A COMPARATIVE STUDY ON THE BENDING STRENGTH OF EUROPEAN SPRUCE AND FUJIAN CHINESE FIR

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Abstract. This paper compared the bending properties of European spruce (*Picea abies (L.) H. Karsten*) and Chinese fir (*Cunninghamia lanceolata (Lamb.) Hook.*) with differing densities and knot patterns to identify the most appropriate uses for the latter species. As expected, reduced density and increased knot size negatively affected the modulus of elasticity (MOE) and the modulus of rupture (MOR) of both species. The MOEs of European spruce were higher than those of Fujian Chinese fir and were higher in samples without knots. The effect of knots on bending strength was more pronounced in European spruce. The results indicated that Fujian Chinese fir and European spruce could be substituted for each other in some less-demanding structural applications, which helps improve the utilization of the latter species.

Keywords: European spruce (*Picea abies (L.) H. Karsten*), Fujian Chinese fir (*Cunninghamia lanceolata (Lamb.) Hook.*), modulus of elasticity, modulus of rupture, knots, density.

INTRODUCTION

Chinese fir (*Cunninghamia lanceolata (Lamb.) Hook.*) has the advantages of fast growth, good mechanical properties, and resistance to fungal attack. Acetone, methanol, and ethyl acetate extracts of Chinese fir heartwood had inhibitory effects on the growth of the white-rot fungus (*Trametes versicolor* (L. ex Fr.) Quél.) and the brown-rot fungus *Gloeophyllum trabeum* (Pers. ex Fr.) Murr (Yan et al 2019; Zhang et al 2020; Liu et al 2023). Chinese fir is widely used for engineered wood products as well as in wood-frame buildings (Longuetaud et al 2022; Ponzecchi et al 2022; Shen et al 2022). Chinese fir may also have potential applications in mass timber buildings (Zhang and Qiu 2023).

Chinese fir is one of the most important plantation trees in China in terms of planting area and basal volume (Löf et al 2023; Yu et al 2023). However, the boles of this species have many knots and low mechanical properties making it difficult to use in some high-grade furniture and decorative applications (Zarna et al 2023; Zong et al 2023). As a result, imported European spruce is widely used in construction, infrastructure, and other applications (Jian et al 2023). However, it is difficult to control the quality of the material source since the timber is imported in the sawn form (Walsh-Korb and Avérous 2019; Li et al 2021). Substitution of home-grown Chinese fir in the construction would allow for tighter quality control and increase the utilization of this resource (Kumar et al 2016; Meijer et al 2021).

The physical and mechanical properties of wood vary widely among species and are critical for proper utilization (Reynolds et al 2016; Zhan et al 2019; Palizi and Toufigh 2022; Martineau et al 2023). Mechanical properties of wood are closely related to density, knots, and other factors and vary widely between species (De Santis and Fragiacomo 2021). The main focus with Chinese fir has been on growth rates, with less concern for wood quality, including density and knot sizes (Zhao et al 2021).

Zhong et al (2011) showed that the process of compression in spruce included elastic, yield, and compaction stages. They also showed that the

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axial compression failure mode of spruce was mostly from buckling and folding of wood fiber, whereas the radial or tangential failure modes were mostly due to slippage and layering of wood fiber. The axial compressive yield strength of spruce was about nine times that of radial and tangential yield strength which were nearly equal. Yuka et al (2018) showed that wood density significantly impacted mechanical properties, whereas the shape and deformation of wood cells also played a key role in the structural characteristics. Liu et al (2007) examined the modulus of elasticity (MOE) and the modulus of rupture (MOR) to create a mathematical model to predict the bending performance and fracture mode of black spruce. Fischer et al (2016) established the relationship between MOE and MOR with tree characteristics, including altitude, latitude, tree age, and density by conducting tests on spruce trees at 17 sites in eastern Norway. This model evaluated wood performance but also predicted the impact of silvicultural practices on wood quality.

Several standards 《GB/T 26899-2011 Structural glued laminated timber》, 《GB/T 29897—2013 Visual grading rules for dimension lumber in light wood frame construction》, and 《LY/T 2228—2013 Finger jointed structural dimension lumber in light wood frame construction》 all relate the quality and grade of structural sawn timber to mechanical properties and engineering wood uses. European spruce (*Picea abies*) and Chinese fir (*Cunninghamia lanceolata*) structural sawn timber need to meet the requirements of the above standards.

The purpose of this paper was to compare the properties of Chinese fir with those of European spruce for structural applications in relation to variations in density and knots.

MATERIALS AND METHODS

Materials

Kiln-dried European (Norway) spruce was obtained from Sweden through Suzhou Kunlun Green Building Wood Structure Technology Co., Ltd (Table 1). The lumber was sawn to 17 mm × 38 mm × 330 mm long and conditioned to 12-15% MC.

Chinese fir was cut from 20- to 30-yr-old second rotation trees (180-250 mm diameter at breast height) obtained from the Shengsheng Wood Industry Co., Ltd. of Shunchang County, Fujian Province, China (Table 1). The lumber was sawn into 40 mm × 140 mm × 4000 mm sections that were kiln-dried at low temperatures from the original 60-80% MC to 12-15% MC before being further processed into 17 mm × 38 mm × 330 mm long beams.

The European spruce samples were sorted to produce 20 specimens in three density ranges (Table 2). The Chinese fir samples were similarly sorted to produce four density ranges each containing 20 specimens. Four groups were sorted for Chinese fir to account for the slightly wider density range for this species. A total of 500 specimens were examined. In both cases, only specimens with a slope of grain less than 15°, excluding the area around any knots, were selected. The effect of the knot area on flexural properties was assessed in a separate test where beams were cut so that knots of different diameters were positioned to be within 100 mm on either side of where the load would be applied.

The beams were cut so that they contained a single knot with the dimensions divided into four groups: ($d < 10$ mm, $d = 10$-20 mm, $d =$ 20-30 mm, $d > 30$ mm).

Bending Test

The specimens were loaded on the narrow face to failure in a third-point bending on an Instron 3369 microcomputer electronic universal mechanical testing machine according to procedures described

Table 1. Range and average density of European spruce and Chinese fir specimens used in the experiments.

	Specimens	Density range (g/cm^3)	Average density (g/cm^3)
European spruce	60	0.30 -0.40	0.36 g/cm^3
Chinese fir	80	0.30-0.50	0.40 g/cm^3

Table 2. Treatments used to assess the effects of density and knots on flexural properties of European spruce or Chinese fir.[a]

Treatment group	European spruce	Chinese fir
Density 1	0.344-0.361 g/cm^3	0.327-0.382 g/cm^3
Density 2	0.370-0.382 g/cm^3	0.391-0.430 g/cm^3
Density 3	0.391-0.445 g/cm^3	0.446-0.485 g/cm^3
Density 4	—	0.494-0.543 g/cm^3
Knot 1	<10 mm diameter	<10 mm diameter
Knot 2	10-20 mm diameter	10-20 mm diameter
Knot 3	20-30 mm diameter	20-30 mm diameter
Knot 4	>30 mm diameter	>30 mm diameter

[a]Each treatment was replicated on 20 beams per wood species.

in Chinese Standard GB/T 50329-2012 (standard for test methods of timber structures, GB/T 1936.1-2009 test methods for bending strength of timber) with a span to the depth ratio of 16.5 and a loading rate of 5 mm/min. Displacement and load were continuously recorded. According to the standard GB/T 1936.1-2009, the effects of shear were ignored. Each test took 2-3 min.

The linear portion of the load/deflection curve was used to calculate MOE, whereas the ultimate load was used to calculate MOR:

$$\mathrm{MOE}=\Delta PL^3/(4bh^3\Delta y) \quad (1)$$

$$\mathrm{MOR}=3P_{\max}L/(2bh^2) \quad (2)$$

where L is the span, b is the width of the specimen, h is the height of the specimen, y is the stress-strain diagram value, P is the load for which stress-strain diagram, and $P_{\max}$ is the breaking load.

RESULTS AND DISCUSSION

Effect of Density on Bending Resistance of European Spruce and Fujian Chinese Fir

Effect of density on bending resistance of European spruce. The density range of European spruce was relatively narrow, ranging from 0.3 to 0.4 g/cm^3, whereas that of Fujian Chinese fir was slightly larger, ranging from 0.3 to 0.5 g/cm^3 (Table 1). For this reason, four density groups were used for Chinese fir instead of the three used for European spruce. MOEs of the three groups of European spruce were 10.41, 12.42, and 13.96 GPa for the low, medium, and high-density groups, respectively, and were similar to commercial values with fairly low coefficients of variation (COV) of 8%, 10%, and 11%, respectively (Table 3). MORs of the same material were 35.85, 40.88, and 42.80 MPa, with COVs of 8%, 10%, and 9%, respectively. The lower COVs likely reflected the fact that the timber was further segregated from the general population. As the density is generally well-correlated with MOE and MOR, this would tend to narrow the variation in a given group. The data were subjected to an analysis of variance and tests of normality to identify treatments that differed significantly from one another ($\alpha = 0.01$) (Table 3).

As can be seen from Fig 1, the load was applied to European spruce from the narrow side, and failures tended to be in tension. The bending strength of the European spruce groups was divided by the average density of each group to more closely examine the relationships between these two properties. The results still indicated that denser materials still retained more capacity (99.58 MPa[cm^3]/g, 113.56 MPa[cm^3]/g, and 118.89 MPa[cm^3]/g for the three groups). These results were analyzed using the Min-Max normalization method. Bending strength values of the above three groups of European spruce and Chinese fir under unit density were linearly transformed, and the resulting values were 0, 0.06, and 0.09, respectively. The results suggest that Chinese fir has slightly higher bending strength per unit of mass than European spruce. These differences may be reflected in the anatomical arrangement of the cells.

Table 3. Effect of density on MOR and MOE of European spruce.[a]

Density range (g/cm^3)	MOE (GPa)	MOR (MPa)
0.344-0.361	10.41 ± 0.81	35.85 ± 2.85
0.370-0.382	12.42 ± 1.03**	40.88 ± 4.26**
0.391-0.445	13.96 ± 1.54**	42.79 ± 3.68**

[a]Values represent averages of 20 species per group. Values followed by ** signify very significant differences ($0.01 \le \alpha < 0.05$) between each group.

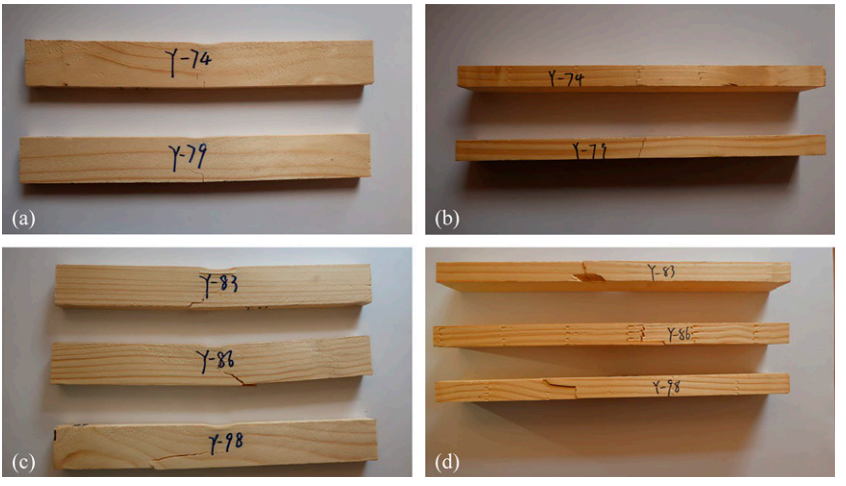

Figure 1. Examples of failure modes of knot-free European spruce subjected to loading to failure in third-point bending.

Effect of density on bending resistance of Fujian Chinese fir. MOEs of the four density groups of Chinese fir were 6.11, 6.20, 6.05, and 6.57 MPa (Table 4). These values were similar to previous reports for this species. However, variations were much higher with COVs of 14%, 21%, 22%, and 22%, respectively. Density was not as well-correlated with MOE as with European spruce.

MORs of the four density groups of Chinese fir were 84.12, 102.17, 108.56, and 126.11 MPa, with COVs of 8%, 8%, 10%, and 14%, respectively. There was a strong correlation between density and MOR with this species. As with the European spruce, the samples primarily failed in tension (Fig 2).

MORs of three groups of European spruce were divided by the average density (35.85 MPa/0.36 g/cm^3, 40.88 MPa/0.36 g/cm^3, and 42.80 MPa/0.36 g/cm^3) to obtain MORs on a unit mass basis of 99.58 MPa(cm^3)/g, 113.56 MPa(cm^3)/g, and 118.89 MPa(cm^3)/g, respectively. The Chinese fir data were similarly divided by average density (84.12 MPa/0.4 g/cm^3, 102.17 MPa/0.4 g/cm^3, 108.56 MPa/0.4 g/cm^3, and 126.11 MPa/0.4 g/cm^3) to produce MORs per unit mass of 210.30 MPa(cm^3)/g, 255.43 MPa(cm^3)/g, 271.40 MPa(cm^3)/g, and 315.28 MPa(cm^3)/g, respectively. The above results were analyzed using the Min-Max normalization method, and the MORs/unit of mass of the above seven groups of European spruce and Fujian Chinese fir were linearly transformed, and the results mapped to the range [0-1]. The values suggested that Chinese fir was slightly stronger per unit of mass than European spruce.

Table 4. Effect of density on modulus of elasticity (MOR) and modulus of rupture (MOR) of Fujian Chinese fir.[a]

Density group (g/cm^3)	MOE (GPa)	MOR (MPa)
0.327-0.382	6.11 + 0.87	84.12 + 7.05**
0.391-0.430	6.20 + 1.27	102.17 + 8.67**
0.446-0.485	6.05 + 1.36	108.567 + 11.21**
0.494-0.543	6.57 + 1.44	126.11 + 17.10**

[a]Values represent 20 replicates per group.

Effect of Knots on Flexural Properties

European spruce and Chinese fir specimens with knots both tended to fail in tension around the knots (Figs 3 and 4). This would be a typical mode of failure given that knots present a void in the wood as well as deviations in grain direction that lead to reduced properties. Load/displacement curves tended to be higher for European spruce and tended to have higher failure values (Fig 5).

Effect of knots on bending resistance of European spruce. The European spruce in this study had only a few knots that ranged from 10 to 30 mm in diameter and were mostly sound.

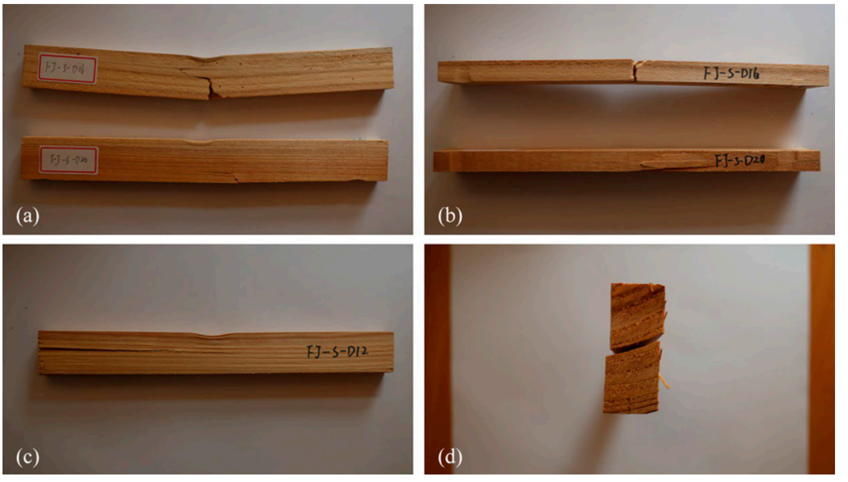

Figure 2. Examples of failure modes of knot-free Fujian Chinese fir subjected to third-point loading.

The MOEs in compression parallel to the grain of four groups of European spruce with different knot sizes were 13.16, 12.95, 12.67, and 11.04 GPa and were similar to the reported values (Table 5 and 6). The COVs were 29%, 30%, 28%, and 37%, which were much higher than COVs for wood.

MORs of three groups of European spruce with different knot sizes were 43.49, 38.27, 36.01, and

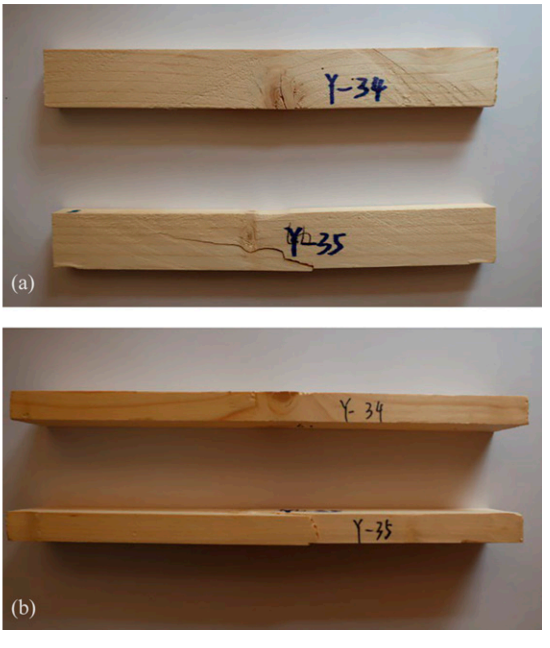

Figure 3. Examples of failure modes on European spruce beams with knots of various sizes subjected to third-point loading.

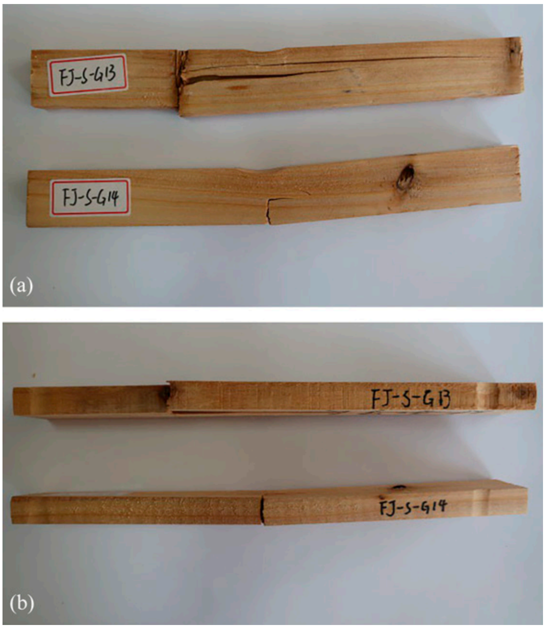

Figure 4. Examples of failure modes of Fujian Chinese fir with knots of varying sizes that were tested to failure in third-point loading.

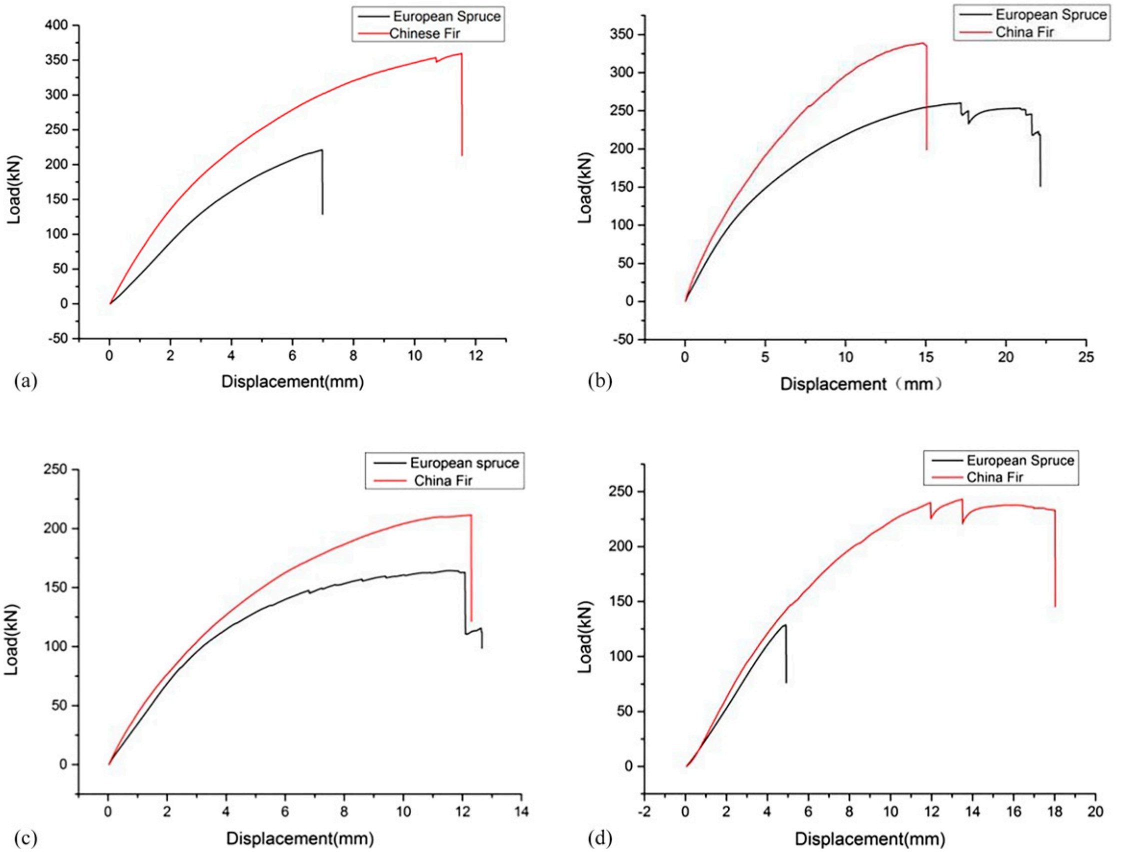

Figure 5. Load/displacement curves of typical European spruce and Chinese fir beams with knot diameters of (a) $d < 10$ mm, (b) $d = 10\text{-}20$ mm, (c) $d = 20\text{-}30$ mm, and (d) $d > 30$ mm.

28.20 Mpa with COVs of 18%, 16%, 22%, and 35%, respectively. COVs were again higher, reflecting the variability induced by the variable grain around the knots.

MOE and MOR both decreased with increased knot size, although the effects were small for knots less than 20 mm in diameter.

Effect of knots on bending resistance of Fujian Chinese fir. MOEs of the five groups of Fujian Chinese fir with different sizes increased from 6.09 Gpa to 6.24 MPa, 6.39 GPa, and 6.93 GPa, and the COVs were 29%, 36%, 39%, and 25% as the knot size increased. As discussed, these variations were higher than typical values for wood. Although the values were much lower than those for European spruce, it is unclear why they increased with larger knots. It is possible that the density of the Chinese fir knots affected the test results.

MORs of the knot groups of Fujian Chinese fir with different knot sizes declined slightly with increasing knot sizes ranging from 111.99, 115.005, 105.62, and 99.69 Mpa with COVs of 23%, 22%, 21%, and 13%, respectively. As with the MOE values, the COVs tended to be higher than those for clear beams, likely reflecting the variations induced by more variable grain. Unlike European spruce, Chinese fir MORs declined with knot size which would be a more typical response.

As can be seen from Fig 5, Fujian Chinese fir with the same knot sizes had better mechanical

Table 5. Effect of knots on MOE and MOR of European spruce with different knot sizes.

Knot size (mm)	MOE (GPa)[a]	% Reduction	MOR (MPa)[a]	% Reduction
<10	13.16 ± 2.23	10	40.21 ± 3.79	8
10-20	12.95 ± 2.35**	11	38.27 ± 5.61**	12
20-30	12.67 ± 2.64**	13	36.01 ± 8.08**	17
>30	11.04 ± 2.71**	24	28.20 ± 7.50**	35

[a]Values represent the means of 20 samples per group. Values with an asterisk differ significantly from the no knot group at $\alpha = 0.05$.

Table 6. Effect of knot diameter on flexural properties of Fujian Chinese fir.

Knot diameter (mm)	MOE (GPa)	% Reduction	MOR (MPa)[a]	% Reduction
<10	6.09 ± 1.78	0.9	111.99 ± 25.33**	33
10-20	6.29 ± 2.27	2.5	107.68 ± 16.21**	28
20-30	6.39 ± 2.51	4.1	105.62 ± 21.78**	26
>30	6.92 ± 1.71	12.8	99.69 ± 12.63**	19

[a]Values represent the means of 20 samples per knot category. Values with an asterisk differ significantly from the knot-free control ($\alpha = 0.05$).

properties than European spruce although both timbers experienced declined with increased knot size. European spruce tended to experience fracture failures, whereas the Chinese fir exhibited more slippage or shear that allowed some recovery when the load was removed.

CONCLUSIONS

Increased density was associated with increased MOE and MOR of both species, but the effect was more enhanced with Chinese fir. Increased knot diameter was associated with reduced MOE for European spruce but this effect was only found with the larger diameter knots for Chinese fir. MOR was negatively affected by both species.

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