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Modulus of Elasticity and Bending Strength of Scots Pine (*Pinus sylvestris* L.) Wood from Commercial Thinnings

Reeta Stöd [1,*], Juhani Marttila [2], Laura Tomppo [3], Antti Haapala [4] and Erkki Verkasalo [2]

[1] Doctoral Programme in Science, Forestry and Technology, University of Eastern Finland, 80101 Joensuu, Finland
[2] Natural Resources Institute Finland, 80101 Joensuu, Finland; juhani.marttila@luke.fi (J.M.); erkki.verkasalo@luke.fi (E.V.)
[3] Department of Technical Physics, University of Eastern Finland, 70211 Kuopio, Finland; laura.tomppo@uef.fi
[4] Department of Chemistry, University of Eastern Finland, 80101 Joensuu, Finland; antti.haapala@uef.fi
* Correspondence: stod@student.uef.fi

Abstract: The static bending properties of Scots pine (*Pinus sylvestris* L.) clear wood were studied using a material collected from commercial thinning forests in eastern Finland. In *Myrtillus* type, the modulus of elasticity and bending strength of the first thinning wood were 7.8 GPa and 66.0 MPa, respectively, whereas for more mature wood from the second thinnings, the modulus of elasticity and bending strength were 10.0 GPa and 80.3 MPa. The results were compared with final fellings, which resulted in the modulus of elasticity of 10.1 GPa and bending strength of 81.8 MPa. The bending properties of the first thinning material were low, and thus they did not indicate any potential for applications requiring high strength or stiffness and material homogeneity. On the contrary, the properties of Scots pine wood from the second commercial thinnings may be comparable with or sometimes even better than those of the final-felling wood. The results can be utilised in wood marketing, procurement, sorting, allocation to different industries and end-uses, as well as in wood processing, product sales, and branding.

Keywords: bending strength; clear wood; harvesting; mechanical properties; modulus of elasticity; Scots pine; thinning; wood materials; wood industry; wood products

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1. Introduction

Young and advanced thinning forests cover approximately 69% of the total forest land area in Finland, and their proportion has increased by roughly eight percentage points during the past 20 years [1]. These forests are an important source of raw material for the wood-processing industry, especially for pulp mills, but also for sawing and further processing, such as joinery, furniture, packaging products, and environmental construction [2–4]. Moreover, especially the first thinnings provide renewable energy wood for municipal and private uses. Small-sized trees, such as pulpwood, are the most important source of forest chips for bioenergy in Finland, with a total volume of 6.4 million cubic metres in 2022 [5]. The volume of forest chips from small-sized trees increased by 8% from the year 2021, being markedly larger than the other main sources, namely logging residues (2.9 Mm^3), stumps (0.3 Mm^3), and dead or decayed large roundwood (0.6 Mm^3) [5]. There is currently very limited use of thinning wood for any higher value-added uses due to the notion that small-diameter pine with juvenile wood is inferior in strength and in the overall quality for anything more advanced than pulp or energy.

The first thinnings and other management cuttings are performed to improve the vitality, health, and quality of forests and to promote the growth of remaining trees so that the growth and recovery of the most valuable timber assortments will be secured in the future [6,7]. The impact of a thinning operation, even when conducted intensively, along with the growth response it triggers, results in only minor effects on wood properties, such as density and tracheid length [8,9]. Thus, it may be assumed that the growth response does not significantly affect the mechanical wood properties of the remaining trees either.

Where clear wood is concerned, its strength and stiffness are mainly dependent on the wood density, and the degree of this effect varies according to the mechanical property in question, as, for example, the increment of strength and modulus of elasticity in bending along with density are nearly linear [10,11]. Density and several other wood properties vary markedly according to the growth conditions. The spacing of trees and climatic factors, both at micro and macro levels, affect the growth rate of conifers and, consequently, the density of wood. Trees tend to grow quickly in nutrient-rich sites and in sites with wide spacing, which leads into a larger share of earlywood within growth rings and thus, to lower mean density [10,12–18]. Due to the structural differences between earlywood and latewood, the density of earlywood is markedly lower and, consequently, several mechanical properties are lower for earlywood than for latewood [10,16,19–21]. In wood products, the high growth rate is visible through wide annual rings and large knot diameters, particularly when the wood is from fertile site type forests and those regenerated by planting [12,14].

When thinning for quality, i.e., removing trees of the lowest external quality and completing the thinning with smaller trees from below, the yield of merchantable timber is low and the thinning removal most likely contains trees with a multitude of external and internal defects [7,22–25]. The proportion of defected trees and severity of defects depend on the general quality of the forest before thinning, the knottiness, stem form, checks and scars being the most important factors. Leaning or crooked stems tend to contain reaction wood, i.e., compression wood in conifers, and the stem form defects decrease the probability of obtaining saw logs [2,16,26,27]. The chemical composition of compression wood differs from the normal wood by approximately 8%–9% higher lignin content and 10% lower cellulose content [10,11,19,28,29]. The density of compression wood is 20%–40% higher, but the strength properties are at the same level or lower than in normal wood, resulting in a markedly lower strength-to-weight ratio [10,11,30]. In addition, compression wood is defined as a defect in mechanical wood processing due to larger longitudinal shrinkage, tendency to twist, and darker colour [27].

Young coniferous trees are characterised by a substantial presence of juvenile wood [10,31]. Juvenile wood is formed in the core area of a tree at all heights, and it is stated to cover the first 10–20 year rings from the pith outwards, although the exact border between the juvenile and mature woods cannot be determined due to the gradual change in a transition zone [24,31–33]. Thus, the within-tree variability of wood properties from pith to bark mostly reflects the characteristics of juvenile wood, as well as the differences between juvenile and mature wood [24,27,34]. In pines, the auxin hormone, which is produced in the live crown, has been identified as one of the factors controlling the formation of juvenile wood, in addition to, for instance, environmental factors, cambial age, and distance from the pith [33,35,36].

In comparison with mature wood, the density and mechanical properties of juvenile wood are lower, as the cell walls are thin and the proportion of latewood is small [10,24,29,31,36–38]. The microfibril angle in the S_2 layer of the secondary wall is high, which increases the longitudinal shrinkage and reduces stiffness [10,39]. In addition, the juvenile wood is prone to contain compression wood and spiral grain, to have a lower modulus of elasticity, and to show higher variation in wood properties [27,31,32]. The extensive longitudinal shrinkage, lower density, weaker structure, and the tendency to dry fast cause checking and drying deformations in wood products, particularly when juvenile and mature wood are present in the same piece of timber [40].

Due to defects and the presence of juvenile wood and reaction wood, the mechanical properties of young wood material are usually lower than those of mature wood. Particularly, in first thinnings, the harvesting removal may contain the smallest but also the most defected trees of the forest. The density and bending strength of Scots pine wood are known to markedly increase along with the age of a tree. In [41], the lowest values of density and static bending strength were recorded in the youngest age class with 30-year-old pine trees, which was anticipated to be due to the juvenile wood effect.

The objective of this study was to determine the modulus of elasticity and bending strength of Scots pine (*Pinus sylvestris* L.) clear wood from commercial thinnings, in comparison with the wood material from final fellings, and to assess how different stand and tree characteristics affect these mechanical properties.

2. Materials and Methods

The study material was collected from twelve Scots pine (*Pinus sylvestris* L.)-dominated forests in eastern Finland (62–63° N, 30° E), in the boreal forest region. The stand types selected for the study were typical for Scots pine in the said geographic area, representing the first thinning forests (6), second thinning forests (4), and mature, final felling forests (2). The site types varied from *Myrtillus* type on mineral soils to dwarf-shrub transformed type on drained peatlands, and the sample sizes for different combinations of stand and site types were limited. This was accepted since the focus of the study was not on the forest growth conditions but to investigate the potential of thinning wood with respect to its mechanical properties. Characteristics of the study stands by the stand type and site type have been presented in [42].

One to eight temporary sample plots with a minimum area of 200 m^2 were established at study stands. All trees of each sample plot, on average 40 trees per plot, were measured for parameters such as the breast-height diameter (dbh) and height. In addition, several external quality indicators, such as the crown height and diameter of the thickest dead branch, were either measured or visually assessed.

Ten trees were felled from each study stand to represent the harvesting removal. The selection of removed trees was performed following the principles of thinning for quality, with the specification that a removed tree had to contain at least one 2.5 m stem part, which would have been suitable for mechanical processing based on its external quality. The sample trees were cut into test logs down to the over-bark diameter of 8 cm without following commercial bucking instructions. Totals of 123, 172, and 158 logs were obtained from the first thinning stands, second thinning stands, and final felling stands, respectively. The logs were classified according to their vertical position in a tree as butt logs (cut from the height of 0–4 m), middle logs (4–8 m), and top logs (over 8 m).

The test logs were sawn through-and-through in the east–west direction, which had been marked in the trees in the forest. The approximate green thickness of the boards was 50 mm, and 2–6 boards were obtained from a log. Most of the boards represented the centre yield of sawn timber because of the small diameter of logs from thinnings, while more boards were obtained from final felling stands and butt logs. The boards were numbered to trace them back to the original tree, log, and radial position. The boards were stacked for air drying and protected from rain and direct sunlight.

The standard test specimens for determining the bending properties of clear wood were prepared from the seasoned boards, which were sawn from the south-facing side of the sample trees (Table 1) [43]. The specimen dimensions were 20 mm × 20 mm × 340 mm (radial × tangential × longitudinal), and they were free from visible defects. The specimens were conditioned to a constant moisture content of 12% in the standard environment. The air-dry density (henceforth referred to as density) of specimens was determined as the ratio of their weight and volume (ρ_{12}, kg/m^3). The modulus of elasticity, MOE (E_{12}, GPa), was determined by a four-point bending test with the universal material testing machine Lloyd 6000R (Lloyd Instruments PLC, Fareham, UK) and the extensometer Heidenhain-Metro MT 12 (Dr. Johannes Heidenhain GmbH, Traunreut, West Germany), according to ISO 3349 [44], and the static bending strength (modulus of rupture), MOR (σ_{12}, MPa), by a three-point bending test according to the standard ISO 3133 [45], as described by Kučera [43]:

$$E_{12} = \frac{Fl^3}{36bh^3 f} \tag{1}$$

$$\sigma_{12} = \frac{3F_{max}l}{2bh^2} \quad (2)$$

where F = difference between the higher load (25% of the maximum load in bending) and the lower load (10% of the maximum load in bending) (N), l = distance between the supports (cm for modulus of elasticity and mm for bending strength), b = specimen width (mm), h = specimen thickness (mm), f = deflection (mm), and F_{max} = maximum load (N).

Table 1. Means and standard deviations of density, modulus of elasticity (MOE), and bending strength (MOR) of clear wood according to the stand type. N is the number of clear wood specimens.

Stand Type	Site Type (Number of Stands)	N	Density (kg/m³)	Std. Dev. (kg/m³)	MOE (GPa)	Std. Dev. (GPa)	MOR (MPa)	Std. Dev. (MPa)
First thinning	*Myrtillus* type (2)	40	410.5	29.7	7.8	1.4	66.0	8.8
	Vaccinium type (2)	42	466.6	67.6	9.7	1.8	81.1	15.2
	Vaccinium vitis-idaea transformed type (2)	46	432.1	36.7	8.3	1.4	70.0	9.8
Second thinning	*Myrtillus* type (1)	81	446.6	56.6	10.0	2.4	80.3	17.6
	Vaccinium type (1)	89	467.2	53.8	10.2	1.9	84.8	14.9
	Calluna type (1)	27	513.3	64.8	11.7	1.6	94.5	14.1
	Dwarf-shrub transformed type (1)	22	519.2	49.5	11.3	1.5	96.2	10.0
Final felling	*Myrtillus* type (2)	277	455.4	60.9	10.1	2.5	81.8	17.8

The means and standard deviations of density, modulus of elasticity, and bending strength were calculated by the stand type, site type, and log section. Due to the uneven structure of data, the comparisons between all stand types were possible only in *Myrtillus* type, whereas *Vaccinium* type enabled comparisons between the first and second thinnings.

The linear mixed model (LMM) approach was used to study the variability of bending properties and the effects of selected stand and stem characteristics on them. The models were fit to the data using the linear mixed-effects models (MIXED) procedure in IBM SPSS Statistics v29 (IBM Corporation, Armonk, NY, USA). The variation in bending strength was analysed separately with and without the modulus of elasticity as a potential predictor, in the first case to show the total potential of prediction and, in the latter case, to reveal more efficiently the true effects of the material origin and growth-related wood characteristics. The prediction accuracy of models was determined by calculating the proportion of explained variance (R^2), bias, and root mean square error (RMSE). Only fixed effects were used in obtaining the predicted responses. The relative error (bias% and RMSE%) was calculated by dividing the bias and RMSE by the mean of the predicted response.

Two-way analysis of variance (ANOVA) was used to study the differences in MOE and MOR between the stand and log types. Confidence threshold of 95% ($p < 0.05$) was used in the determination of statistical significance.

3. Results and Discussion

3.1. Density and Bending Properties by Stand Type

The descriptive statistics of density, bending strength, and modulus of elasticity in different stand and site types are presented in Table 1. According to two-way ANOVA, the differences between stand types in modulus of elasticity ($F(2, 390) = 25.372$) were statistically significant ($p < 0.001$) in *Myrtillus* type. The post hoc tests indicated that first thinnings had lower MOE than second thinnings and final fellings, whereas no significant differences were detected between second thinnings and final fellings. In addition, for MOR, differences ($p < 0.001$) between the stand types ($F(2, 390) = 25.322$) were statistically significant in *Myrtillus* type. First thinnings had lower MOR than second thinnings and final fellings, but the difference between second thinnings and final fellings was not statistically significant. In *Vaccinium* type, the differences between first and second thinnings in density, bending strength, and modulus of elasticity were of minor magnitude and not statistically significant.

Irrespective of the stand type, the levels of modulus of elasticity and bending strength were somewhat lower in our data than in an earlier study on Scots pine wood from mature stands in Finland [46]. In comparison to a study from the 1940s, the bending strength and modulus of elasticity were considerably lower in the first thinnings and final fellings of our study, except for the results from southern Finland in [47]. This might indicate actual changes in the wood quality over time but also different growth conditions of studied forests as well as notable differences in sampling. In second thinnings, the bending properties were at the same level as in [48] from southern and south-western Finland. The MOR recorded in our study was somewhat lower in final fellings, despite the similar values of modulus of elasticity. There, the sample means of bending strength ranged from 71.2 to 89.2 MPa, and those of modulus of elasticity from 8.2 to 11.0 GPa, between different regions within the natural distribution area of Scots pine in Europe [48]. It should be noted that these older studies were using the three-point bending test, which often gives lower values for modulus of elasticity than the four-point bending test used in the current paper [47,48]. More recently, a bending strength of 84 MPa and modulus of elasticity of 9 GPa were reported for mature Scots pine in Scotland [49]. In different growth conditions of fresh mixed coniferous forests in Poland, the 30-year-old trees reached an MOR of 74 MPa and basic density of 455 kg/m^3 at the stem base until 2.3 m [41].

Descriptive statistics of density, bending strength, and modulus of elasticity according to the stem part in *Myrtillus* type are presented in Table 2. For MOE, the differences between log sections ($F(2, 390) = 17.053$) were statistically significant ($p < 0.001$). Top logs had lower MOE than butt logs or middle logs, whereas the differences between butt logs and middle logs, as well as the interaction of stand type and stem part, were insignificant. The MOR was markedly higher in butt logs than in middle or top logs ($F(2, 390) = 19.418$), and the differences were statistically significant ($p < 0.001$). No differences were found between the middle and top logs, and the interaction of stand type and stem part was insignificant. Most of the specimens from the middle and top logs were located within 50 mm from the pith. This was due to the relatively small size of the logs and causing their lower average density and strength properties. The larger log diameters in the butt log section enabled more boards from each log, and thus more specimens were obtained from the area with higher wood density, i.e., farther away from the pith.

Table 2. Means and standard deviations of density, modulus of elasticity (MOE), and bending strength (MOR) of clear wood according to the log section in *Myrtillus* site type. N is the number of clear wood specimens.

Stand Type	Stem Part	N	Density (kg/m³)	Std. Dev. (kg/m³)	MOE (GPa)	Std. Dev. (GPa)	MOR (MPa)	Std. Dev. (MPa)
First thinning	0–4 m (Butt log)	26	411.8	30.4	7.7	1.4	65.8	9.0
	4–8 m (Middle log)	14	408.1	29.4	7.9	1.4	66.4	8.6
Second thinning	0–4 m (Butt log)	26	482.3	68.4	11.5	2.8	91.9	20.7
	4–8 m (Middle log)	24	439.1	46.5	10.0	2.2	78.9	15.1
	>8 m (Top log)	31	422.6	35.2	8.9	1.5	71.7	10.0
Final felling	0–4 m (Butt log)	70	491.0	83.5	11.2	3.1	90.7	24.1
	4–8 m (Middle log)	64	450.4	60.4	10.3	2.7	82.7	18.2
	>8 m (Top log)	143	440.2	36.6	9.4	1.8	77.1	11.4

The increasing density from pith to bark and the highest bending strength and modulus of elasticity in the stem base are typical for Scots pine and other coniferous species [16,50]. In Poland, the mean basic density of 466–509 kg/m^3 was reported for the Scots pine specimens from the juvenile wood area, and 565–617 kg/m^3 for the mature wood [51]. Similarly, Schönfelder et al. noted for Scots pine wood in Czech Republic the vertically decreasing trend of density from the base (534 kg/m^3) to the middle (477 kg/m^3) of the trunk, as well as horizontally increasing density from the pith outwards (489–566 kg/m^3) [52].

3.2. Models for Modulus of Elasticity and Bending Strength

Modulus of elasticity MOE (E_{12}, in GPa) and bending strength, i.e., modulus of rupture MOR (σ_{12}, in MPa), were modelled by the linear mixed models:

$$E_{12} = b_0 + \rho + x + u_s + u_{ts} + \varepsilon, \quad (3)$$

$$\sigma_{12,1} = b_0 + \rho + x + u_s + u_{ts} + \varepsilon, \quad (4)$$

and

$$\sigma_{12,2} = E_{12} + u_s + u_{ts} + \varepsilon, \quad (5)$$

where

E_{12} = modulus of elasticity (GPa)
b_0 = intercept,
ρ = air-dry density (kg/m^3)
x = dummy term of radial position (>50 mm)
u_s = random stand effect
u_{ts} = random tree effect
ε = random error term
σ_{12} = modulus of rupture (MPa)

Using density and radial position as fixed factors resulted in a high R^2 value and a relatively low RMSE in the models (Equations (3) and (4), Tables 3 and 4). Other factors, such as the stand type and log section, did not significantly improve the model. This was due to the high explanatory power of density. It largely accounted for the differences between the stand types and log sections, as, in general, a higher density in mature stands indicates better mechanical properties.

In the linear mixed model for the modulus of elasticity, the fixed effects included the density and the radial position of the specimen (Table 3). The RMSE for the model was 13.6% (1.35 GPa). The random effect of a tree was the source of 30% of the total random variation. The positive impact of density was consistent with previous research [16,27,53].

Along with the increasing density, the radial position of the specimen indicated an increasing modulus of elasticity from the pith to the bark. Especially the MOE of Scots pine has been noted to be dependent on the radial position within a tree [51]. The higher microfibril angle close to pith as well as elsewhere in the juvenile wood area may explain part of the radial variation of MOE in this study. Earlier research has proven that density, MOR, and MOE are negatively correlated with the microfibril angle [54,55]. Furthermore, the microfibril angle is significantly higher in juvenile wood than in mature wood.

Table 3. Linear mixed model (Equation (3)) for the modulus of elasticity (MOE) of clear wood.

Variable	Estimate	Std. Error	t-Value	Sig.
Intercept	−1.896	0.4799	−3.951	<0.001
Density	0.025	0.0010	24.289	<0.001
Radial position > 50 mm	1.473	0.1379	10.680	<0.001
Random Effect	**Estimate**			
Stand	0.120			
Tree	0.586			
Residual	1.270			
Fitting Statistics				
R^2	66.3%			
Bias	0.08 (0.86%)			
RMSE	1.35 (13.7%)			

Table 4. Linear mixed models (Equations (4) and (5)) for the bending strength (MOR) of clear wood.

	Equation (4)				Equation (5)			
Variable	**Estimate**	**Std. Error**	**t-Value**	**Sig.**	**Estimate**	**Std. Error**	**t-Value**	**Sig.**
Intercept	−29.126	2.4675	−11.804	<0.001	14.475	1.3169	10.992	<0.001
Density	0.237	0.0053	44.560	<0.001				
Radial position > 50 mm	5.759	0.7289	7.901	<0.001				
MOE					6.781	0.1189	57.009	<0.001
Random Effect	**Estimate**				**Estimate**			
Stand	2.852				2.067			
Tree	7.087				11.106			
Residual	37.324				37.989			
Fitting Statistics								
R^2	84.6%				83.3%			
Bias	0.58 (0.7%)				−0.46 (−0.6%)			
RMSE	6.72 (8.3%)				7.01 (8.6%)			

In the linear mixed model for bending strength, both the density and the radial position of the specimen were included as fixed effects. The stand and tree were considered as random effects (Table 4, Equation (4)). The random effect of a tree accounted for 17.6% of the total random variation. The bending strength showed an increasing trend radially, from the pith to the bark, and, additionally, a high density indicated greater strength. Like in several earlier studies, the within-tree variation of bending strength was strongly associated with that of the wood density [49,56,57]. Density was observed to significantly influence the bending strength and, to a lesser extent, the modulus of elasticity of Finnish Scots pine [46]. Moreover, significant differences were noted between the juvenile wood area and mature wood area [46]. Models containing several factors, such as the latewood percentage or annual ring width, in addition to density, radial position, and MOE, would improve the coefficient of determination, especially when modelling material properties from a specific geographical area [46].

On the contrary, a study on ponderosa pine (*Pinus ponderosa*) has observed very weak relationships between specific gravity, modulus of elasticity, and modulus of rupture [58]. This was assumed to be due to the relatively high shares of juvenile wood and compression wood in the tested small-diameter trees. The predictive capacity of the models based on individual structural properties, such as density, could be improved with the increasing resolution of wood structure characterisation [59,60]. For instance, considering the properties of earlywood and latewood could enhance the model. This is because the environmental factors have been observed to affect latewood properties, while variation between trees impacts earlywood properties [61].

In an alternative model for bending strength, the modulus of elasticity was used as the only fixed effect (Table 4, Equation (5)). The random effects were the same as in Equation (4). The random effect of a tree accounted for 21.7% of the total random variation. Bending strength increased along with the modulus of elasticity. The strong positive correlation of modulus of elasticity and bending strength has been demonstrated in several earlier studies [46,60,61].

Both MOR models (Equations (4) and (5)) predicted the bending strength well, without major differences in the fitting statistics. Therefore, both models would be applicable in practice when utilising the non-destructive tests to predict the bending strength. An earlier study on the modulus of rupture of sawn timber included factors such as site type, log section, and board dimension in the linear mixed model analysis [42]. In the case of clear wood samples without knots, cracks, or other defects, a more simple approach can be used. Equations (3) and (4) are applicable with relatively limited input data, i.e., density and radial position. In Equation (5), MOE is the only fixed factor, which, however, often requires more sophisticated measurement methods than determination of density and radial position as in Equation (4).

Figure 1 illustrates the modulus of elasticity by density according to the radial position (Equation (3)). MOE was strongly dependent on the radial position. The difference in MOE between the juvenile wood zone and the maturing or mature wood zone was noted to be statistically significant in earlier research, where the mean MOE of juvenile wood ranged from 4.0 GPa to 5.6 GPa, and that of mature wood ranged from 8.1 GPa to 10.2 GPa, depending on the geographical location of the forest [51]. Observed from the Finnish data, the MOR and MOE of juvenile wood were 25%–32% lower than those of mature wood [46]. This is because the proportion of earlywood near the pith, as well as the growth speed, is high, and, therefore, density is low.

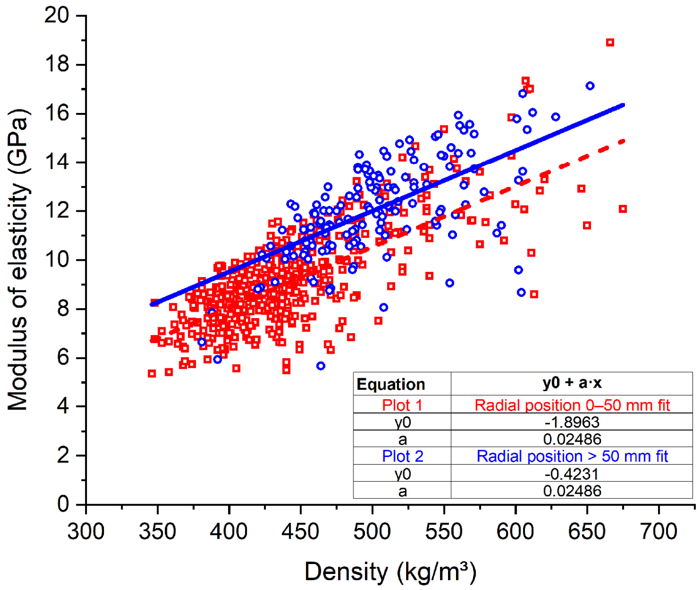

Figure 1. Modulus of elasticity (MOE) by density depending on radial position of each specimen (Equation (3)), with linear fit of data ($y = y_0 + ax$, in which y_0 is intercept, a is coefficient, and x refers to density) for specimens originating close (≤50 mm) or farther away (>50 mm) from the tree pith.

The Pearson correlation of density and modulus of elasticity was strong (r = 0.836). Figure 1 shows that the variation of MOE increased along with the increasing density, which might indicate the presence of reaction wood in some of the samples and its adverse effects on the mechanical properties despite the higher density [62]. For certain Northern American tree species, the MOE of reaction wood has been reported to be 49%–92% of the MOE of normal wood [63].

Figure 2 illustrates the bending strength by density according to the radial position (Equation (4)). The Pearson correlation of density and bending strength was very strong (r = 0.927). The radial position, when considered as a fixed factor, had less impact on the bending strength than on the modulus of elasticity. Comparing the models for MOE (Equation (3)) and MOR (Equation (4)), the MOR model was more precise due to its higher R^2 and lower RMSE (Tables 3 and 4). Fixed factors being the same, a higher coefficient of determination (R^2) was produced for the model of MOR, while the estimates of random effects were higher for the model of MOE.

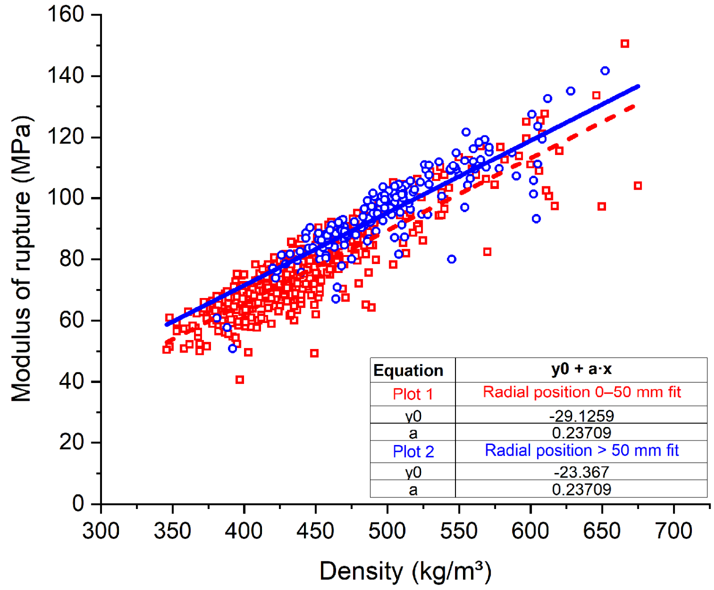

Figure 2. Bending strength (MOR) by density depending on radial position of each specimen (Equation (4)), with linear fit of data ($y = y_0 + ax$, in which y_0 is intercept, a is coefficient, and x refers to density) for specimens originating close (≤50 mm) or farther away (>50 mm) from the tree pith.

Figure 3 shows the relationship of bending strength and modulus of elasticity in all data (Equation (5)). The Pearson correlation of MOR and MOE was very strong (r = 0.929); hence, the modulus of elasticity alone was a very good predictor of the bending strength. In Equations (4) and (5), the R^2 and RMSE values were close to each other (Table 4). In the MOR model of Equation (4) (Figure 2), however, the predicted values of outliers were higher than the measured values. This might indicate a deviating grain angle or the presence of reaction wood, as in the model for MOE according to Equation (3) (Figure 1). In the MOR model of Equation (5) (Figure 3), most of the outliers had higher measured values than predicted values, i.e., the model somewhat underestimated the bending strength, at least for the outliers.

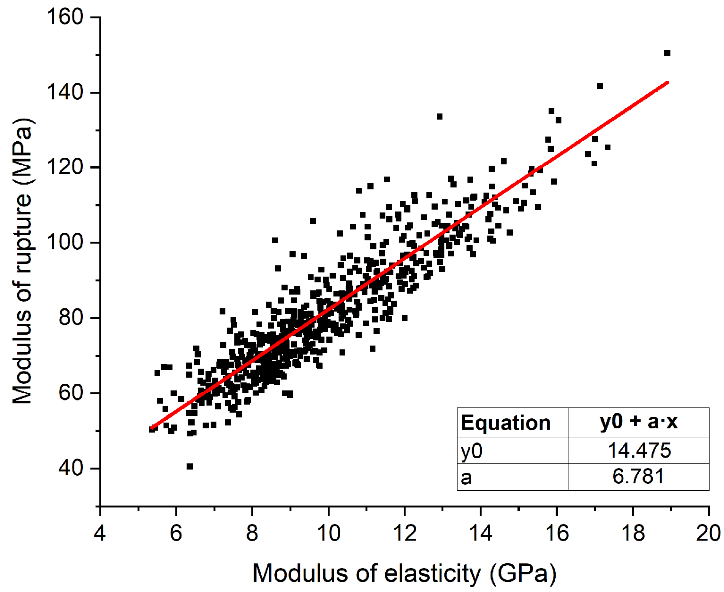

Figure 3. Bending strength (MOR) by modulus of elasticity (MOE) of each specimen (Equation (5)), with linear fit of data ($y = y_0 + ax$, in which y_0 is intercept, a is coefficient, and x refers to MOE).

4. Conclusions

The results of this study showed higher wood density, modulus of elasticity, and bending strength for the mature wood than for the young Scots pine wood. This was noted when comparing the first thinning stands with the other stand types, as well as between the juvenile wood and mature wood areas in individual trees. The differences between the first thinning stands and other stand types were statistically significant, and the radial position within a tree was noted to significantly affect both the MOE and MOR of clear wood. The vertical differences within a tree were insignificant in the first thinning stands, whereas in older stand types, the strength properties were the highest in the butt logs, with a notable decrease from the base to the top.

In the mixed-effect models, density and radial position as fixed factors successfully predicted both the modulus of elasticity and the bending strength. Notably, these factors are also easily measurable within sawmills when assessing the quality of sawn timber. In the linear mixed model for bending strength, modulus of elasticity as the only fixed factor reached approximately the same coefficient of determination as the other model with density and radial position. However, in comparison to density and radial position as fixed factors, predicting MOR with the help of MOE might need safety coefficients in strength grading due to its outlier structure.

The wood properties vary markedly in the juvenile wood area, while the properties of mature wood are more constant, and, therefore, these should be studied separately. The increased variation of MOE was related to high density values. Thus, high density might indicate either a high latewood proportion or the occurrence of compression wood. The compression wood is found in leaning and crooked coniferous trees, which are usually removed from the forest stand in the first or second thinnings to promote the growth of the remaining high-quality trees.

The sample trees of this study included at least one stem part which met the quality and size requirements for either a small-sized or a normal log. Thus, the sample trees have likely been of somewhat higher quality than the general recovery from thinning forests in practical forestry. Nevertheless, the weaker clear wood properties, in addition to the knots and other technical defects present in the removed trees, indicate that the first thinning wood of this study would not have been suitable for applications where high strength, stiffness, or material homogeneity are required. Instead, the second thinning wood would have provided comparable or sometimes even better properties than the final-felling wood. This should be considered in wood marketing, procurement, sorting, allocation to different industries and end-uses, as well as in wood processing, product sales, marketing, and branding. Wood products industries should pay greater attention to utilising the growing resources of Scots pine from young and middle-aged thinning forests to secure their raw material supply in the future and drive technology and product development toward higher resource efficiency and productivity and a more diversified and competitive product range. Future research should provide the industry with the information needed to achieve the aforementioned targets.

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