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1 Relationships between wood properties of small clear specimens and 2 structural-sized boards in three softwood species

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11 **Abstract**

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

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

30 **Introduction**

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

37 Research on wood mechanical properties has been historically carried out on small clear
38 specimens. Due to their size they are straightforward to obtain, fast to condition and easy to
39 test in bending, for example. A number of different standards have been developed to
40 standardise the testing procedures of small clear specimens (BS 373 (British Standards
41 Institution, 1957), ASTM D143-14 (American Society for Testing Materials, 2014), ISO
42 13061-4 (International Organization for Standardization, 2014)). Testing of small clear
43 specimens has one main distinction over testing of larger specimens, as it excludes the effect
44 of various defects (knots, slope of grain, resin pockets...) on the properties. It is still a
45 frequently used approach among forestry and wood science researchers seeking to examine the
46 cause-effect relationship between various silvicultural treatments, genotypes, site quality, etc.
47 and wood properties.

48 However, the end product is almost never a small clear specimen, but a structural-sized
49 board with all the material heterogeneity found in wood. Testing structural-sized timber in
50 bending requires more resources and time than testing small clear specimens. The structural-
51 sized boards are also harder to transport, take longer to condition and require more expensive

52 specialized equipment to perform the tests. Madsen (1992) suggested that small clear
53 specimens and structural-sized boards should be considered as two different materials when
54 looking at strength properties from an engineering perspective due to the failure initiation
55 location. While using small clear specimens for derivation of reliable strength properties was
56 deemed unsuitable by Madsen (1992), he also recognized the potential of linking properties of
57 small clear specimens to structural-sized timber with more accurate adjustment factors or better
58 analysis methods.

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

70 A study by Gil-Moreno (2018) examined the relationships between properties of structural
71 timber and the corresponding clear specimens across four different species, Noble fir (*Abies*
72 *procera* Rehd.), Norway spruce (*Picea abies* (L.) H. Karst.), Western red cedar (*Thuja plicata*
73 Don ex D.Don) and Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). A relatively good
74 relationship ($R^2 = 0.63$) was reported overall between the moduli of elasticity of both sizes,
75 with structural-sized boards showing on average 20% higher stiffness than small clear
76 specimens. Slightly stronger relationships were reported when comparing the mean stiffness of

77 individual trees ($R^2 = 0.68$), while a lower correlation was found ($R^2 = 0.35$) overall when
78 comparing the mean bending strength of individual trees. The same study also investigated the
79 use of dynamic MOE for prediction of static MOE and MOR in both specimen sizes. The
80 dynamic elastic modulus is determined acoustically by measuring the wave velocity as it travels
81 through the board and is commonly used to estimate mechanical/physical properties in a non-
82 destructive way. The values of dynamic MOE in both small clear specimens and structural-
83 sized boards were higher than the static MOE. The correlation between static and dynamic
84 MOE was found to be relatively strong in both specimen sizes ($R^2 = 0.88$ in small clear
85 specimens, $R^2 = 0.90$ in boards). The relationships between dynamic MOE and static MOR
86 were weaker ($R^2 = 0.57$ in small clear specimens, $R^2 = 0.43$ in boards). In addition, an overall
87 correlation of $R = 0.50$ was reported between density of clear wood and static MOR in boards.

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

96 The relationships between dynamic and static MOE of structural-sized boards were reported
97 as relatively good by several studies across multiple species and specimen sizes (Larsson et al.,
98 1998; Divos and Tanaka, 2005; Yang, 2015; Vikram et al., 2011; Simic et al., 2019), coinciding
99 with a rise in the use of machine grading and non-destructive evaluation of timber over the last
100 two decades. The correlation between static and dynamic MOE was also reported to be

101 relatively good in small clear specimens across several species (Raymond et al., 2007; Haines
102 et al., 1996).

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

117 **Material and methods**

118 The material for this study was part of a larger research project looking at how silvicultural
119 practice affects the wood properties (Krajnc et al 2019a, 2019b). Sixty individual mature trees
120 (20 of each species) were felled and the first two 3-metre long logs per tree were taken and
121 sawn into boards. The stands were located in the west of Ireland and were around 55 years old
122 at the time of felling. Half of the trees came from regularly thinned stands and half from
123 unmanaged stands. More stand-level information can be found in Krajnc et al (2019a, 2019b).
124 Mean diameters at breast height of the sample trees were 30.2 cm for Douglas-fir (with a

125 standard deviation SD of 7.6 cm), 33.2 cm for Norway spruce (SD = 9.8 cm) and 42.1 cm for
126 Sitka spruce (SD = 11.3 cm). Before sawing, the outer border of the juvenile core of 15 growth
127 rings was coloured white on the bottom face of each log. This marked area was then used to
128 assess the proportion of juvenile wood in each board and categorize its radial position. Three
129 different categories were used (no juvenile wood, more than 0% and less than 50%, more than
130 50%). A total of 1376 structural-sized boards were included in the current study, of which 271
131 were Douglas-fir, 368 Norway spruce and 737 Sitka spruce. The cross-sectional dimensions of
132 the boards were 45 mm x 100 mm and they were 3000 mm long. The boards were kiln dried
133 and their fundamental frequency was measured using a laser accelerometer Viscan (Microtec,
134 Brixen, Italy). The moisture content was measured at the time of test for all boards of Douglas-
135 fir and for a sub-sample of both spruce species. All dimensions were measured at the time of
136 the vibration test. The boards were stored in a conditioning chamber at 20 °C and 65% relative
137 humidity until a constant mass was attained. All boards were then tested in four-point bending
138 over a span of 18 times the depth according to EN 408 (CEN, 2012) to determine the global
139 MOE and bending strength. The global MOE is calculated using the relationship between
140 applied force and measurements of mid-span deflection relative to the supports of the test piece
141 in a four-point bending test. The moisture content at the time of testing was determined using
142 EN 13183-1 (CEN, 2002) and all tested properties were adjusted to 12% moisture content using
143 the equations provided by EN 384 (CEN, 2010). Immediately after the testing, a small clear
144 specimen was extracted from the undamaged part of each board as close as possible to the
145 fracture location. The specimens were of dimensions 20 mm x 20 mm x 300 mm and were
146 randomly cut from the board cross section while ensuring that no knots or other defects were
147 present. A total of 1337 specimens were extracted, of which 268 were Douglas-fir, 367 Norway
148 spruce and 702 were Sitka spruce. Some structural-sized boards were too damaged by testing
149 to provide a small clear specimen, leading to the smaller number of specimens than structural-

150 sized boards. The specimens were conditioned further in the conditioning chamber until
151 constant mass was attained, after which their acoustic velocity was measured in the longitudinal
152 direction using a PL-200 ultrasound device (Proceq, Schwarzenbach, CH) using exponential
153 transducers operating at a frequency of 54 kHz. The signal was excited using a voltage of 400V
154 and the amplification gain used was 20x. All device parameters were kept the same for all tests
155 and a special clamping device was constructed to keep the pressure of the transducers the same
156 throughout all tests. Each measurement was recorded three times and the average time of flight
157 was computed for each specimen. After measuring the dimensions of the specimens, they were
158 tested in three-point bending over a span of 14 times the depth in accordance with the BS 373
159 (British Standards Institution, 1957).

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

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

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

$$E_{dyn,clears} = \left(\frac{l}{t}\right)^2 \rho_{clear} \quad (2)$$

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

173 **Results and Discussion**

174 **Mechanical and physical properties by specimen size**

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

182 [Table 1 about here]

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

190 Several past studies have reported similar trends in small clear specimens as found by the
191 current study (Haines et al., 1996; Raymond et al., 2007; Baar et al., 2015). The differences
192 between mechanical and physical properties of structural-sized boards and small clear
193 specimens in the current study were most likely a consequence of a relatively high degree of

194 heterogeneity found within a board or the different test setups (different span-to-depth ratios,
195 loading characteristics or specimen size) used in bending. As shown by Brancheriau et al.
196 (2002) in small clear specimens of six different species, the three-point bending test
197 underestimated the value of the elastic modulus by 19% in comparison to four-point bending
198 tests. Although the differences between structural-sized boards and small clear specimens in
199 the current study are smaller than 19% and are closer to 10%, the study by Brancheriau et al.
200 (2002) only tested small clear specimens and the results are therefore not directly comparable
201 to the current study.

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

212 Hein et al. (2018) examined the differences in bending strength of small clear specimens of
213 *Eucalyptus* between three- and four-point bending tests. Higher bending strengths were found
214 when specimens of the same size were tested in three-point bending over the same span than
215 when tested in four-point bending. In the current study, significantly higher differences were
216 found in bending strength when comparing structural-sized boards and small clear specimens
217 than what was reported by Hein et al. (2018). The higher differences were most likely due to
218 the presence of knots in structural-sized board and the larger volume under test. This is in line

219 with what was reported by Madsen (1992) on the effects of size and knots or other natural
220 characteristics on mechanical properties of wood. In small clear specimens, the failure
221 commonly takes place in the compression zone, progressing to a tension failure by lowering of
222 the neutral axis of the specimen. In structural-sized boards, however, the failure more
223 commonly occurs as a mixed-mode failure in the tension zone of the specimens due to the
224 presence of knots or other natural characteristics.

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

228

229 **The correlations of mechanical and physical properties across and within specimen** 230 **size**

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

237 [Table 2 about here]

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

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

248 In mechanical and physical properties of small clear specimens, the highest correlations
249 were found between the elastic modulus and bending strength in all three examined species,
250 followed by correlation between bending strength and density. The lowest correlations were
251 found between density and the elastic modulus. Similar values of correlations among
252 mechanical and physical properties of small clear specimens were reported by Raymond et al.
253 (2007) in *Pinus radiata* and by Baar et al. (2015) in five tropical species.

254

255 **Mean mechanical and physical properties of individual trees**

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

262 [Figure 1 about here]

263 As only looking at individual tree mean values can obscure the potential difference in
264 variability of mechanical or physical properties, the within tree variability was examined using
265 a coefficient of variation (Figure 2). Higher variability was found in the bending strength of

266 boards than in small clear specimens, while the opposite trend was found in modulus of
267 elasticity.

268 [Figure 2 about here]

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

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

285

286 **Prediction of mechanical and physical properties of structural-sized boards from** 287 **mechanical or physical properties of small clear specimens**

288 A series of linear regression models was used to examine the possibility of predicting
289 mechanical and physical properties of structural-sized boards from mechanical or physical
290 properties of small clear specimens. The results of the analysis can be seen in Table 3. The

291 best relationships were found between densities of clear wood in all three species (R^2 from
292 0.43 to 0.64). Overall, the relationships were higher in Norway spruce and Sitka spruce species
293 than in Douglas-fir. Outside of densities, the relationships were relatively weak. No
294 differences were found in the strength of any of the relationships when looking at either radial
295 or longitudinal (first or second log) position of the samples.

296

297 [Table 3 about here]

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

313

314 **Prediction of mechanical and physical properties using the dynamic modulus of**
315 **elasticity**

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

330 [Table 4 about here]

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

337 [Table 5 about here]

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

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

355

356 **Conclusions**

357 The current study found poor-to-moderate relationships between the mechanical or physical
358 properties of structural-sized timber and small clear specimens. The correlations between
359 specimen sizes appeared to be species dependent. Although the mechanical and physical
360 properties correlated with one another overall, the degree of correlation varied by specimen
361 size, testing method and the measurement approach (destructive vs. non-destructive). However,
362 the mechanical and physical properties of both specimen sizes correlated quite well between

363 themselves on the level of an individual tree. This implies that both specimen sizes could be
364 used to compare relative quality of timber on an individual tree level, provided only one
365 specimen size is used across the whole sample. In a similar fashion, non-destructive evaluation
366 of specimens could present a viable alternative to destructive tests, depending on which
367 material property is of interest and the level of estimation accuracy required. While the dynamic
368 MOE reflected the static MOE relatively well, the relationship between dynamic MOE and
369 static MOR was weaker in both specimen sizes. It is likely that the relationships could be
370 generalized to other softwood species with similar ranges of density, elastic modulus and
371 bending strength. Additionally, the examined relationships could be under the influence of
372 either growing conditions or silvicultural practices, which could be examined in future studies.
373 More research on hardwoods and more softwood species is also needed to establish the cause
374 and the nature of the differences between species.

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476

477 **Tables**

478

479 Table 1: Mechanical properties of structural-sized boards and small clear specimens, displaying mean values and

480 coefficients of variation (in brackets).

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

481

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

482

483

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

<i>Douglas-fir</i>							
<i>E_{m,boards}</i>	0.69	0.62	0.37	0.33	0.38	0.87	0.29
***	<i>f_{m,boards}</i>	0.55	0.2	0.24	0.37	0.64	0.14
***	***	<i>ρ_{boards}</i>	0.3	0.38	0.66	0.71	0.24
***	**	***	<i>E_{m,clears}</i>	0.82	0.58	0.46	0.73
***	***	***	***	<i>f_{m,clears}</i>	0.68	0.37	0.58
***	***	***	***	***	<i>ρ_{clears}</i>	0.44	0.5
***	***	***	***	***	***	<i>E_{dyn,boards}</i>	0.39
***	*	***	***	***	***	***	<i>E_{dyn,clears}</i>
<i>Norway spruce</i>							
<i>E_{m,boards}</i>	0.77	0.69	0.57	0.57	0.63	0.91	0.61
***	<i>f_{m,boards}</i>	0.61	0.46	0.51	0.53	0.75	0.46
***	***	<i>ρ_{boards}</i>	0.58	0.59	0.76	0.74	0.51
***	***	***	<i>E_{m,clears}</i>	0.87	0.77	0.61	0.87
***	***	***	***	<i>f_{m,clears}</i>	0.79	0.59	0.75
***	***	***	***	***	<i>ρ_{clears}</i>	0.64	0.7
***	***	***	***	***	***	<i>E_{dyn,boards}</i>	0.64
***	***	***	***	***	***	***	<i>E_{dyn,clears}</i>
<i>Sitka spruce</i>							
<i>E_{m,boards}</i>	0.69	0.54	0.57	0.51	0.48	0.91	0.59
***	<i>f_{m,boards}</i>	0.52	0.37	0.46	0.41	0.67	0.35
***	***	<i>ρ_{boards}</i>	0.48	0.62	0.8	0.57	0.39
***	***	***	<i>E_{m,clears}</i>	0.8	0.63	0.64	0.87
***	***	***	***	<i>f_{m,clears}</i>	0.77	0.56	0.68
***	***	***	***	***	<i>ρ_{clears}</i>	0.5	0.54
***	***	***	***	***	***	<i>E_{dyn,boards}</i>	0.66
***	***	***	***	***	***	***	<i>E_{dyn,clears}</i>

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

487

488

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

y	x	a (\pm StE)	b (\pm 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

491

492

493

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

496

y	x	a (\pm StE)	b (\pm 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

497

498

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

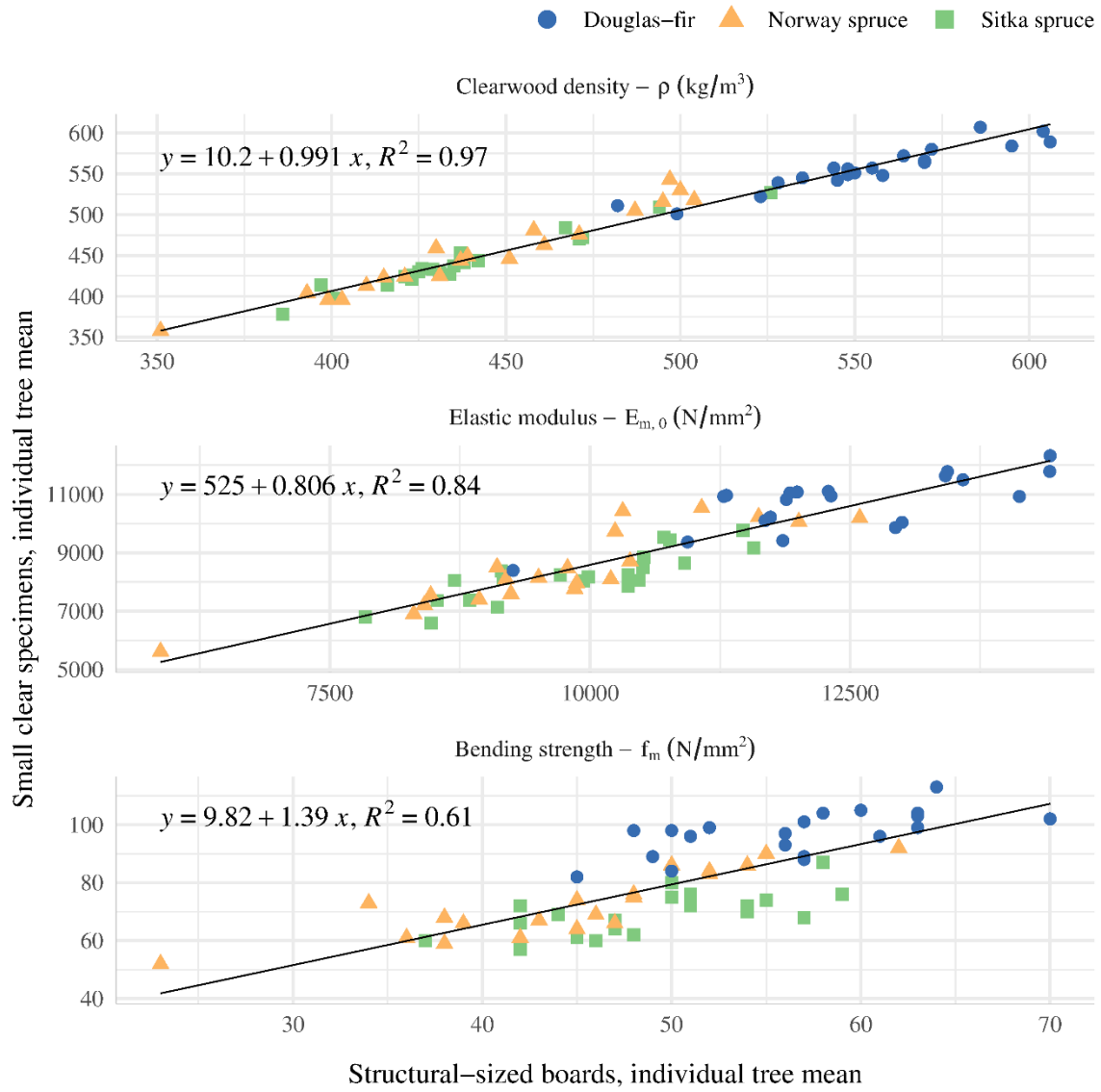
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y	x	a (\pm StE)	b (\pm StE)	R ²
Douglas-fir				
ρ_{boards}	$E_{dyn,boards}$	0.01 (9e-04)	350 (13)	0.49
$E_{m,boards}$	$E_{dyn,boards}$	0.7 (0.03)	1632 (380)	0.75
$f_{m,boards}$	$E_{dyn,boards}$	0.004 (3e-04)	-8 (5)	0.42
Norway spruce				
ρ_{boards}	$E_{dyn,boards}$	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

502

503

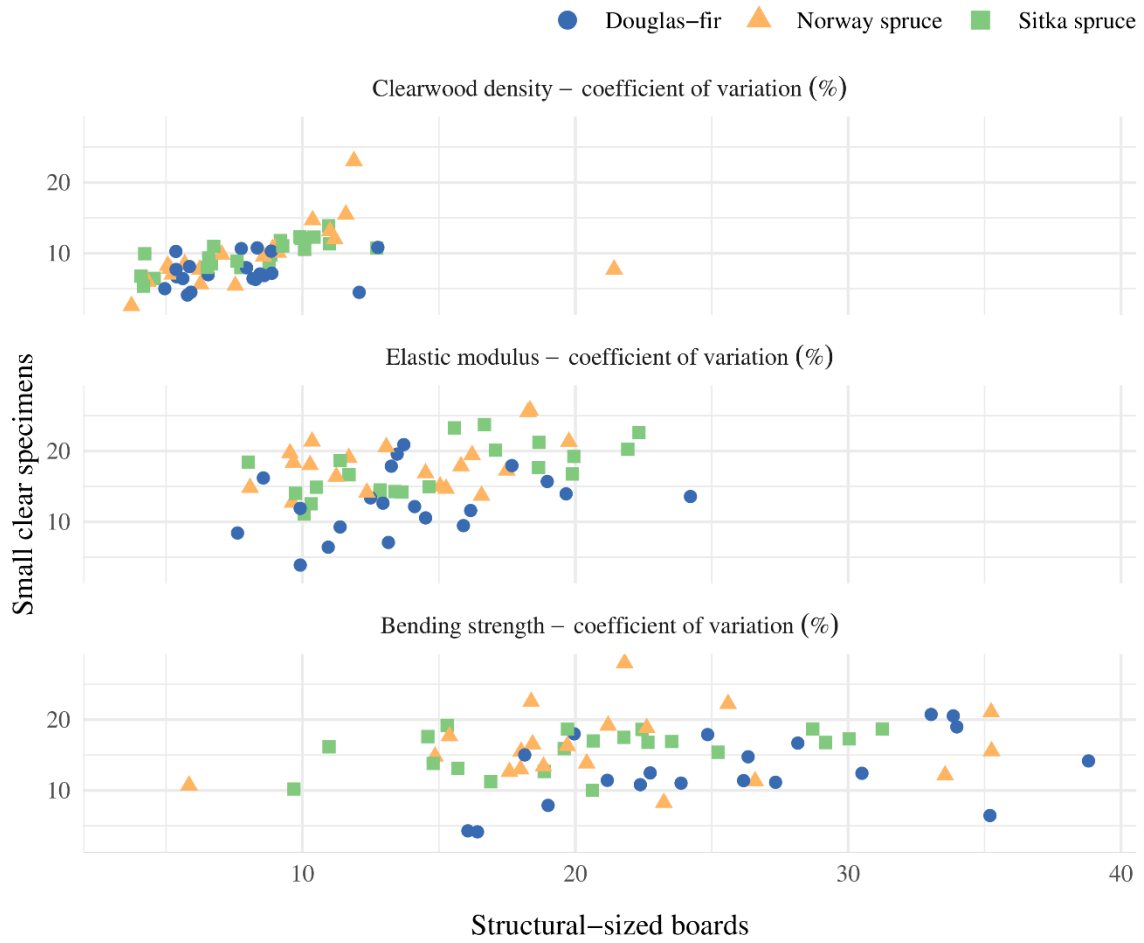
504 **Figures**
505



506

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

509



510

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

512