989, Takata et al. 1992, Zhang 1995, Koga et al. 1996, Zhu et al. 2000, Livingston et al. 2004, Shirai and Kitahara 2010, Kimura and Fujimoto 2014, McLean et al. 2016, Pollet et al. 2017). For example, Zhang (1995) pointed out that with increasing growth rate, the wood mechanical properties in the softwood with gradual transition from earlywood to latewood (*Abies* and *Picea*) decreased significantly, and this, to a lesser extent, applies to the softwood with an abrupt transition from earlywood and latewood (*Larix* and *Pinus*), and growth rate showed an appreciably less effect on modulus of elasticity (MOE), compared to the modulus of rupture (MOR) and compressive strength parallel to the grain. These results suggest that the magnitude of the effects of radial growth rate on wood properties depends on the wood species. Thus, the effects of radial growth rate on juvenile wood properties should be evaluated for trees growing on a *P. sylvestris* plantation.

In the present study, juvenile wood properties were examined to uncover basic information about wood properties in plantation-grown *P. sylvestris* trees in Mongolia to promote the establishment of plantations there. Based on the results, the effects of the radial growth rate on juvenile wood properties were also evaluated using mixed-effect models.

Materials and methods

Materials

Sample *Pinus sylvestris* L. trees were collected from a plantation located in Selenge, Mongolia (50°05'–12'N, 106°14'–31'E). The plantation was established in 2002 using two-year-old seedlings with an initial spacing of 4.0 × 1.0 m. The experimental thinning treatment was conducted in 2016 in half of the area. Detailed information about the plantation was reported in a previous paper (Ganbaatar et al. 2021). In 2020, dominant, medium, and suppressed trees (three trees in each growth category) were selected from non-thinned and thinned sites (nine trees in each site). However, the data obtained from two different sites were combined because the annual ring width of these trees was similar (Table 1). The statistical values of growth characteristics are listed in Table 2. The logs (30 cm in length) were collected from 1.3 to 1.6 m above the ground's surface. The logs were processed into radial boards with a thickness of about 30 mm. The radial boards were used for the following experiments.

Table 1. Effects of thinning treatment on annual ring width in the sample trees collected from non-thinning and thinning sites

Site	*n*	Mean	*SD*	Minimum	Maximum	*t*-value (*p*-value)
Non-thinning	9	2.6	0.7	1.6	3.6	0.602
Thinning	9	2.4	0.7	1.5	3.4	(0.556)

Note: *n* – number of sample trees; *SD* – standard deviation. The *t*- and *p*-values were obtained by *t*-test between the non-thinning and thinning sites.

Table 2. Mean values and standard deviations of growth characteristics and wood properties the sample trees collected from non-thinning and thinning sites

Property	Growth category			Mean / total
	Dominant	Medium	Suppressed	
n	6	6	6	18
D (cm)	10.7 (0.3)	7.9 (0.5)	5.3 (0.2)	8.0 (2.3)
TH (m)	7.1 (0.3)	6.1 (0.6)	5.6 (0.4)	6.3 (0.8)
ARW (mm)	3.2 (0.3)	2.4 (0.1)	1.7 (0.2)	2.5 (0.7)
BD (g/cm^3)	0.37 (0.02)	0.40 (0.02)	0.41 (0.02)	0.39 (0.03)
MOE (GPa)	4.83 (0.43)	4.28 (1.12)	4.45 (0.78)	4.52 (0.81)
MOR (MPa)	55.9 (1.7)	57.7 (5.9)	60.5 (5.2)	58.0 (4.8)
CS (MPa)	25.4 (1.3)	26.0 (2.7)	25.5 (1.9)	25.6 (2.0)

Note: *n* – number of trees; D – stem diameter at 1.3 m above the ground; TH – tree height; ARW – annual ring width; BD – basic density; MOE – modulus of elasticity; MOR – modulus of rupture; CS – compressive strength parallel to grain. Values in parentheses indicate standard deviations.

Wood properties

To measure the annual ring width, 1-cm-thick radial strips with pith were obtained from sample radial boards. The surface of the strip was sanded. The cross-sectional images were captured by a scanner (GT-9300UF, EPSON, Nagano, Japan) with the resolution of 600 dpi. The annual ring width of each ring was measured using ImageJ programme (Rasband 2018).

To measure the basic density, wedge-shaped specimens (30° in centre angle) were prepared from 18 individuals, and the specimens were then cut at every three annual rings. The samples were soaked in tap water for one week because the samples were dried. The wet volume was determined using a water displacement method, and the specimens were then dried at 103°C to determine the oven-dry weight. Basic density (*BD*) was determined using the following formula:

$$BD\ (\mathrm{g/cm^3}) = \frac{Wo}{Vw}$$

where

Wo is the oven-dry weight, and

Vw is the wet volume.

Bark-to-bark radial boards (with pith, 10 mm in thickness) were prepared of 18 individual trees. The boards were successively cut at 10 mm intervals from pith to bark side to prepare the static bending specimens (ca. 10 [R] by 10 [T] by 160 [L] mm). In addition, the annual ring number at the centre of transverse section in each specimen was recorded as the representative annual ring number from pith of the specimen. In total, 125 specimens were obtained from 18 boards. The specimens were kept in a desiccator with saturated sodium chloride solution at 25°C for one month. A static bending test was conducted by a universal testing machine (MSC-5/500-2, Tokyo Testing Machine, Tokyo, Japan). The load was applied to the centre of specimens with a 140 mm span and a speed of 2 mm/min. The MOE and MOR were calculated using the following equations:

$$\mathrm{MOE\ (GPa)} = \frac{\Delta P l^3}{4 \Delta y b h^3} \bullet 10^{-3} \ ;$$

$$\mathrm{MOR\ (MPa)} = \frac{3Pl}{2bh^2} \ ,$$

where

ΔP (N) is the difference in the load between two specific positions under the proposal limit;

l represents span (140 mm);

Δy (mm) represents deflection corresponding to ΔP;

b (mm) is the width of the specimen;

h (mm) is the height of the specimen; and

P (N) is the maximum load.

After the static bending test, small-clear specimens (ca. 10 [R] by 10 [T] by 10 [L] mm) were obtained to determine the moisture content and density when testing from the specimens without any visual defects. The mean value and standard deviation of moisture content and density when testing in bending specimens were 10.2 ± 1.1% and 0.50 ± 0.05 g/cm^3, respectively.

Compressive test specimens (ca. 10 [R] by 10 [T] by 40 [L] mm) were obtained from the specimens without any visual defects after the bending test. The same testing machine for the static bending test was used for the compressive test. The load was applied at 0.5 mm/min. The size and weight of the specimens were measured before testing to determine the density when testing. The compressive strength parallel to grain (s) was calculated using the following formula:

$$\sigma\ \mathrm{(MPa)} = \frac{Pm}{A} \ ,$$

where

Pm (N) is the maximum load, and

A (mm^2) is the cross-sectional area of the specimen.

After the tests, the oven-dry weight of the sample was determined to calculate the moisture content. The mean values and standard deviations of the compressive test specimens were 13.6 ± 0.4% and 0.49 ± 0.05 g/cm^3, respectively.

To evaluate the radial variations of MOE, MOR, and compressive strength, the annual ring number from the pith located in the centres of the specimens on the cross-section was recorded in each specimen.

Statistical analysis

Statistical analysis was conducted using R software environment, version 4.0.3 (R Core Team 2020). To evaluate the radial variations of wood properties (basic density, MOE, MOR, and compressive strength), the following mixed-effect models with a random effect of growth categories were developed by using the lmer function in lme4 packages and lmerTest packages (Bates et al. 2015) and the nlme function in the nlme package (Pinheiro and Bates 2000) according to our previous reports (Nezu et al. 2022, Sarkhad et al. 2022):

$$\text{Model I-i:}\ \ y_{ij} = (\alpha_0 + Growth_i) \bullet RN_{ij} + \alpha_1 + e_{ij} \ ;$$

$$\text{Model I-ii:}\ \ y_{ij} = \alpha_0 \bullet RN_{ij} + \alpha_1 + Growth_i + e_{ij} \ ;$$

$$\text{Model II-i:}\ \ y_{ij} = (\beta_0 + Growth_i) \ln RN_{ij} + \beta_1 + e_{ij} \ ;$$

$$\text{Model II-ii:}\ \ y_{ij} = \beta_0 \bullet \ln RN_{ij} + \beta_1 + Growth_i + e_{ij} \ ;$$

$$\text{Model III-i:}\ \ y_{ij} = (\gamma_0 + Growth_i) RN_{ij}^2 + \gamma_1 \bullet RN_{ij} + \gamma_2 + e_{ij} \ ;$$

$$\text{Model III-ii:}\ \ y_{ij} = \gamma_0 RN_{ij}^2 + (\gamma_1 + Growth_i) \bullet RN_{ij} + \gamma_2 + e_{ij} \ ;$$

$$\text{Model III-iii:}\ \ y_{ij} = \gamma_0 \bullet RN_{ij}^2 + \gamma_1 \bullet RN_{ij} + \gamma_2 + Growth_i + e_{ij} \ .$$

In addition, the radial variation of annual ring width was evaluated based on a logistic formula with the random effect of growth categories:

$$\text{Model IV-i:}\ \ y_{ij} = \frac{\varepsilon_0 + Growth_i}{1 + \varepsilon_1 \bullet \exp(-\varepsilon_2 \bullet RN_{ij})} + e_{ij} \ ;$$

$$\text{Model IV-ii:}\ \ y_{ij} = \frac{\varepsilon_0}{1 + (\varepsilon_1 + Growth_i) \bullet \exp(-\varepsilon_2 \bullet RN_{ij})} + e_{ij} \ ;$$

$$\text{Model IV-iii:}\ \ y_{ij} = \frac{\varepsilon_0}{1 + \varepsilon_1 \bullet \exp(-[\varepsilon_2 + Growth_i] \bullet RN_{ij})} + e_{ij} \ ,$$

where

y_{ij} is the measured value of the *j*-th annual ring of the individual tree in the *i*-th growth category;

α_0, α_1, β_0, β_1, γ_0, γ_1, γ_2, ε_0, ε_1, and ε_2 represent fixed-effect parameters;

$Growth_i$ is the random-effect parameter of the *i*-th growth category;

RN_{ij} is the *j*-th annual ring number from the pith in individual trees in the *i*-th growth category; and

e_{ij} is the residual, respectively.

The optimal model for explaining the radial variation of the wood property was selected using the Akaike Information Criterion (AIC; Akaike 1998). To estimate the juvenile wood properties, values of wood properties in every annual ring from pith to the 20th annual ring were calculated using fixed-effect parameters in the selected models. Then, mean values were also calculated.

To evaluate the effects of radial growth rate on wood properties, the following linear mixed-effect model was used (Nezu et al. 2022):

$$y_{ij} = \mu + Growth_i + e_{ij}\ ,$$

where

y_{ij} is the measured value (mean value of individual tree) of the j-th individual tree of the i-th growth category;

μ is the fixed-effect parameter;

$Growth_i$ is the random-effect parameter of the growth category i; and

e_{ij} is the residual.

The variance component ratio of the growth category (VC_c) was calculated using the following equation (Nakagawa and Schielzeth 2010, Nezu et al. 2022):

$$VC_c = \frac{\delta_c}{\delta_c + \delta_e} \bullet 100\ ,$$

where

δ_c is the variance component of the growth category, and

δ_e represents residual variance, respectively.

Results

Table 2 indicates the statistical values of growth characteristics and wood properties. The mean values of wood properties were 2.5 mm for annual ring width, 0.39 g/cm^3 for basic density, 4.52 GPa for MOE, 58.0 MPa for MOR, and 25.6 MPa for compressive strength parallel to the grain, respectively.

Radial variations of wood properties are illustrated in Figure 1. The ideal models for radial variations of juvenile wood were logarithmic function with random intercept (Model II-i) for basic density, linear function with random slope (Model I-i) for MOE, and linear function with random intercept (Model I-ii) for MOR and compressive strength (Tables 3 and 4). Based on the results of model selections, all wood properties tested in the present study increased from the pith to the bark in the juvenile wood phase (Figure 1). Figure 2 depicts the dis-

Table 3. Comparison of AIC among mixed-effect models for radial variations of wood properties

Model	Wood property				
	ARW	BD	MOE	MOR	CS
I-i	-	–340.75	**392.11**	887.43	664.28
I-ii	-	–349.00	394.54	**884.20**	**662.62**
II-i	-	**–350.08**	399.26	-	672.61
II-ii	-	–342.25	400.33	-	672.15
III-i	-	–328.02	399.78	897.30	672.12
III-ii	-	-	402.25	893.59	672.04
III-iii	-	–323.39	404.69	890.46	670.39
IV-i	**1162.53**	-	-	-	-
IV-ii	1312.68	-	-	-	-
IV-iii	1214.18	-	-	-	-

Note: ARW – annual ring width; BD – basic density; MOE – modulus of elasticity; MOR – modulus of rupture; CS – compressive strength parallel to grain; "-" – model failed to converge or model was not applied. Bold values indicate the minimum AIC values among developed models.

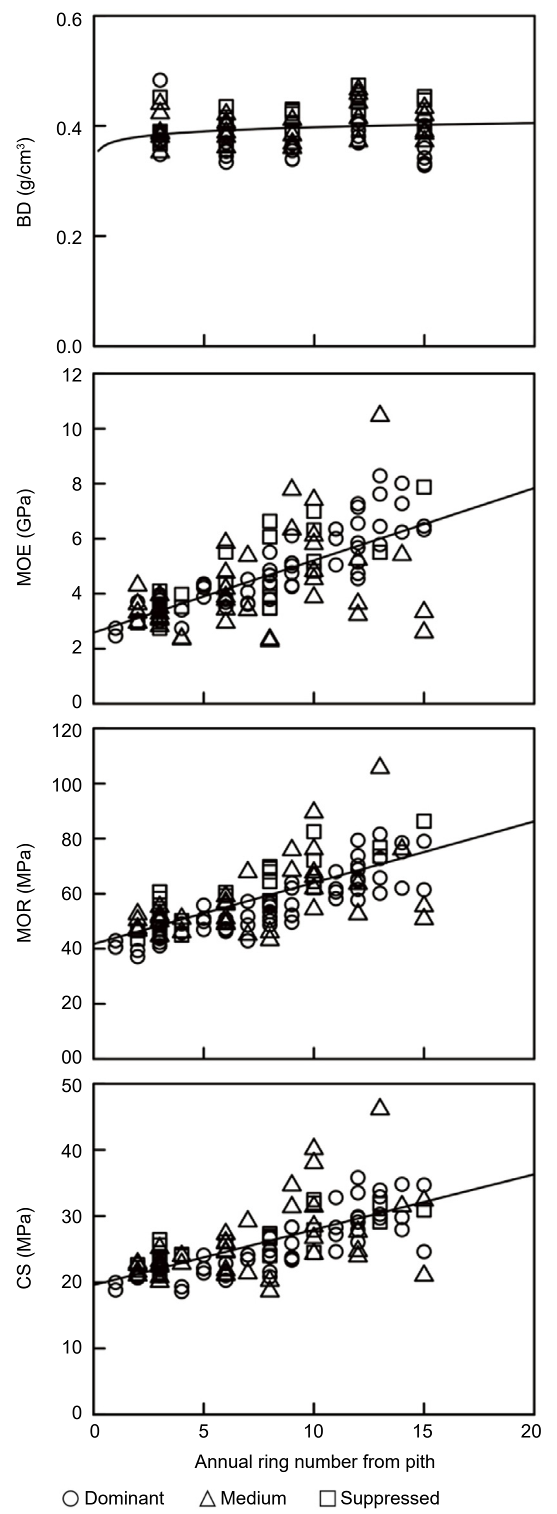

Figure 1. Radial variations of wood properties

Note: Number of sample trees = 18. BD – basic density; MOE – modulus of elasticity; MOR – modulus of rupture; CS – compressive strength parallel to grain. Regression lines and a regression curve indicate the formula with only the fixed-effects parameters of the best-fitted models selected by AIC (Tables 3 and 4).

Table 4. Fixed-effect and random-effect parameters in the selected optimal model for radial variations of wood properties

Property	Selected model	Parameter	Fixed effect			Random effect			Estimated mean value	
			Estimates	*SE*	*p*-value	Dominant	Medium	Suppressed	Mean	*SD*
ARW	IV-i	ε_0	36.640	4.927	< 0.001	10.485	–0.660	–9.825	1.8	1.1
		ε_1	16.786	1.388	< 0.001					
		ε_2	0.359	0.016	< 0.001					
BD	II-i	β_0	0.011	0.008	0.170	–0.013	0.002	0.010	0.40	0.01
		β_1	0.372	0.012	< 0.001					
MOE	I-i	α_0	0.263	0.0322	< 0.001	0.017	–0.033	0.015	5.35	1.56
		α_1	2.588	0.2102	< 0.001					
MOR	I-ii	α_0	2.224	0.183	< 0.001	–3.612	–0.305	3.917	65.1	13.2
		α_1	41.776	2.758	< 0.001					
CS	I-ii	α_0	0.837	0.080	< 0.001	–0.731	0.225	0.506	28.4	5.0
		α_1	19.586	0.818	< 0.001					

Note: *SE* – standard error; *SD* – standard deviation; ARW – annual ring width; BD – basic density; MOE – modulus of elasticity; MOR – modulus of rupture; CS – compressive strength parallel to grain. Wood properties values in each annual ring from pith to 20th annual ring were calculated using the fixed-effect model listed in this Table, and mean values were then calculated.

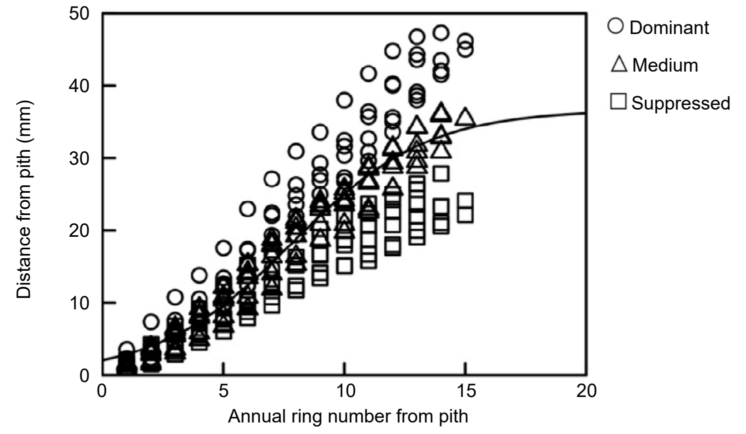

Figure 2. Distance from pith in relation to annual ring number from pith

Note: Number of sample trees = 18. A regression curve indicates the logistic function with only the fixed-effect parameters in the best fitted model selected by AIC (model IV-i).

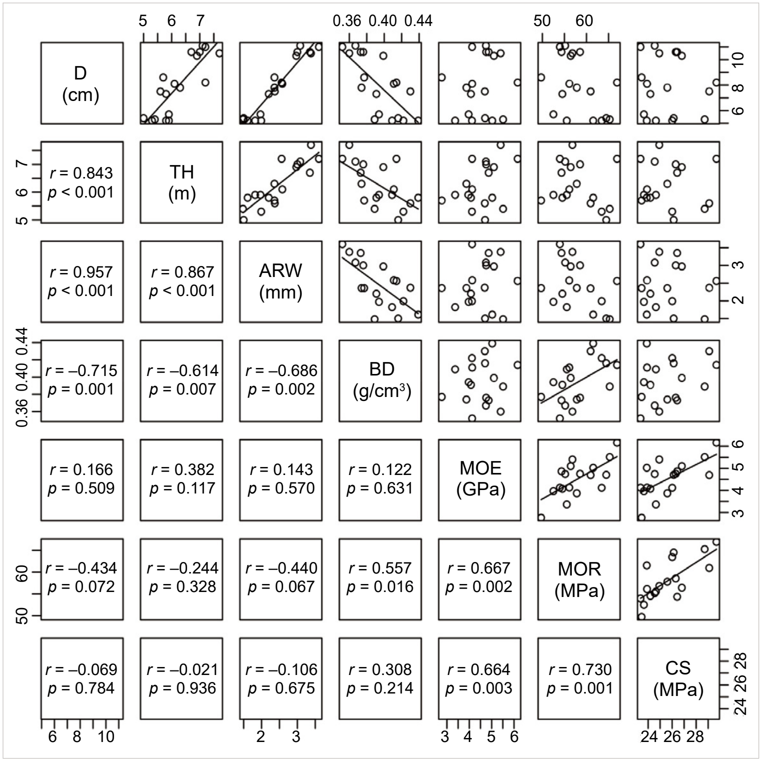

Figure 3. Correlation coefficients among measured properties

Note: Number of sample trees = 18. D – stem diameter at 1.3 m above the ground; TH – tree height; ARW – annual ring width; BD – basic density; MOE – modulus of elasticity; MOR – modulus of rupture; CS – compressive strength parallel to grain; *r* – correlation coefficient; *p* – *p*-value for correlation coefficient.

tance from the pith in relation to the annual ring number from the pith. The radial pattern of distance from pith up to 15 years from the pith was well fitted on Model IV-i (Tables 3 and 4).

Basic density was positively correlated with MOR ($r = 0.557$, $p = 0.016$) (Figure 3). No significant correlations were found between basic density and other mechanical properties (Figure 3). Relatively higher correlation coefficients were found between the mechanical properties of wood (Figure 3).

The mean values of each growth category are also presented in Table 2. Growth characteristics (stem diameter and tree height) and annual ring width differed among the growth categories. A similar pattern was also found in basic density: dominant trees exhibited relatively lower basic density compared to trees in other growth categories. However, the mean values of the mechanical properties of wood were similar among growth categories.

The variance component ratios in the linear mixed-effects model for each property are listed in Table 5. Large values of variance component ratios for the growth category were found for growth characteristics and annual ring width. In contrast, those values were less than 10%, or the models failed to converge in wood properties, except for basic density. The variance component ratio of the growth category for basic density was 50%.

Table 5. Variance components in linear mixed-effects model for each property

Property		Variance component (%)	
		Growth category	Residual
Growth characteristic	D	98.3	1.7
	TH	74.3	25.7
Wood property	ARW	92.5	7.5
	BD	50.0	50.0
	MOE	-	-
	MOR	7.5	92.5
	CS	-	-

Note: D – stem diameter at 1.3 m above the ground; TH – tree height; ARW – annual ring width; BD – basic density; MOE – modulus of elasticity; MOR – modulus of rupture; CS – compressive strength parallel to grain; "-" – model failed to converge.

Discussion

Verkasalo and Leban (2002) reported that mean values of annual ring width, wood density at 12% moisture content, MOE, and MOR of juvenile wood in *P. sylvestris* were 2.6 mm, 0.45 g/cm^3 (445.2 kg/m^3), 9.97 GPa (9,972 MPa), and 71.1 MPa, respectively, in trees growing in Finland, and 5.0 mm, 0.50 g/cm^3 (504.3 kg/m^3), 9.46 GPa (9,458 MPa), and 67.8 MPa respectively, in trees growing in France. Takahashi et al. (1983) also reported that the mean values in *P. sylvestris* imported from Russia were 1.3 mm for annual ring width, 0.345 g/cm^3 for basic density, 9.41 GPa (96 tonf/cm^2) for MOE, 81.7 MPa (833 kgf/cm^2) for MOR, and 42.7 MPa (435 kgf/cm^2) for compressive strength, respectively. Sarkhad et al. (2022) also reported that the basic density, MOE, MOR, and compressive strength of juvenile wood (wood up to about 20th annual ring from pith) in *P. sylvestris* trees grown in a natural forest in Mongolia were 0.37 g/cm^3, 7.64 GPa, 69.4 MPa, and 30.5 MPa, respectively. To compare with previous data, mean values up to the 20th annual ring from the pith were estimated using obtained fixed-effect models for radial variations (Table 4). As a result, the mean values of annual ring width, basic density, MOE, MOR, and compressive strength were 1.8 mm, 0.40 g/cm^3, 5.35 GPa, 65.1 MPa, and 28.4 MPa, respectively (Table 4). Except for MOE, these estimated values were similar to those previously obtained in juvenile wood harvested from trees naturally grown in Mongolia (Sarkhad et al. 2022). Thus, we conclude that wood obtained from plantation-grown *P. sylvestris* is not always of lower quality compared to wood from natural forests in Mongolia. On the other hand, radial growth rate (annual ring width), wood density and bending properties of juvenile wood obtained in the present study showed lower values than trees growing in Europe (Verkasalo and Leban 2002). These differences might be due to differences of genetic source, climatic conditions, and etc.

Ishiguri et al. (2009) reported that in *Cryptomeria japonica* D. Don, MOE in juvenile wood was affected by microfibril angle rather than wood density. However, wood density was highly correlated with MOR in juvenile wood. In *P. sylvestris*, the values of correlation of determination (r^2) between MOE and wood density at 12% moisture content were lower in juvenile wood ($r^2 = 0.582$ in Finland trees, and $r^2 = 0.189$ in French trees) than in mature wood ($r^2 = 0.636$ in Finland trees, and $r^2 = 0.651$ in French trees) (Verkasalo and Leban 2002). A similar result between basic density and MOE or MOR was obtained in the present study (Figure 3). Thus, further research is necessary to elucidate the relationships between microfibril angle and the mechanical properties of juvenile wood in *P. sylvestris*. On the other hand, correlation coefficients between mechanical properties were reported by several researchers (Pikk and Kask 2004, Tumenjargal et al. 2020, Sarkhad et al. 2022). Similar results were also obtained in the present study, suggesting that mechanical properties can be evaluated by other mechanical properties.

Among wood properties except for annual ring width, the variance component ratio of the growth category was relatively high for basic density and annual ring width but low or zero for other wood properties (Table 5), suggesting that mechanical properties of juvenile wood were not affected by the radial growth rate in *P. sylvestris* planted in Mongolia. Still, a faster radial growth rate in dominant trees resulted in producing relatively lower wood density compared to the medium and suppressed trees. These phenomena also corresponded to the correlation coefficients between growth characteristics and juvenile wood properties; growth characteristics were negatively correlated with basic density but not with mechanical properties (Figure 3). However, differences in basic density between dominant trees and other trees in the other two growth categories were not substantial (Table 2). Thus, we conclude that growth promotion in the early stages of growth in plantations of this species in Mongolia may not always produce lower-quality juvenile wood. However, a faster radial growth rate in Mongolia resulted in producing relatively lower basic density wood.

Conclusion

The present study aimed to elucidate the juvenile wood properties in plantation-grown *P. sylvestris* trees in Mongolia to promote the establishment of plantations of this species in Mongolia and boreal areas. Based on the results of the selection of mixed-effects models, the values of all wood properties tested in the present study increased from pith to bark in the juvenile wood phase. By using the best model for radial variation, mean values of juvenile wood properties (up to the 20th annual ring from pith) were estimated: annual ring width = 1.8 mm, basic density = 0.40 g/cm^3, MOE = 5.35 GPa, MOR = 65.1 MPa, and compressive strength = 28.4 MPa. With a few exceptions, these values were similar to those obtained in the trees grown in natural forests in Mongolia, suggesting that plantation-grown trees in Mongolia do not always exhibit a lower quality of wood compared to wood from trees grown in Mongolian natural forests. Thus, if wood resources of *P. sylvestris* are mainly produced from plantations rather than natural forests in Mongolia, the quality of wood from plantations is almost identical to that from natural forests. In addition, the results of variance component analysis revealed that wood properties, except for basic density, were not affected by the radial growth rate in *P. sylvestris* trees planted in Mongolia. Even if the variance component ratio of the growth category reached 50%, differences in basic density between dominant trees and trees in two other growth categories were not substantial. Based on the results obtained in the present study, we conclude that appropriate radial growth promotion in the initial stage of growth in *P. sylvestris* trees planted in Mongolia exerts no negative impact on juvenile wood properties.

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