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Relationships between wood properties of small clear specimens and structural-sized boards in three softwood species

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Abstract

Research on the mechanical and physical properties of wood is commonly carried out on either small clear specimens or structural-sized boards. The first approach was more frequently utilised in the past, while the latter is more commonly used nowadays. However, there is very little information on how the two approaches relate with one another. This study aims to quantify the relationships between mechanical (modulus of elasticity, bending strength) and physical properties (density) of both specimen sizes. A total of 1376 structural-sized boards from three different species (Douglas-fir, Norway spruce and Sitka spruce) were tested in bending, after which a small clear specimen was extracted from the undamaged portion of each board and re-tested in bending. Prior to destructive testing, all boards and clear specimens were evaluated using non-destructive technology. Poor-to-moderate relationships were found between all measured mechanical and physical properties of structural-sized timber and small clear specimens. In both specimen sizes the properties correlated with one another within the same specimen size, as well as across the two sizes. The strength of correlations appears to be somewhat species dependent. Relatively good relationships were identified when comparing the mean tree values of the properties examined, suggesting either method can be used for a tree level comparison. The non-destructive evaluation of specimens was shown to reflect the

measured properties moderately well, with the relationships changing significantly depending on which measured property was being predicted.

Introduction

Timber quality can be evaluated on many different levels, as the definition of quality is dependent on the end purpose of a certain wood product. In sawn timber used in construction in Europe a strength classification system EN 338 (CEN, 2016) is used. According to this system, sawn-timber boards are sorted into strength classes, determined by the elastic modulus (MOE), bending strength (also known as modulus of rupture, MOR) and density of clear wood. However, this system is only applicable to structural-sized timber.

Research on wood mechanical properties has been historically carried out on small clear specimens. Due to their size they are straightforward to obtain, fast to condition and easy to test in bending, for example. A number of different standards have been developed to standardise the testing procedures of small clear specimens (BS 373 (British Standards Institution, 1957), ASTM D143-14 (American Society for Testing Materials, 2014), ISO 13061-4 (International Organization for Standardization, 2014)). Testing of small clear specimens has one main distinction over testing of larger specimens, as it excludes the effect of various defects (knots, slope of grain, resin pockets…) on the properties. It is still a frequently used approach among forestry and wood science researchers seeking to examine the cause-effect relationship between various silvicultural treatments, genotypes, site quality, etc. and wood properties.

However, the end product is almost never a small clear specimen, but a structural-sized board with all the material heterogeneity found in wood. Testing structural-sized timber in bending requires more resources and time than testing small clear specimens. The structural-sized boards are also harder to transport, take longer to condition and require more expensive specialized equipment to perform the tests. Madsen (1992) suggested that small clear specimens and structural-sized boards should be considered as two different materials when looking at strength properties from an engineering perspective due to the failure initiation location. While using small clear specimens for derivation of reliable strength properties was deemed unsuitable by Madsen (1992), he also recognized the potential of linking properties of small clear specimens to structural-sized timber with more accurate adjustment factors or better analysis methods.

Very few studies have examined the relationship between material properties of boards and properties of small clear specimens. They are to a degree correlated, as shown by research carried out in the past. For example, a recent study by Butler et al. (2016) examined the relationships between mechanical and physical properties determined on clear specimens with dimensions of 25 x 25 x 410 mm and structural-sized timber of four different sizes of loblolly pine (*Pinus taeda* L.), using linear regression for quantifying the relationships. The study reports an overall a coefficient of determination R^2 of 0.22 for relating MOE of clear specimens to MOE of boards, reducing to 0.11 for bending strength and increasing to 0.50 when comparing densities. The strength of the relationship in MOE was also reported to be affected by the sample orientation with regard to applied load direction (tangential, radial or mixed). The test orientation appears to have had no effect on bending strength.

A study by Gil-Moreno (2018) examined the relationships between properties of structural timber and the corresponding clear specimens across four different species, Noble fir (*Abies procera* Rehd.), Norway spruce (*Picea abies* (L.) H. Karst.), Western red cedar (*Thuja plicata* Don ex D.Don) and Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). A relatively good relationship (R^2 = 0.63) was reported overall between the moduli of elasticity of both sizes, with structural-sized boards showing on average 20% higher stiffness than small clear specimens. Slightly stronger relationships were reported when comparing the mean stiffness of individual trees (R^2 = 0.68), while a lower correlation was found (R^2 = 0.35) overall when comparing the mean bending strength of individual trees. The same study also investigated the use of dynamic MOE for prediction of static MOE and MOR in both specimen sizes. The dynamic elastic modulus is determined acoustically by measuring the wave velocity as it travels through the board and is commonly used to estimate mechanical/physical properties in a non-destructive way. The values of dynamic MOE in both small clear specimens and structural-sized boards were higher than the static MOE. The correlation between static and dynamic MOE was found to be relatively strong in both specimen sizes (R^2 = 0.88 in small clear specimens, R^2 = 0.90 in boards). The relationships between dynamic MOE and static MOR were weaker (R^2 = 0.57 in small clear specimens, R^2 = 0.43 in boards). In addition, an overall correlation of R = 0.50 was reported between density of clear wood and static MOR in boards.

Teder et al. (2012) examined the use of ultrasound on boards of Norway spruce before destructively testing the specimens. Ultrasound measurements were performed in the longitudinal, radial and tangential directions. Measurements in the longitudinal direction proved best for predicting static modulus of elasticity and bending strength - the correlation between MOE or MOR and acoustic velocity was reported as R^2 = 0.37 and R^2 = 0.18, respectively. The inclusion of moisture content of the board was also found to significantly improve the prediction of the elastic modulus. The analyses also showed that the larger the measuring distance, the better the dependent variables can be predicted.

The relationships between dynamic and static MOE of structural-sized boards were reported as relatively good by several studies across multiple species and specimen sizes (Larsson et al., 1998; Divos and Tanaka, 2005; Yang, 2015; Vikram et al., 2011; Simic et al., 2019), coinciding with a rise in the use of machine grading and non-destructive evaluation of timber over the last two decades. The correlation between static and dynamic MOE was also reported to be relatively good in small clear specimens across several species (Raymond et al., 2007; Haines et al., 1996).

The current study aims to further examine the relationships between mechanical and physical properties of both structural-sized timber and small clear specimens within and between each of the two specimen sizes, determined in non-destructive and destructive tests. Three softwood species were included in the current study – Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Norway spruce and Sitka spruce (*Picea sitchensis* (Bong.) Carr). The relationships are also evaluated on an individual tree level to determine which approach to evaluating wood properties on a tree level shows better potential. The insights provided by quantifying those relationships between the different approaches will help with design of future experiments studying wood quality, as an additional aim of the study is to assess the different ways of evaluating timber quality with regard to specimen size and measurement approach (destructive vs. non-destructive). Information provided by the current study may also provide a link between historical results obtained by testing small clear specimens and newer approaches examining wood quality at the board level, enabling the reutilization of historical data in future research.

Material and methods

The material for this study was part of a larger research project looking at how silvicultural practice affects the wood properties (Krajnc et al 2019a, 2019b). Sixty individual mature trees (20 of each species) were felled and the first two 3-metre long logs per tree were taken and sawn into boards. The stands were located in the west of Ireland and were around 55 years old at the time of felling. Half of the trees came from regularly thinned stands and half from unmanaged stands. More stand-level information can be found in Krajnc et al (2019a, 2019b). Mean diameters at breast height of the sample trees were 30.2 cm for Douglas-fir (with a standard deviation SD of 7.6 cm), 33.2 cm for Norway spruce (SD = 9.8 cm) and 42.1 cm for Sitka spruce (SD = 11.3 cm). Before sawing, the outer border of the juvenile core of 15 growth rings was coloured white on the bottom face of each log. This marked area was then used to assess the proportion of juvenile wood in each board and categorize its radial position. Three different categories were used (no juvenile wood, more than 0% and less than 50%, more than 50%). A total of 1376 structural-sized boards were included in the current study, of which 271 were Douglas-fir, 368 Norway spruce and 737 Sitka spruce. The cross-sectional dimensions of the boards were 45 mm x 100 mm and they were 3000 mm long. The boards were kiln dried and their fundamental frequency was measured using a laser accelerometer Viscan (Microtec, Brixen, Italy). The moisture content was measured at the time of test for all boards of Douglas-fir and for a sub-sample of both spruce species. All dimensions were measured at the time of the vibration test. The boards were stored in a conditioning chamber at 20 ˚C and 65% relative humidity until a constant mass was attained. All boards were then tested in four-point bending over a span of 18 times the depth according to EN 408 (CEN, 2012) to determine the global MOE and bending strength. The global MOE is calculated using the relationship between applied force and measurements of mid-span deflection relative to the supports of the test piece in a four-point bending test. The moisture content at the time of testing was determined using EN 13183-1 (CEN, 2002) and all tested properties were adjusted to 12% moisture content using the equations provided by EN 384 (CEN, 2010). Immediately after the testing, a small clear specimen was extracted from the undamaged part of each board as close as possible to the fracture location. The specimens were of dimensions 20 mm x 20 mm x 300 mm and were randomly cut from the board cross section while ensuring that no knots or other defects were present. A total of 1337 specimens were extracted, of which 268 were Douglas-fir, 367 Norway spruce and 702 were Sitka spruce. Some structural-sized boards were too damaged by testing to provide a small clear specimen, leading to the smaller number of specimens than structural-sized boards. The specimens were conditioned further in the conditioning chamber until constant mass was attained, after which their acoustic velocity was measured in the longitudinal direction using a PL-200 ultrasound device (Proceq, Schwarzenbach, CH) using exponential transducers operating at a frequency of 54 kHz. The signal was excited using a voltage of 400V and the amplification gain used was 20x. All device parameters were kept the same for all tests and a special clamping device was constructed to keep the pressure of the transducers the same throughout all tests. Each measurement was recorded three times and the average time of flight was computed for each specimen. After measuring the dimensions of the specimens, they were tested in three-point bending over a span of 14 times the depth in accordance with the BS 373 (British Standards Institution, 1957).

The dynamic modulus of elasticity of boards $E_{dyn,boards}$ was derived from the fundamental frequency (f), board length (l) and whole board density (ρ_{board}). The value was corrected to 12% moisture content using the corrections provided by EN 384 (CEN, 2010), as moisture can have a considerable effect on the dynamic modulus of elasticity (Unterwieser and Schickhofer, 2011; Chan et al., 2011; Nocetti et al., 2015).

$$E_{dyn,boards} = 4l^2 f^2 \rho_{board} \qquad (1)$$

The dynamic modulus of elasticity of small clear specimens $E_{dyn,clears}$ was derived from the time of flight (t), specimen length (l) and specimen density (ρ_{clear}). Moisture content was measured on a subsample of the specimens and the variations were negligible, which is why the corrections for moisture content were not applied. The specimens had been conditioned in the conditioning chamber for several months before testing to achieve 12% moisture content.

$$E_{dyn,clears} = \left({}^{l}/_{t}\right)^2 \rho_{clear} \qquad (2)$$

All calculations and statistical analyses were carried out in the open-source environment R (R Core Team, 2018). Pearson's correlation coefficient and linear regression were used to analyse the relationships between the studied variables.

Results and Discussion

Mechanical and physical properties by specimen size

The mean mechanical and physical properties and their variation (quantified by coefficient of variation) for both specimen sizes are displayed in Table 1. Modulus of elasticity was found to be higher in structural-sized boards than in small clear specimens, while this trend was reversed when looking at bending strength. Density of clear wood appeared not to be influenced by the specimen size. There was less variation in bending strength in small clear specimens than in structural boards. The dynamic MOE was higher than the static MOE in both specimen sizes, although they both exhibited a similar degree of variation.

[Table 1 about here]

While the mechanical and physical properties examined in the current study were shown by previous studies to vary with various different factors (such as specimen size, climate, silvicultural management…), the values of mechanical and physical properties reported in the current study were mostly in the range of previously reported values for the same species (Lavers, 2002; Grottal et al., 2005; Verkasalo and Leban, 2002; Moore et al., 2009; Gardiner et al., 2011; Larsson et al., 1998). The one exception were mechanical and physical properties of Douglas-fir boards, which were slightly higher than previously reported (Henin et al., 2018).

Several past studies have reported similar trends in small clear specimens as found by the current study (Haines et al., 1996; Raymond et al., 2007; Baar et al., 2015). The differences between mechanical and physical properties of structural-sized boards and small clear specimens in the current study were most likely a consequence of a relatively high degree of heterogeneity found within a board or the different test setups (different span-to-depth ratios, loading characteristics or specimen size) used in bending. As shown by Brancheriau et al. (2002) in small clear specimens of six different species, the three-point bending test underestimated the value of the elastic modulus by 19% in comparison to four-point bending tests. Although the differences between structural-sized boards and small clear specimens in the current study are smaller than 19% and are closer to 10%, the study by Brancheriau et al. (2002) only tested small clear specimens and the results are therefore not directly comparable to the current study.

The differences found by the current study were likely partly dependant on the difference in span-to-depth ratios, as the link between span-to-depth ratios during testing and mechanical properties was confirmed by various past studies, including Sorn et al. (2011). They have demonstrated the non-linearity of the relationship between maximum values of MOE or MOR and span-to-depth ratios, showing the impact on MOR as less significant than on MOE. In general, higher values of span-to-depth ratios correspond to higher values of MOE and MOR. This could be the cause of differences in MOE between specimen sizes as found by the current study, as boards were tested with a higher span-to-depth ratio and had higher values of the elastic modulus. However, the differences in MOR were likely not a consequence of the span-to-depth ratios, as the opposite trend would be expected if this was true.

Hein et al. (2018) examined the differences in bending strength of small clear specimens of *Eucalyptus* between three- and four-point bending tests. Higher bending strengths were found when specimens of the same size were tested in three-point bending over the same span than when tested in four-point bending. In the current study, significantly higher differences were found in bending strength when comparing structural-sized boards and small clear specimens than what was reported by Hein et al. (2018). The higher differences were most likely due to the presence of knots in structural-sized board and the larger volume under test. This is in line with what was reported by Madsen (1992) on the effects of size and knots or other natural characteristics on mechanical properties of wood. In small clear specimens, the failure commonly takes place in the compression zone, progressing to a tension failure by lowering of the neutral axis of the specimen. In structural-sized boards, however, the failure more commonly occurs as a mixed-mode failure in the tension zone of the specimens due to the presence of knots or other natural characteristics.

As no single straight-forward explanation could be found for the differences in values of the examined properties in the current study, they were likely caused by a combination of factors discussed above.

The correlations of mechanical and physical properties across and within specimen size

Pearson's correlation coefficients of the examined properties for the three species can be seen in Table 2. In all three examined species, the correlations among the examined properties were in most cases stronger within the same specimen size than across specimen sizes. The relationship between dynamic MOE and static MOE was the strongest among the examined relationships in both specimen sizes across the three species. The elastic modulus and bending strength showed a stronger correlation in small clear specimens than in boards.

[Table 2 about here]

The mechanical and physical properties of both sizes correlated with each other to a varying degree. Similar correlations among mechanical and physical properties of boards in Norway spruce were reported by Høibø et al. (2014), although the correlation coefficients in the current study were slightly lower than in the mentioned study and are closer to what was reported by Gil-Moreno (2018). The correlations overall were lower in Sitka spruce than in Norway spruce.

Douglas-fir was found to have the lowest correlations between the examined properties of both specimen sizes. The correlations found between mechanical and physical properties of boards were higher in the current study than those reported by Moore et al. (2009) for Sitka spruce. This was most likely due to the significantly higher number of boards tested in the current study.

In mechanical and physical properties of small clear specimens, the highest correlations were found between the elastic modulus and bending strength in all three examined species, followed by correlation between bending strength and density. The lowest correlations were found between density and the elastic modulus. Similar values of correlations among mechanical and physical properties of small clear specimens were reported by Raymond et al. (2007) in *Pinus radiata* and by Baar et al. (2015) in five tropical species.

Mean mechanical and physical properties of individual trees

To further study the connection between mechanical and physical properties of both specimen sizes, mean values of the elastic modulus, bending strength and density of clear wood were computed for each tree in both structural sized boards and small clear samples. The relationship between the tree mean values of both specimen sizes is shown in Figure 1. Comparing individual tree mean values, relatively good relationships of the examined properties were found between both specimen sizes across all three grade-determining properties.

[Figure 1 about here]

As only looking at individual tree mean values can obscure the potential difference in variability of mechanical or physical properties, the within tree variability was examined using a coefficient of variation (Figure 2). Higher variability was found in the bending strength of boards than in small clear specimens, while the opposite trend was found in modulus of elasticity.

[Figure 2 about here]

In relation to the tree mean mechanical and physical properties, the current study found higher correlations between values measured on small clear samples and structural-sized timber compared to previous studies (Gil-Moreno, 2018). As Gil-Moreno (2018) used the same test methods on both specimen sizes as the current study, the difference is most likely to a difference in sampling of small clear specimens in relation to structural-sized boards, as in the latter study the small clear specimens were cut from a position higher up in the tree than the structural boards.

In general, the good relationships between the mean tree properties of both specimen sizes would indicate that in order to evaluate the mechanical or physical properties of an individual tree overall, either method could potentially be used. While clearwood density and elastic modulus appeared less sensitive whether small clear specimens or structural-sized boards are used for testing, bending strength of structural-sized samples can only be accurately evaluated on structural-sized timber. Similar variation was observed in both specimen sizes in the elastic modulus and clearwood density, while higher within tree variation was found in bending strength of boards than in small clear samples. This was presumably due to the effect of knots on the strength of individual boards.

Prediction of mechanical and physical properties of structural-sized boards from mechanical or physical properties of small clear specimens

A series of linear regression models was used to examine the possibility of predicting mechanical and physical properties of structural-sized boards from mechanical or physical properties of small clear specimens. The results of the analysis can be seen in Table 3. The best relationships were found between densities of clear wood in all three species (R^2 from 0.43 to 0.64). Overall, the relationships were higher in Norway spruce and Sitka spruce species than in Douglas-fir. Outside of densities, the relationships were relatively weak. No differences were found in the strength of any of the relationships when looking at either radial or longitudinal (first or second log) position of the samples.

[Table 3 about here]

While there appeared to be some degree of correlation between mechanical and physical properties across specimen sizes, an accurate estimation of the properties of structural-sized boards from the mechanical or physical properties of small clear specimens appears unlikely, with the exception of density of clear wood. A similar degree of within-tree variation was found by the current study in the elastic modulus and density in both specimen sizes (Figure 2), while more variability was found in bending strength of boards than in small clear specimens. The correlations of the examined properties between the two specimen sizes do not appear to be related to the within-tree variability of the properties, as the relationships between the examined properties of small clear samples and structural-sized boards were relatively weak when looking at the elastic modulus or bending strength and relatively good when looking at density. The relationships between mechanical and physical properties of both sizes were stronger in the current study in Norway spruce and Sitka spruce than was reported for loblolly pine by Butler et al. (2016). However, the strength of those relationships was lower for Douglas-fir timber than reported for loblolly pine. This indicates that the relationships were likely species dependent, but more research is needed to establish the cause of differences between species.

Prediction of mechanical and physical properties using the dynamic modulus of elasticity

The relationship between dynamic MOE and the examined wood properties was evaluated using a linear regression. The results for small clear specimens across the three species can be seen in Table 4. The highest R^2 when using dynamic modulus of elasticity for prediction was found in the modulus of elasticity (R^2 values from 0.53 to 0.77), followed by bending strength (R^2 values from 0.34 to 0.56) and density (R^2 values from 0.25 to 0.48). The strength of the relationships appeared to be species dependent. Douglas-fir exhibited lower strength of relationships between the examined properties than Norway spruce or Sitka spruce. The relationships were also examined with regard to radial and longitudinal position. When looking at the samples from either first or second log, no differences were found in the strength of the relationships. However, small differences in the strength of the relationships were found looking at different radial positions. Several of the relationships appeared to have improved with increasing radial position (increasing amount of juvenile wood). The improvements were not consistent with either species or any other recorded variables and appeared to be randomly distributed, therefore presumably a coincidence.

[Table 4 about here]

The results of the linear regression analysis for structural-sized boards of the three species can be found in Table 5. As in small clear specimens, the highest R^2 was found when predicting the elastic modulus. The correlation with bending strength and density varied by species. Overall, the strength of the relationships appeared to be again species dependent. Similar to small clear specimens, Douglas-fir exhibited lower strength of relationships between the examined properties than Norway spruce or Sitka spruce.

[Table 5 about here]

The strength of relationships between dynamic and static MOE in small clear specimens in the current study was slightly lower than previously reported values by Gil-Moreno (2018) across four different species, by Raymond et al. (2007) in radiata pine or in Sitka spruce (McLean et al., 2010). However, the relationships were better than reported in five tropical species as reported by Baar et al. (2015). The same observation applies to the correlation between dynamic MOE and static MOR of small clear specimens. The differences were most likely due to the different instruments or device settings used for determination of dynamic MOE of small clear specimens. The relationships also appeared to be species dependent.

In structural-sized boards, the values of R^2 overall were higher, implying that dynamic MOE reflected mechanical and physical properties better in boards than in clear specimens. This could also be a consequence of the two different methods used for determining the acoustic velocity, as resonance was used in boards and ultrasound velocity in clear specimens. The correlation of dynamic MOE and mechanical or physical properties of structural-sized boards were in line with previously reported values on the same species (Larsson et al., 1998; Moore et al., 2009; Vikram et al., 2011). The differences among species were less pronounced in structural-sized timber than in small clear samples, possibly implying that species had a smaller effect on the strength of the relationships in boards than in small clear specimens.

Conclusions

The current study found poor-to-moderate relationships between the mechanical or physical properties of structural-sized timber and small clear specimens. The correlations between specimen sizes appeared to be species dependent. Although the mechanical and physical properties correlated with one another overall, the degree of correlation varied by specimen size, testing method and the measurement approach (destructive vs. non-destructive). However, the mechanical and physical properties of both specimen sizes correlated quite well between themselves on the level of an individual tree. This implies that both specimen sizes could be used to compare relative quality of timber on an individual tree level, provided only one specimen size is used across the whole sample. In a similar fashion, non-destructive evaluation of specimens could present a viable alternative to destructive tests, depending on which material property is of interest and the level of estimation accuracy required. While the dynamic MOE reflected the static MOE relatively well, the relationship between dynamic MOE and static MOR was weaker in both specimen sizes. It is likely that the relationships could be generalized to other softwood species with similar ranges of density, elastic modulus and bending strength. Additionally, the examined relationships could be under the influence of either growing conditions or silvicultural practices, which could be examined in future studies. More research on hardwoods and more softwood species is also needed to establish the cause and the nature of the differences between species.

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Tables

Table 1: Mechanical properties of structural-sized boards and small clear specimens, displaying mean values and coefficients of variation (in brackets).

	Douglas-fir	***Norway spruce***	***Sitka spruce***
N_{boards}	271	368	737
$E_{m,boards}$	12370 (15)	9490 (20)	9920 (20)
$f_{m,boards}$	57 (30)	43 (30)	49 (25)
$\rho_{boards,clearwood}$	560 (10)	440 (10)	440 (10)
$E_{dyn,boards}$	14580 (15)	11520 (20)	11990 (20)
N_{clears}	268	367	702
$E_{m,clears}$	10960 (15)	8230 (25)	8180 (20)
$f_{m,clears}$	99 (15)	70 (20)	68 (20)
ρ_{clears}	560 (10)	440 (15)	440 (15)
$E_{dyn,clears}$	15210 (20)	11760 (25)	12030 (20)

Note: Elastic moduli and bending strength in *MPa*, density in kgm^{-3}.

Table 2: Correlation matrix of mechanical properties of structural-sized boards and small clear specimens of Douglas-fir, Norway spruce and Sitka spruce. Displaying Pearson's correlation coefficient above and p values below the diagonal.

Douglas-fir

$E_{m,boards}$	0.69	0.62	0.37	0.33	0.38	0.87	0.29
***	$f_{m,boards}$	0.55	0.2	0.24	0.37	0.64	0.14
***	***	ρ_{boards}	0.3	0.38	0.66	0.71	0.24
***	**	***	$E_{m,clears}$	0.82	0.58	0.46	0.73
***	***	***	***	$f_{m,clears}$	0.68	0.37	0.58
***	***	***	***	***	ρ_{clears}	0.44	0.5
***	***	***	***	***	***	$E_{dyn,boards}$	0.39
***	*	***	***	***	***	***	$E_{dyn,clears}$

Norway spruce

$E_{m,boards}$	0.77	0.69	0.57	0.57	0.63	0.91	0.61
***	$f_{m,boards}$	0.61	0.46	0.51	0.53	0.75	0.46
***	***	ρ_{boards}	0.58	0.59	0.76	0.74	0.51
***	***	***	$E_{m,clears}$	0.87	0.77	0.61	0.87
***	***	***	***	$f_{m,clears}$	0.79	0.59	0.75
***	***	***	***	***	ρ_{clears}	0.64	0.7
***	***	***	***	***	***	$E_{dyn,boards}$	0.64
***	***	***	***	***	***	***	$E_{dyn,clears}$

Sitka spruce

$E_{m,boards}$	0.69	0.54	0.57	0.51	0.48	0.91	0.59
***	$f_{m,boards}$	0.52	0.37	0.46	0.41	0.67	0.35
***	***	ρ_{boards}	0.48	0.62	0.8	0.57	0.39
***	***	***	$E_{m,clears}$	0.8	0.63	0.64	0.87
***	***	***	***	$f_{m,clears}$	0.77	0.56	0.68
***	***	***	***	***	ρ_{clears}	0.5	0.54
***	***	***	***	***	***	$E_{dyn,boards}$	0.66
***	***	***	***	***	***	***	$E_{dyn,clears}$

*Note: '***' $p < .001$, '**' $p < .01$, '*' $p < .05$*

Table 3: Results of linear regression analysis (y = ax + b), using mechanical properties of small clear specimens for predicting mechanical properties of structural-sized boards.

y	x	a (± StE)	b (± StE)	R^2
Douglas-fir				
ρ_{boards}	ρ_{clears}	0.7 (0.05)	194 (25)	0.43
ρ_{boards}	$E_{m,clears}$	0.009 (0.002)	464 (20)	0.09
ρ_{boards}	$f_{m,clears}$	1 (0.2)	440 (20)	0.15
$E_{m,boards}$	ρ_{clears}	16 (2)	3559 (1320)	0.15
$E_{m,boards}$	$E_{m,clears}$	0.5 (0.07)	7366 (770)	0.14
$E_{m,boards}$	$f_{m,clears}$	43 (8)	8083 (770)	0.11
$f_{m,boards}$	ρ_{clears}	0.1 (0.02)	-13 (10)	0.14
$f_{m,boards}$	$E_{m,clears}$	0.002 (6e-04)	35 (5)	0.04
$f_{m,boards}$	$f_{m,clears}$	0.3 (0.06)	31 (5)	0.06
Norway spruce				
ρ_{boards}	ρ_{clears}	0.6 (0.03)	155 (10)	0.57
ρ_{boards}	$E_{m,clears}$	0.02 (0.001)	300 (10)	0.34
ρ_{boards}	$f_{m,clears}$	2 (0.1)	293 (10)	0.35
$E_{m,boards}$	ρ_{clears}	18 (1)	1452 (530)	0.39
$E_{m,boards}$	$E_{m,clears}$	0.6 (0.04)	4840 (350)	0.33
$E_{m,boards}$	$f_{m,clears}$	69 (5)	4657 (370)	0.33
$f_{m,boards}$	ρ_{clears}	0.1 (0.009)	-3 (4)	0.28
$f_{m,boards}$	$E_{m,clears}$	0.003 (3e-04)	17 (3)	0.22
$f_{m,boards}$	$f_{m,clears}$	0.4 (0.04)	14 (3)	0.27
Sitka spruce				
ρ_{boards}	ρ_{clears}	0.7 (0.02)	128 (9)	0.64
ρ_{boards}	$E_{m,clears}$	0.01 (0.001)	317 (8)	0.24
ρ_{boards}	$f_{m,clears}$	2 (0.1)	278 (8)	0.39
$E_{m,boards}$	ρ_{clears}	16 (1)	2857 (480)	0.24
$E_{m,boards}$	$E_{m,clears}$	0.7 (0.04)	4565 (290)	0.33
$E_{m,boards}$	$f_{m,clears}$	73 (5)	4963 (320)	0.26
$f_{m,boards}$	ρ_{clears}	0.09 (0.008)	9 (3)	0.17
$f_{m,boards}$	$E_{m,clears}$	0.003 (3e-04)	25 (2)	0.14
$f_{m,boards}$	$f_{m,clears}$	0.4 (0.03)	19 (2)	0.21

Table 4: Results of linear regression analysis (y = ax + b), using the dynamic MOE of small clear specimens for prediction of mechanical properties of clear specimens.

y	x	a (± StE)	b (± StE)	R^2
Douglas-fir				
ρ_{clears}	$E_{dyn,clears}$	0.009 (0.001)	428 (15)	0.25
$E_{m,clears}$	$E_{dyn,clears}$	0.4 (0.03)	4331 (390)	0.53
$f_{m,clears}$	$E_{dyn,clears}$	0.003 (3e-04)	50 (4)	0.34
Norway spruce				
ρ_{clears}	$E_{dyn,clears}$	0.02 (9e-04)	256 (10)	0.48
$E_{m,clears}$	$E_{dyn,clears}$	0.6 (0.02)	1366 (210)	0.75
$f_{m,clears}$	$E_{dyn,clears}$	0.004 (2e-04)	21 (2)	0.56
Sitka spruce				
ρ_{clears}	$E_{dyn,clears}$	0.01 (7e-04)	291 (9)	0.31
$E_{m,clears}$	$E_{dyn,clears}$	0.6 (0.01)	1375 (150)	0.77
$f_{m,clears}$	$E_{dyn,clears}$	0.004 (1e-04)	25 (2)	0.47

Table 5: Results of linear regression analysis (y = ax + b), using the dynamic MOE of boards for prediction of mechanical properties of boards.

y	x	a (± StE)	b (± StE)	R^2
Douglas-fir				
ρ_{boards}	$E_{dyn,boards}$	0.01 (9e-04)	350 (13)	0.49
$E_{m,boards}$	$E_{dyn,boards}$	0.7 (0.03)	1632 (380)	0.75
$f_{m,boards}$	$E_{dyn,boards}$	0.004 (3e-04)	-8 (5)	0.42
Norway spruce				
ρ_{boards}	$E_{dyn,boards}$	0.02 (8e-04)	240 (9)	0.56
$E_{m,boards}$	$E_{dyn,boards}$	0.7 (0.02)	1245 (200)	0.83
$f_{m,boards}$	$E_{dyn,boards}$	0.004 (2e-04)	-3 (2)	0.56
Sitka spruce				
ρ_{boards}	$E_{dyn,boards}$	0.01 (6e-04)	295 (8)	0.32
$E_{m,boards}$	$E_{dyn,boards}$	0.7 (0.01)	1078 (150)	0.84
$f_{m,boards}$	$E_{dyn,boards}$	0.004 (1e-04)	6 (2)	0.45

Figures

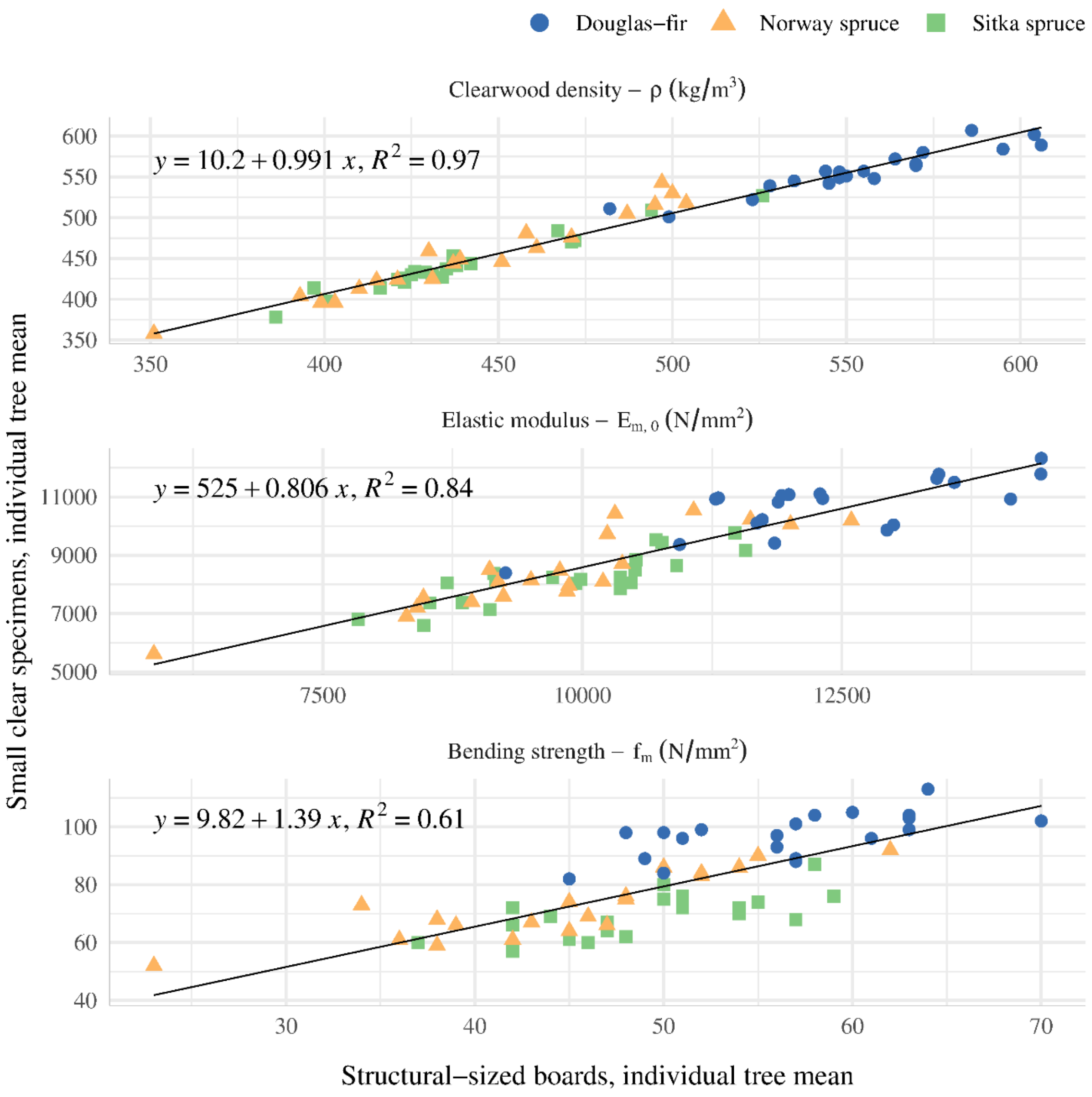

Figure 1: Mean tree mechanical properties, determined on structural-sized boards versus mechanical properties of small clears.

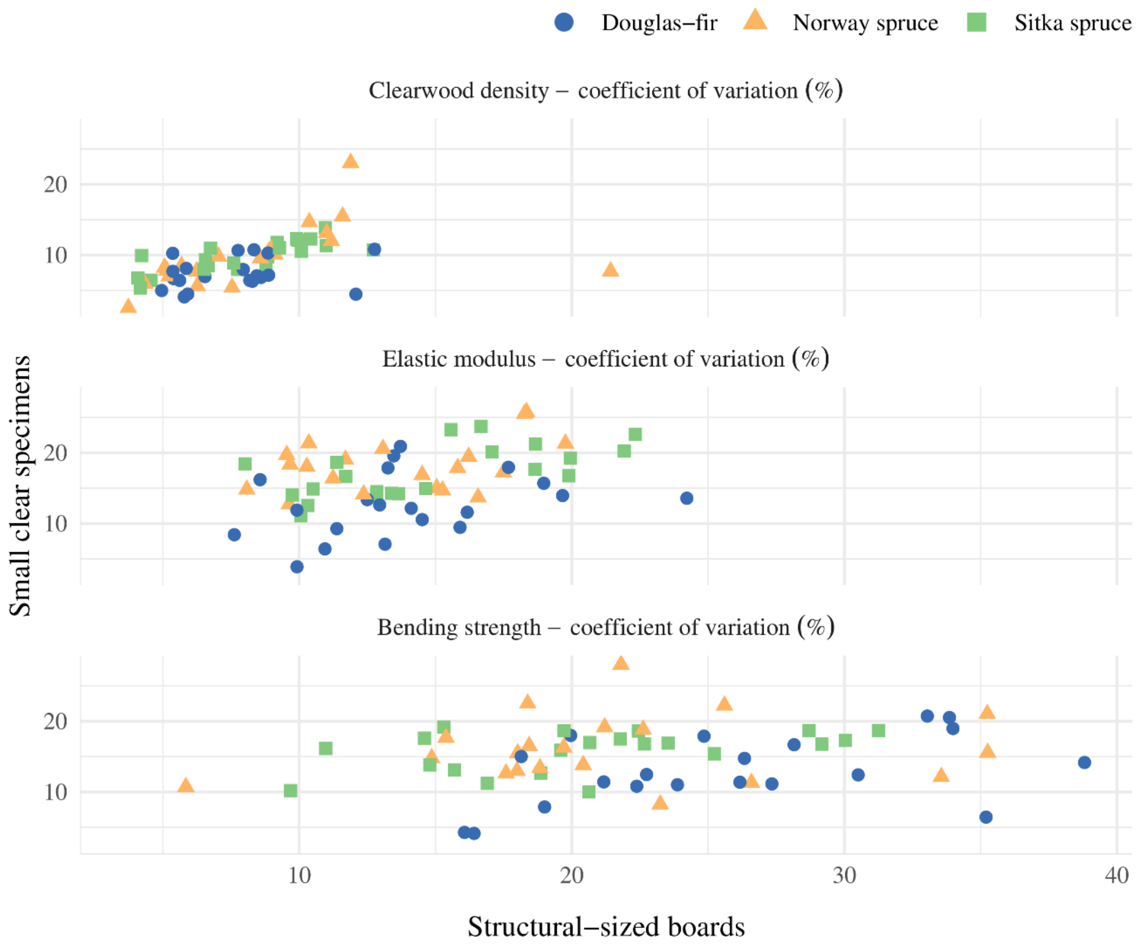

Figure 2: Within tree variability of mechanical properties by individual trees, displaying coefficient of variation.