Anatomical characteristics and mechanical properties of *Larix sibirica* grown in south-central Siberia

Authors:

Akio Koizumi
Faculty of Agriculture, Hokkaido University, Sapporo, 060-8589 Japan.
Katsuhiko Takata
Institute of Wood Technology, Akita Prefectural University, Noshiro, 016-0876 Japan.
Kana Yamashita
Forestry and Forest Products Research Institute, Kukizaki, 305-8687 Japan.
Ryogo Nakada
Forest Tree Breeding Center, Juo, 319-1301 Japan.

SUMMARY

Tracheid length, microfibril angle, spiral grain, wood density, MOE, MOR, compressive strength, modulus of rigidity and their inter-relationships were investigated for 50 Siberian larch trees (*Larix sibirica*) collected from five natural stands. No inter-stand variation in tracheid length, microfibril angle and spiral grain was observed. No effect of tracheid length and microfibril angle on the mechanical properties was observed. Inter-stand variation in wood density was significant especially within the latewood. Minimum density within a ring seemed to be the major source of variation for average density within the heartwood, whereas the effect of maximum density on average density was greater within the sapwood. Wood density, which was much higher for a given ring width than in plantation-grown Japanese larch (*Larix kaempferi*), had a major effect on the mechanical properties.

Key words: *Larix sibirica*, tracheid length, microfibril angle, wood density, X-ray densitometry, mechanical property, strength.

INTRODUCTION

Larix species are distributed in boreal forests of the northern hemisphere. They are also planted as valuable sources of structural lumber because of the high growth rate at a young age and the mechanical quality of the mature wood. For example, Japanese larch (*Larix kaempferi*) is widely planted in northern Japan. One of the major stocks of larch wood is distributed in Russia, where it reaches about 22.9 billion m^3 and makes 30.4% of total stock of Russian forests (Abaimov et al. 1998). The genus *Larix*, native to Russia, is classified into three or more species (Abaimov et al. 1998). Although the taxonomy of larch species in Siberia is rather controversial, *Larix sibirica* is common among classifications by several researchers (Kisanuki 2000). The western border of its natural distribution is the Ob River (Fig. 1). The eastern border of *L.sibirica* is adjacent to *L.gmelinii*, which grows on permafrost in the Baikal range and the hybrid larch, *L.* × *czekanowskii*, occurs in the overlap area (Abaimov et al. 1998).

The potential for utilization of Siberian larch wood and seed source for commercial plantations has been attracting the interest of researchers (Martinsson & Takata 2000). However, only a few references concerning mechanical quality of Siberian larch wood are available (Gupta et al. 1996; Krankina & Ethington 1995; Iijima 1983). Furthermore, the genetic origins and the environmental information on the stands from which the tested woods were sampled are not included in these papers.

In this paper, the anatomical characteristics and mechanical properties of *Larix sibirica* sampled from five natural stands in south-central Siberia are discussed in relation to those of plantation-grown Japanese larch.

MATERIALS AND METHODS

Sample stands

Sample sites are shown in Fig. 1 along with the natural distribution of *Larix* species in Russia, where the classifications of the major four species follow Abaimov et al. (1998). Three sample sites were chosen within the southern area of the natural distribution where rather high productivity is expected. The Baikal, Khakasia and Altai sites are located in eastern, central and southwestern region of the natural distribution, respectively. The Baikal and Khakasia sites are forest steppe where the annual precipitation is less than 500mm. *Larix sibirica* is mixed with *Pinus sylvestris* and *Betula pendula* at the Baikal and Khakasia sites, respectively. The Altai site is at an elevation of more than 1000m in the northwest of the Altai Mountains, and is a pure stand of *Larix sibirica*. Details of the five naturally regenerated stands selected from the three sites are summarized in Table 1.

Sampling of specimens, measurement of MOE and grain spirality

Ten trees of average radial growths and stem form were selected at each stand. The trees were felled and cross-cut at 1.2m and 3.2m above the ground to obtain 2m-long logs. The dynamic modulus of elasticity of the logs (E_{log}) was measured on site using the longitudinal vibration method (Sobue 1986; Koizumi et al. 1997a). A 10cm-thick disk was then taken from the butt end of each log for measurements of tracheid length, microfibril angle, and for X-ray densitometry. The maximum spiral-grain angle (MSGA) was measured on the 10 cm-thick disks using splitting method (Okura & Toriyama 1952) for the two stands at the Baikal site and the stand at Khakasia 2. Briefly, the splitting method involves cleaving the disk longitudinally with an axe, then measuring the angle at which it breaks open. The other two stands, at Khakasia 1 and Gorno Altai, were measured during the preliminary expedition of the research project in 1998. Quarter-sawn planks were taken from the 1.3 to 1.6m height section of the logs at the Baikal and Khakasia 2 site for mechanical tests of small clear specimens.

Measurement of tracheid length

Tracheid length (TL) of the latewood of every second ring from the pith was measured for each of the ten sample disks. After macerating with Jeffrey's solution (10% nitric acid: 10% chromic acid: water, 1:1:18), the length of 50 tracheids per growth ring were measured and averaged. Tracheid length was not measured for earlywood because considerable variation was expected.

Measurement of microfibril angle

The microfibril angle (MFA) of the S_2 layers of latewood tracheids was measured for selected growth rings for each of the ten sample disks, according to the method used by Hirakawa and Fujisawa (1995). The angles of the pit apertures on the tangential wall of latewood tracheids observed with the method agreed well with S_2 microfibril angles measured using the iodine method and the scanning electron microscope wall scribing method (Hirakawa & Fujisawa 1995). Tangential sections of 15 μm thickness were cut from the last formed latewood with a microtome at the 5th, 10th, 20th, 30th, 40th and, if possible, the 50th and 60th ring from the pith. Micrographs of the slit-like pit aperture on the tangential wall were taken with the light microscope. The angles between the pit apertures and the axis of each tracheid were taken as microfibril angles. The angles of 30 tracheids were measured per growth ring and averaged.

X-ray densitometry

Bark to bark radial strips of 5mm thickness were prepared from the air-dried blocks cut from the sample disks. After conditioning at 20℃ and 65% RH, without warm-water extraction, the strips were X-rayed onto film using 280 seconds of irradiation time. The current intensity and voltage were 14mA and 17kV, respectively. The distance between the X-ray source and the specimen was 250cm. The developed films were scanned with a densitometer (Joice Loeble 3CS) to obtain density measurements across the growth rings. The slit size for scanning was 50 and 500 μm in the radial and tangential direction, respectively. The border between sapwood and heartwood was determined by visual inspection, based on color difference.

The growth ring parameters of ring width (RW), minimum density within a ring (D_{min}), maximum density within a ring (D_{max}) and ring density (RD: average density within a ring) were determined for each growth ring. A threshold density, 0.55g/cm^3 was used as the boundary between earlywood and latewood in the ordinary procedure. However, in a number of growth rings, the density measured within the growth ring was sometimes higher, or sometimes lower, than the threshold density. For these growth rings we could not determine the earlywood or latewood density, so we report only the D_{min} and D_{max}.

Mechanical properties of the small clear specimens

After conditioning at 20℃ and 65% RH for a few weeks, two small clear specimens of mature wood were cut from both of each bark to bark quarter-sawn plank. The dimensions were 20 × 20 mm^2 in cross section and 300mm in length. Most of the specimens included both sapwood and heartwood. The mechanical properties of the small clear specimens were tested following Japan Industrial Standards Z2101 (Japanese Standards Association 1994). Ring width (RW_{scs}), wood density (WD_{scs}), modulus of elasticity (E_{scs}), modulus of rupture (MOR_{scs}) and compressive strength parallel to grain (CS_{scs}) were included in the results. Modulus of rigidity (G_{scs}) was determined using torsional tests (Koizumi et al. 1997b). The average moisture contents for the specimens was 13.5%/

Statistical analyses

One-way analyses of variance were carried out among the anatomical characteristics at rings 10, 20, 30 and 40 from the pith to test for differences between the stand averages for these characteristics at several cambial ages. Simple correlation analyses were carried out between D_{min}, D_{max} and RD of growth rings within each stand to determine the effects of D_{min} and D_{max} on RD. Correlations between the anatomical characteristics and the mechanical properties were also studied to determine which characteristics had a major effect on the mechanical properties.

RESULTS AND DISCUSSIONS

The stand averages and the coefficients of variation obtained from the anatomical study are summarized in Table 2, where the growth ring parameters are reported separately for heartwood and sapwood.

Tracheid length

The pattern of average tracheid length (TL) as a function of cambial age did not vary among stands (Fig. 2; Table 3). The coefficients of variation among the sample trees within a stand were 5 to 17% for each sampling ring. TL increased rapidly with cambial age up to about 20 years and then increased gradually thereafter (Fig. 2). Krauk et al. (1998) reported 3.6mm for the average latewood tracheid length of 100- to 160-year-old trees of *Larix sibirica* from the stands near Krasnoyarsk. Stand averages were 2.8 to 3.1mm at the 20th growth ring, which were shorter than those reported for *L. kaempferi* (3.5 to 4mm; Shigematsu 1990; Koga et al. 1996).

Microfibril angle

The microfibril angle (MFA) rapidly decreased as cambial age increased for the fist few rings from the pith and then decreased gradually thereafter (Fig. 3). No significant difference between the sample stands was observed except for MFA at the 20th growth ring from the pith (Table 3). The coefficients of variation among the sample trees within a stand were 12 to 35% for each sampling ring. Stand averages were 22.0 to 29.4° at the 20th growth ring, which were considerably larger than the 10 to 15° reported for *L. kaempferi* (Suzuki 1968; Okano et al. 1969), and for some other coniferous species: e.g., 20° for *Pinus radiata* (Donaldson 1992), 21° for *Pinus taeda* (Megraw et al. 1998). Yamashita et al. (2000) reported 5 to 29° for the average MFA at the 15th, 20th and 25th growth ring of 18 cultivars of *Cryptomeria japonica*.

Spiral grain

Maximum spiral grain (MSGA) was between 1 and 6° for most samples and was to the left (Fig. 4). Left-hand spiral grain is one of the characteristics of larch species especially in their juvenile stages (Mikami 1988). No significant difference in MSGA between the sample stands was observed. Stand averages were 3.2 to 3.4°, which were smaller than the 4–5° reported for *L. kaempferi* (Mikami 1988; Koizumi et al. 1987).

Growth ring parameters

RW decreased with the ring number from the pith (Fig. 5). This may be a general trend observed in light demanding species. The lines in Fig. 5 show the averages of ten sample trees within each stand. The variation in RW among the sample stands was not so large but highly significant after 30 growth rings (Table 3).

RD increased gradually with ring number within the heartwood region and then decreased within the sapwood region (Fig. 6c). One of the reasons may be the existence of arabinogalactan deposits in the outer part of the heartwood (Côté et al. 1989). Another reason for the gradual increase in RD within the heartwood region may be the maturity effect observed in D_{max}, which increased with cambial age up to about 10 years (Fig. 6b). The variation in RD among the sample stands was significant after 20 growth rings and was much larger than the variation in RW (Table 3). RDs for the Baikal site were higher than for the other sites (Fig. 6c). The RD for the Altai site was low. The inter-stand variation in D_{min} after 30 growth rings seemed to be the source of variation in the RD of heartwood (Table 4). On the other hand, the variation in D_{max} seemed to be the reason for the difference for the Altai site (Fig. 6b; Table 3). The contribution of D_{max} to RD was greater in sapwood than in heartwood (Table 4).

The relationship between RW and RD for heartwood and sapwood is shown in Fig. 7, in which each plot represents the average RD for corresponding 0.5mm-ring-width classes. The average RDs for the sample stands were 580 to 660kg/m^3 for the 3mm of ring-width classes, which were higher than those for plantation-grown *L. kaempferi* (380 to 480kg/m^3; Koizumi et al. 1987). The heartwood of the Baikal site tended to show a high density even below 1mm in RW. RD in sapwood of all sites showed a positive correlation with RW, which suggests the formation of starved wood or senescent wood in narrow growth rings in sapwood. To consider the maturity or age effect on the relationship between RW and RD, the fluctuations of the correlation coefficient between RD and RW calculated for every five years are shown in Fig. 8; e.g., the plot at 20 years of cambial age represents the correlation coefficient for rings 16 to 20 from the pith. The relationship between RD and RW changed from a negative correlation to a positive one with cambial age for all sample stands beyond about 20 to 40 rings from the pith. Zhu et al. (1998) reported a similar trend for a 75-year-old plantation of *L. kaempferi*.

Mechanical properties

The dynamic MOE of a log (E_{log}) obtained by using the longitudinal vibration method is widely employed as an index to mechanical properties in Japan. The perimeter of the log, including bark, is used in the calculation of the volume to estimate apparent density in the ordinary procedure. However, the bark of *L. sibirica* is thick, up to 10–13mm, and its effect on density calculation would not be negligible. Although the bark thickness was subtracted in the calculation of E'_{log} in Table 5, the values are still approximations because the bark weight was not subtracted. E_{scs} was not expected to agree well with E_{log} because the small clear specimens had been taken from the outer region of the logs. The poor correlation between E_{log} and E_{scs} indicates that it is difficult to make precise predictions of wood properties from the MOE of logs using the ordinary longitudinal vibration method (Fig. 9).

The small clear specimens from the Baikal site showed high MOE and high strength (Fig. 10). Iijima (1983) reported the average values of RW_{scs}, WD_{scs}, E_{scs}, MOE_{scs} and CS_{scs} for larch lumber imported from Russia (*L. gmelinii* or *L. cajanderi*) as 2.1mm, 610kg/m^3, 13.5GPa, 104MPa, 49MPa, respectively. These values are similar to those for Khakasia 2. The specific MOE for the small clear specimens were 21 to 22GPa which is similar to that for the mature wood of *L. kaempferi* (20GPa; Nakai & Yamai 1982; Koizumi et al. 1987) and *L. laricina* (22GPa; Forest Products Laboratory

1987).The intercept of the regression line of E_{scs} and MOE_{scs} with WD_{scs} for *L. kaempferi* seems to be lower than for *L. sibirica* in Fig. 10, where the range of density and the regression line for *L. kaempferi* (Koizumi et al. 1987) are shown. This may be due to the effect of juvenile wood included in the specimens of *L. kaempferi.* The specific MOE was similar to the other species such as *Cryptomeria japonica* (20 to 22GPa; Nakai & Yamai 1982; Koizumi et al. 1997b), but smaller than 23 to 30GPa for Douglas fir and the 27GPa for Sitka spruce (Forest Products Laboratory 1987). The relationship between E_{scs} and MOR_{scs} for *L. sibirica* was similar to that of *L. kaempferi*, although a small inter-stand difference was observed (Fig. 11).

Table 6 shows the correlation coefficients between the anatomical characteristics and the mechanical properties for the small clear specimens irrespective of sample stands. Values for TL, MFA and the growth ring parameters in the table are the averages of the sampling rings beyond 30 rings from the pith, which approximately corresponds to the sampling region of the small clear specimens. RD and D_{min} showed positive correlation and RW showed negative correlation with the mechanical properties. Yamashita et al. (2000) suggested that MFA explains the variation in MOE among the cultivars of *Cryptomeria japonica*. Although MFA is considered to affect specific strength, the correlation between MFA and the specific MOE was not found (r=0.144). TL, MFA and D_{max} cannot be used as indices of the mechanical properties for L. sibirica because no effects of these parameters on mechanical properties were observed (Table 6).

CONCLUSION

There was no inter-stand variation in tracheid length, microfibril angle and maximum spiral grain angle. Inter-stand variation in ring density was significant especially after 20 rings from the pith, in what was considered mature wood. The wood from the Baikal site had a very high density, especially for the narrow growth rings. Minimum density showed a major contribution to the high density for the Baikal site and seemed to be the source of variation for ring density within the heartwood. The wood from the Altai site in the mountain range had a low density. This may be attributed to the very low maximum density for the Altai site. The contribution of maximum density to ring density was greater in sapwood than in heartwood. The wood density for Siberian larch at a given ring width was much higher than that for Japanese larch.

An effect of microfibril angle, which was considerable in Japanese larch, on the mechanical properties was not observed. Wood density had a major effect on the mechanical properties. The specific strength and the relationship between MOE and MOR were almost the same as those for mature wood of plantation-grown Japanese larch. The Siberian larch wood with its extremely high density and mechanical properties can be utilized in structural applications.

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REFERENCES

Abaimov,A.P., J.A.Lesinski, O.Martinsson & L.Milyutin. 1998. Variability and ecology of Siberian larch species. Swedish Univ. of Agr. Sci. Report No.43: 1-123.

Côté,W.A., A.C.Day, B.W.Simson & T.E.Timell. 1989 Studies on larch arabinogalactan(1). Holzforschung 20: 178-192.

Donaldwon,L.A. 1992. Within- and between- tree variation in microfibril angle in Pinus radiate. NZ J. For. Sci. 22: 77-86

Forest Products Laboratory. 1987. Wood Handbook. USDA Forest Service, Madison, WI, USA.

Gupta,R. & R.L.Ethington. 1996. General physical characteristics of dahurian larch (Larix

dahurica) from the Russian Far East. Forest Products J. 46: 90-93.
Gupta,R., R.L.Ethington & D.W.Green. 1996. Mechanical stress grading of dahurian larch structural lumber. Forest Products Journal 46: 79-86.
Hirakawa,Y. & Y.Fujisawa. 1995. The relationships between microfibril angles of the S_2 layer and latewood tracheid lengths in elite sugi tree (Cryptomeria japonica) clones. Mokuzai Gakkaishi 41: 123-131.
Iijima,Y. 1983. The mechanical properties of the Siberian larch wood. Bulletin Toyama Wood Products Research Institute No.1: 1-39.
Japanese Standards Association. 1994. JIS Handbook-Methods of tests for woods. Tokyo.
Krauk, E.V., G.S. Kovrigin & N.S. Kulikova. 1998. Peculiarities of microscopic structure of Siberian larch wood (Larix sibirica). Abstracts Larix-98: 46-47.
Kisanuki,H. 2000. Study on the morphological and ecological characteristics of the genus Larix with special reference to its molecular phylogeny. Bulletin Tokyo Univ. Forests No.104: 63-146.
Koga,S.,J.Tsutsumi,K.Oda & T.Fujimoto. 1996. Effects of thinning on basic density and tracheid length of karamatsu (Larix leptolepis). Mokuzai Gakkaishi 42: 605-611.
Koizumi, A., Y. Iijima, T. Sasaki, Y. Kawai, Y. Okazaki & H. Nakatani. 1997a. Strength properties of sugi (Cryptomeria japonica) grown in Akita Prefecture (1). Mokuzai Gakkaishi 43: 46-51.
Koizumi, A., Y. Iijima, T. Sasaki & Y. Okazaki. 1997b. Strength properties of sugi (Cryptomeria japonica) grown in Akita Prefecture (2). Mokuzai Gakkaishi 43: 210-214.
Koizumi,A., K.Ueda & T.Katayose. 1987. Mechanical properties of the thinning crops of plantation-grown Japanese larch. Res. Bull. Exp. For. Hokkaido Univ. 44: 327-354.
Krankina,O. & R.L.Ethington. 1995. Forest resources and wood properties of commercial tree species in the Russian Far East. Forest Products J. 45: 44-50.
Martinsson,O. & K.Takata. 2000. The Russian-Scandinavian larch project - Final report on seed collection and seed germination. Swedish Univ. of Agr. Sci. Working papers No.159: 1-15.
Megraw, R.A., G. Leaf & D. Bremer. 1998. Longitudinal shrinkage and microfibril angle in loblolly pine. In: B.G. Butterfield (ed.), Microfibril angle in wood: 240-252. Proc. IAWA/IUFRO International Workshop on the Significance of Microfibril Angle to Wood Quality, Nov. 1997, Westport, New Zealand. University of Canterbury Press.
Mikami,S. 1988. Breeding for wood quality of Japanese larch, Larix kaempferi (Lamb.) Carr. Bulletin Forest Tree Breeding Institute No.6: 47-152.
Nakai, T. & R. Yamai 1982 The mechanical properties of 35 important Japanese woods. Bull. Forestry & Forest Products Res. Inst. No. 6: 47-152.
Okano,T., T.Sato & S.Hirai. 1969. A study on the distribution of the mean micell angle in the trunks of akamatsu wood and karamatsu wood. Mokuzai Gakkaishi 15: 62-66.
Okura,S. & K.Toriyama. 1952. Studies on twisted fibre in trees(1). Bull. Fac. Agr. Shinshu Univ. 1: 28-35.
Shigematsu,Y. 1990. Wood quality of larch in relation to its growth(1). Wood Industry 45: 445-451.
Sobue,N. 1986. Measurement of Young's modulus by the transient longitudinal vibration of wooden beams using a fast Fourier transformation spectrum analyzer. Mokuzai Gakkaishi 32: 744-747.
Suzuki,M. 1968. The relationship between elasticity and strength properties and cell structures of coniferous wood. Bulletin Forestry & Forest Products Research Institute No.212: 89-149.
Yamashita, K., Y. Hirakawa, Y. Fujisawa & R. Nakada. 2000. Effects of microfibril angle and density on variation of modulus of elasticity of sugi (Cryptomeria japonica) logs among eighteen cultivars. Mokuzai Gakkaishi 46: 510-522.
Zhu,J., T.Nakano & Y.Hirakawa. 1998. Effect of growth on wood properties for Japanese larch (Larix kaempferi)-Differences of annual ring structure between corewood and outerwood. J. Wood Sci. 44: 392-396.

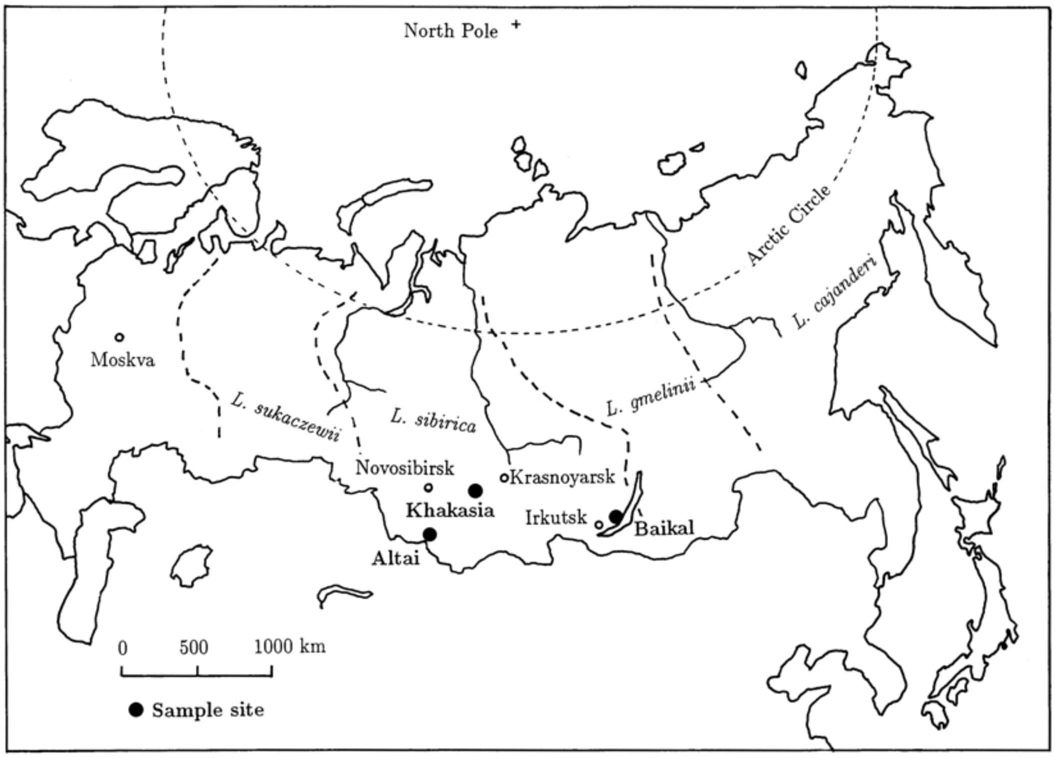

Fig. 1. Distribution of *Larix* species in Russia and the sample sites (adapted from Abaimov et al. 1998).

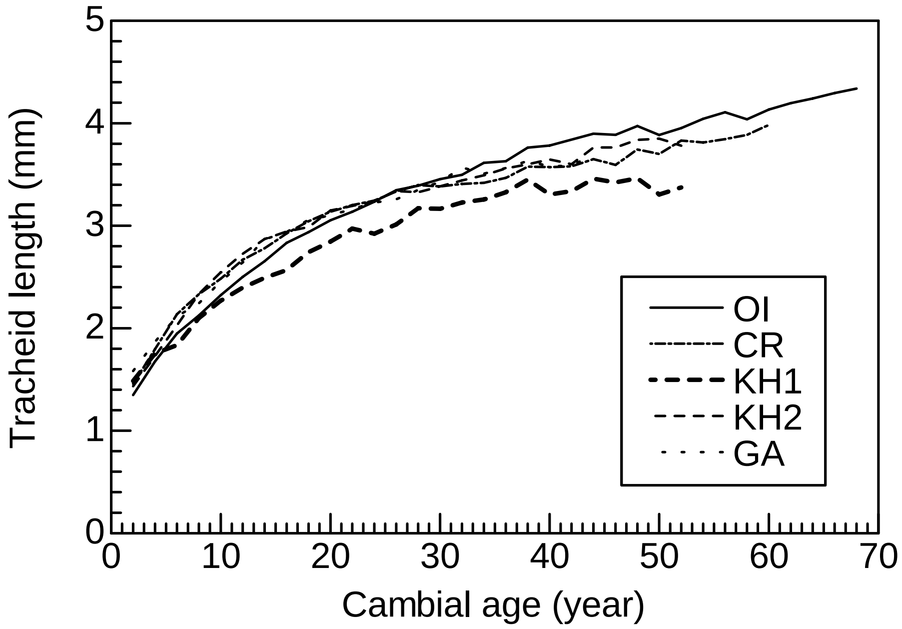

Fig. 2. Tracheid length (TL) trends associated with cambial age for *Larix sibirica* collected from five stands (stand averages). See Table 1 for the stand information.

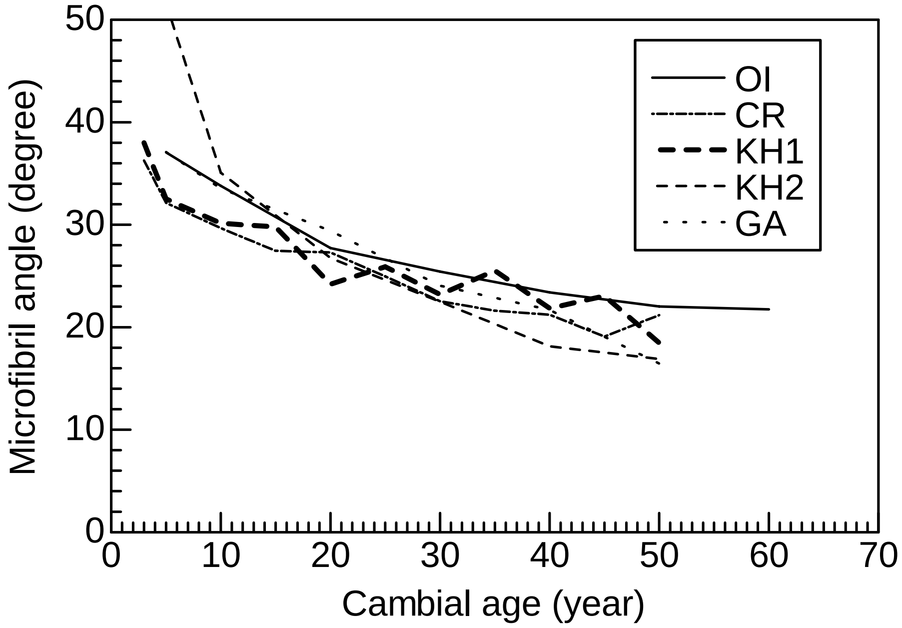

Fig. 3. Microfibril-angle (MFA) trends associated
with cambial age (stand averages). See Table 1 for the stand information.

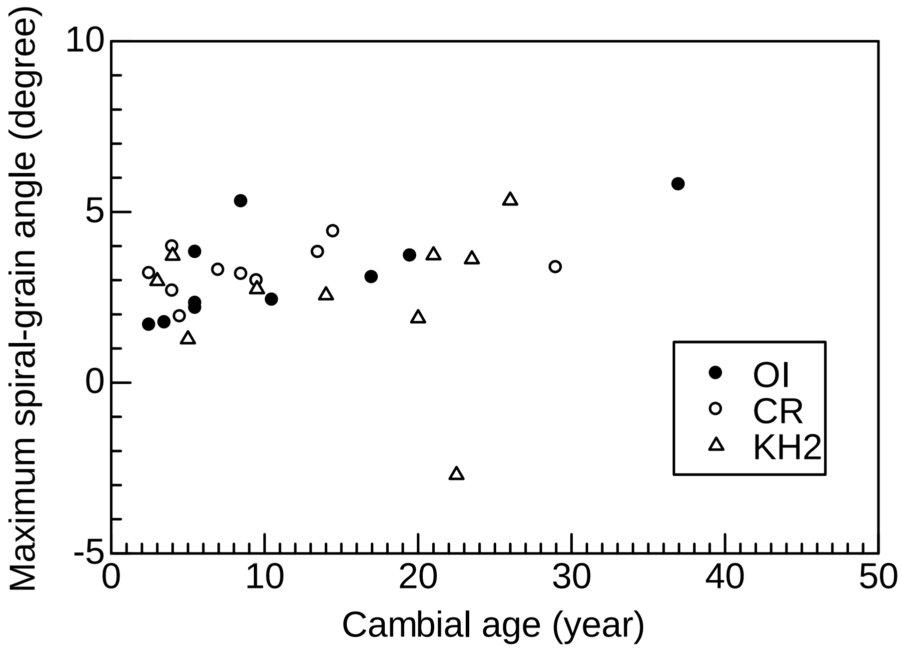

Fig. 4. Maximum spiral grain angle (MFGA) in relation to cambial age. Note: The grain angle of the left-hand spiral is taken as positive value. See Table 1 for the stand information.

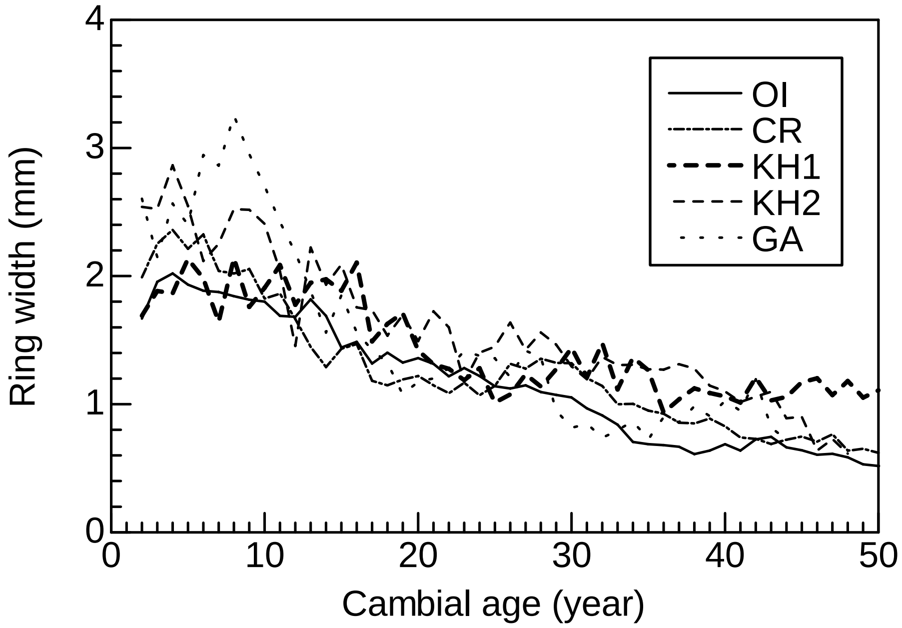

Fig. 5. Ring width (RW) trends associated with cambial age (stand averages). See Table 1 for the stand information.

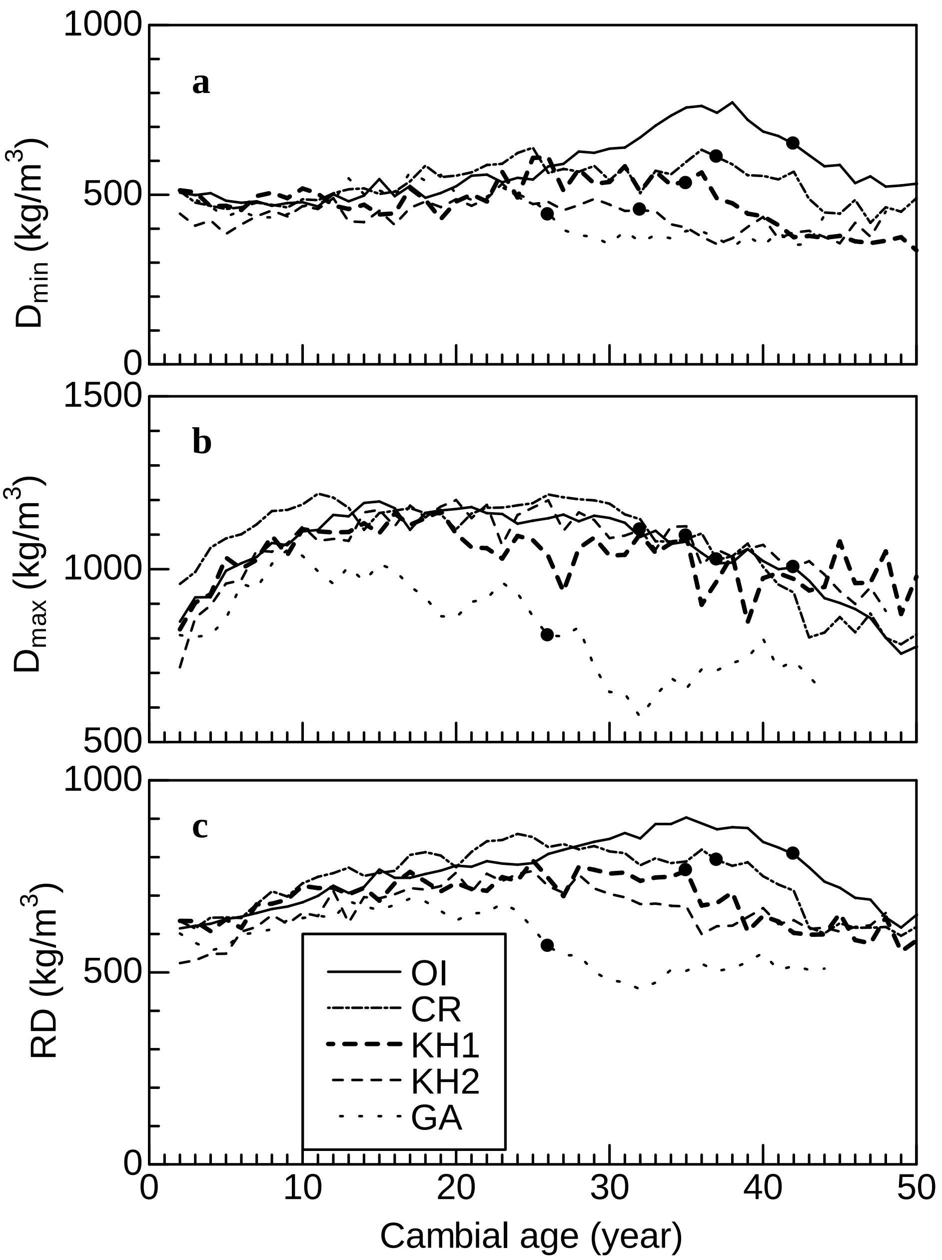

Fig. 6. Minimum density (a), maximum density (b) and ring density (c) trends associated with cambial age (stand averages). Black dots denote the borders between heartwood and sapwood. See Table 1 for the stand information.

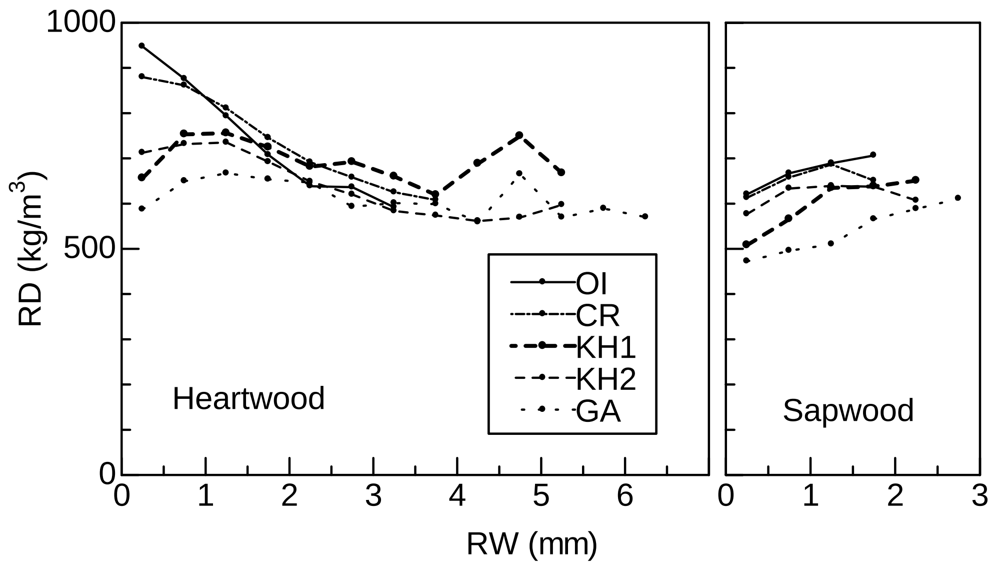

Fig. 7. The relationship between growth ring width (RW) and ring density (RD) separated into heartwood and sapwood See Table 1 for the stand information.

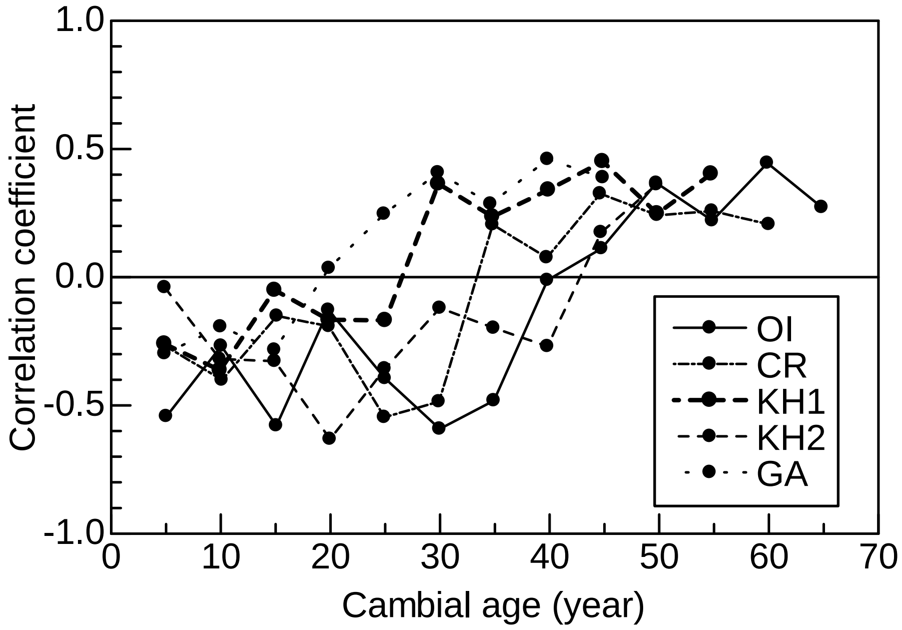

Fig. 8. Correlation coefficients for the relationship between ring width (RW) and ring density (RD) associated with cambial age. See Table 1 for the stand information.

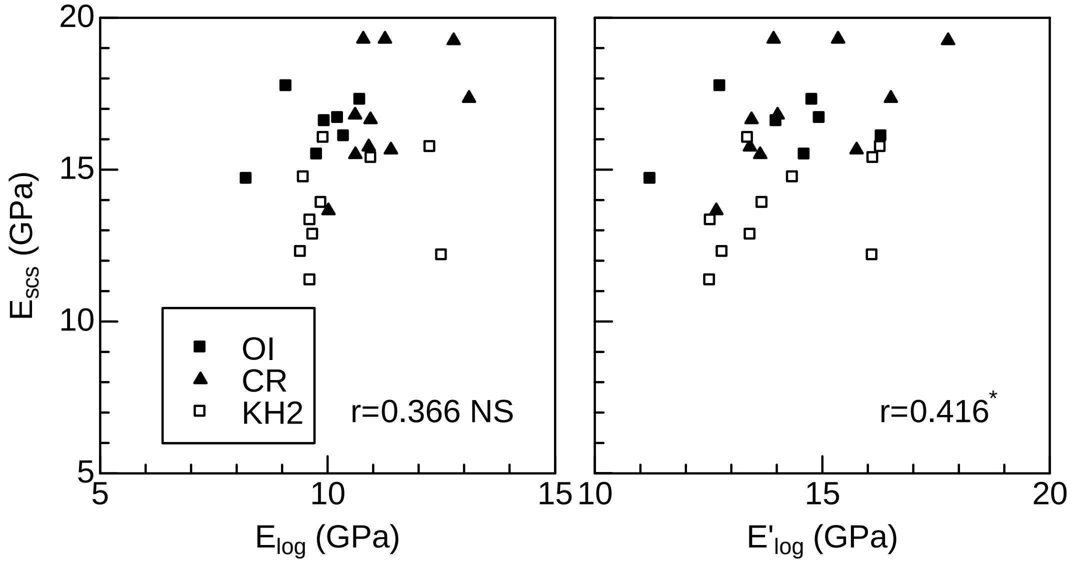

Fig. 9. Comparisons of the dynamic MOE for logs (E_{log}) with the static MOE for the small clear specimens (E_{scs}). NS=not significant; *= significant at 5% level; E_{log}= calculated using the volume without bark. See Table 1 for the stand information.

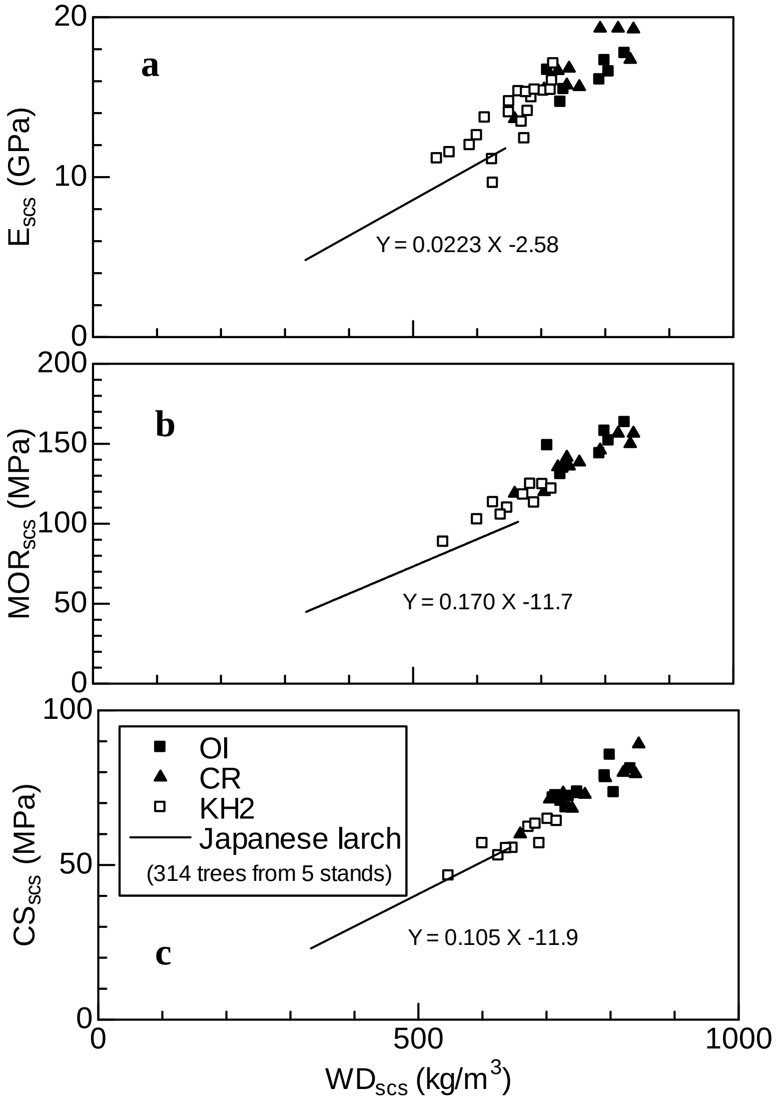

Fig. 10. The relationship between wood density and MOE (a), MOR (b) and compressive strength parallel to the grain (c) for the small clear specimens of *Larix sibirica* (markers) and *Larix kaempferi* (line). See Table 1 for the stand information.

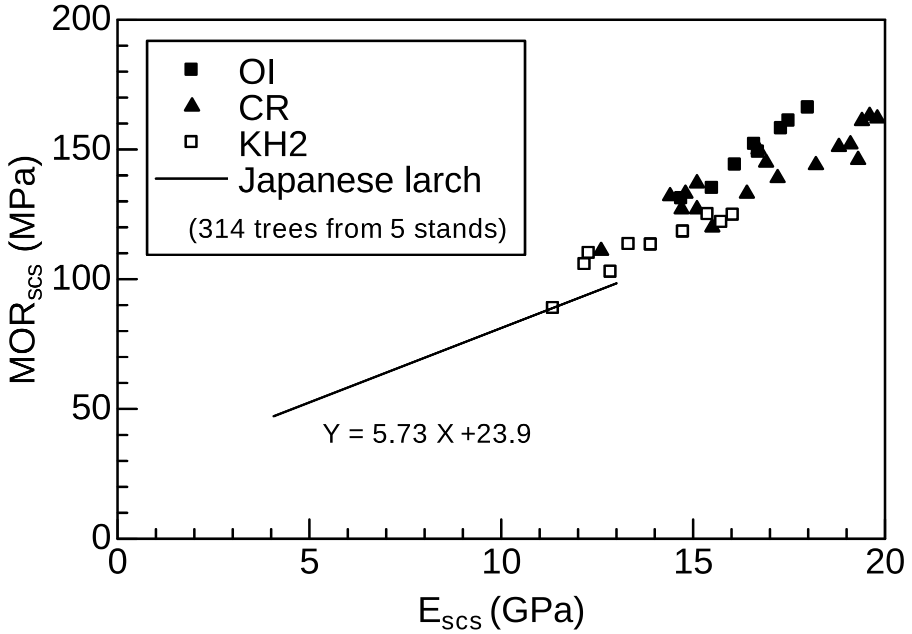

Fig. 11. The relationship between MOE and MOR for the small clear specimens of *Larix sibirica*. See Table 1 for the stand information.

Table 1. Location and tree characteristics of the sample stands.

Symbol	Stand	Site	Latitude	Longitude	Elevation (m)	Stem density (stem/ha)	Age (year)	DBH (cm)	Height (m)
OI	Orikhon Island	Baikal	N53° 09'	E107° 22'	650	1091	70–80	20.2	15.2
CR	Cherno Rude	Baikal	N52° 58'	E106° 38'	680	1610	60–70	18.6	14.3
KH1	Khakasia 1	Khakasia	N54° 45'	E 89° 26'	680	932	50–60	18.7	16.6
KH2	Khakasia 2	Khakasia	N54° 42'	E 89° 18'	565	900	50–60	21.4	20.4
GA	Gorno Altai	Altai	N51° 15'	E 85° 35'	1060	240	40–50	16.1	12.3

Note: DBH and height are stand averages.

Table 2. Anatomical values for *Larix sibirica* at each of the five stands studied (stand averages with coefficents of variation (%) in paretheses). See Table 1 for site information.

Stand	SWW	SWRN	RW(mm)		RD(kg/m^3)		Dmin(kg/m^3)		Dmax(kg/m^3)		MSGA	TL	MFA
	(mm)		H	S	H	S	H	S	H	S	(degree)	(mm)	(degree)
OI	13.1	22.9	1.3	0.6	779	652	587	497	1100	836	3.2	3.1	27.7
	(21.2)	(15.6)	(17.7)	(24.6)	(8.1)	(6.7)	(15.2)	(14.1)	(4.4)	(13.4)	(44.8)	(5.8)	(13.7)
CR	14.3	20.7	1.5	0.7	778	654	548	482	1157	875	3.3	3.1	27.3
	(21.9)	(14.0)	(16.8)	(20.6)	(7.2)	(5.1)	(10.3)	(10.2)	(4.5)	(9.4)	(21.2)	(10.4)	(22.9)
KH1	16.8	16.4	1.6	1.1	728	600	518	385	1078	935		2.8	24.2
	(22.9)	(13.8)	(21.1)	(27.5)	(6.9)	(8.6)	(7.3)	(9.4)	(6.9)	(16.0)		(10.4)	(17.8)
KH2	17.6	15.9	1.9	1.1	682	629	463	383	1091	1021	3.4	3.1	22
	(17.8)	(18.0)	(14.6)	(18.7)	(6.5)	(8.7)	(16.3)	(17.6)	(6.2)	(8.6)	(106.0)	(7.6)	(30.2)
GA	14.8	16.5	2	0.9	641	507	490	386	935	694		3.1	29.4
	(28.0)	(15.5)	(19.7)	(27.6)	(12.7)	(9.7)	(16.7)	(10.8)	(6.8)	(13.0)		(12.2)	(16.8)

SWW= sapwood width; SWRN= sapwood ring number; H= heartwood; S= sapwood; RW= ring width; RD= average density within a ring; Dmin= minimum density within a ring; Dmax= maximum density within a ring; MSGA= maximum spiral-grain angle; TL= tracheid length; MFA= microfibril angle.

Note: TL and MFA are values at the 20th growth rings.

Table 3. Variance ratios (F values) for TL, MFA, and the growth ring parameters among the sample stands obtained from the analysis of variance. The values in the parentheses are variance ratios among the four stands excluding the Altai site.

	Cambial age			
	10	20	30	40
TL	2.04	1.92	1.69	1.87
MFA	2.85	3.11*	1.95	2.83
RW	3.25*	1.41	7.45**	4.091**
	(2.33)	(1.06)	(2.80)	(5.49**)
RD	3.27*	8.45**	39.14**	12.94**
	(3.45*)	(1.11)	(6.54**)	(8.77**)
Dmin	0.53	1.79	16.80**	12.63**
	(0.64)	(2.64)	(6.32**)	(10.10**)
Dmax	4.69**	17.46**	40.19**	5.17**
	(1.94)	(2.27)	(3.69*)	(1.03)

* significant at 5% level; ** significant at 1% level.

Table 4. Correlation coefficients of Dmin and Dmax with RD analyzed on all individual growth rings divided into heartwood and sapwood. See Table 1 for the stand information.

Stand	Dmin		Dmax	
	H	S	H	S
OI	0.83	0.348	0.412	0.724
CR	0.78	0.385	0.462	0.787
KH1	0.616	0.159	0.658	0.815
KH2	0.351	0.302	0.64	0.62
GA	0.812	0.53	0.289	0.81
Overall	0.723	0.401	0.594	0.714

H= Heartwood; S= Sapwood.

Table 5. Mechanical properties for the small clear specimens and dynamic MOE for the logs (stand averages with coefficients of variation(%) in parentheses). See Table 1 for the stand information.

Stand	RWscs (mm)	WDscs (kg/m^3)	Escs (GPa)	MORscs (MPa)	CSscs (MPa)	Gscs (GPa)	sMOE (GPa)	Elog (GPa)	E'log (GPa)
OI	0.68	759	16.4	147.5	74.9	1.31	21.3	9.8	13.9
	(19.4)	(5.8)	(6.4)	(8.0)	(7.1)	(8.2)	(5.4)	(7.2)	(10.9)
CR	1.01	763	17	140	74.5	1.22	22.2	11.2	14.6
	(27.0)	(7.9)	(11.2)	(9.4)	(10.5)	(11.9)	(5.9)	(8.7)	(11.1)
KH1								9.2	12.3
								(13.7)	(14.5)
KH2	1.3	652.0	13.8	112.3	57.9	1.0	21.1	10.3	14.1
	(18.7)	(8.0)	(11.7)	(10.0)	(10.0)	(11.5)	(6.3)	(11.3)	(10.7)
GA								7.6	10.4
								(13.0)	(11.0)

sMOE=specific MOE (Escs/WDscs × 10^3); E'log=dynamic MOE for log specimen calculated on the volume without bark.

Table 6. Correlation coefficients between the anatomical characteristics and the mechanical properties for specimens from three sample stands.

	Escs	MORscs	SCscs	Gscs
RWscs	−0.484	−0.657	−0.614	−0.615
WDscs	0.902	0.946	0.939	0.802
TL[1)]	0.049	0.118	0.14	0.119
MFA[1)]	0.161	0.261	0.229	0.24
RW[1)]	−0.662	−0.767	−0.779	−0.771
RD[1)]	0.657	0.807	0.786	0.706
Dmin[1)]	0.554	0.748	0.73	0.738
Dmax[1)]	−0.264	−0.372	−0.343	−0.479

[1)] Averages for the sampling rings after 30 rings from the pith.