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1 **Some aspects of beech biomechanics: juvenile wood properties,**
2 **sapwood pre-stress and growth forces.**

3
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13
14 **Keywords**

15 Beech; Growth stress; Wood properties; Variability; Radial variation

16 **Abstract**

17 The building of a tree is the result of wood growth through successive division, expansion and
18 maturation of living cells at the periphery of the trunk and branches. During this process,
19 diameter growth is combined with sapwood pre-stress to allow posture control by the generation
20 of growth forces in the living wood cells. These mechanical aspects of tree building can be
21 characterised at each peripheral position by parameters describing the amount of material
22 produced, wood rigidity and the strain induced by the maturation process. In-situ assessment of
23 maturation strains at the trunk periphery of beech trees, combined with laboratory
24 measurements of ring width (*RW*), wood density (*D*) and wood specific modulus (*SM*), was
25 used to examine biomechanical aspects of juvenility corresponding to young stages of the tree,
26 as well as the correlation or trade-off between sapwood pre-stressing and the generation of
27 forces in the living wood layer used to control tree posture. The radial variations of *RW*, *D* and
28 *SM*, averaged over 86 trees, were close to the “typical radial pattern” of juvenile wood for
29 softwood plantation trees: decrease in *RW* and increase in *D* and *SM* from pith to bark in the
30 juvenile phase. But *D* only increased in the very first rings, then remained more or less constant.
31 Furthermore, for all three parameters there were many discrepancies in the pattern of variation
32 between trees and even between plots. This is a good indication that the mechanical juvenility
33 of the wood was more related to the biomechanical conditions experienced by the trees in the
34 young ages than to the age of the tree as such (which is the case for fibre length). The level of
35 pre-stress and posture control forces were strongly dependent on the maturation strain as the
36 first explanatory factor. But pre-stress is independent of *RW*, whereas posture control force is
37 strongly dependent on this growth parameter. This opens the way to trade-offs between these
38 two biomechanical functions of wood fibres.

39

40 **1. Introduction**

41 Wood growth is the process used for tree building (Thibaut 2019) including simultaneously
42 primary growth by elongation or creation of twigs (bud role) and secondary growth by
43 thickening of existing woody axes (cambium role). Primary growth is mostly assessed by the
44 trunk slenderness relating primary growth (HT, total height) to secondary growth (DBH,
45 diameter at trunk basis) at each growth step. Trunk, as a first-order axis, plays the major role in
46 tree biomechanics and its building process is the most studied, mainly through secondary
47 growth (Fournier et al 1991, Thibaut et al 2001, Alméras & Clair 2016). The variation of growth
48 parameters characterizing wood structure and properties is dependent on tree ontogeny and
49 adaptation to changes in the environment of the tree during its life. Juvenility, in particular,
50 describes the evolution of wood parameters during the early years of tree life. But the
51 environment of the tree (access to light, wind influence, etc.) also changes during the young
52 period of tree growth and mechanical adaptation of wood growth occurs in answer to these
53 changes. In this paper, the data obtained on a large panel of beech trees in the context of a
54 European collaborative program “Stresses in beech” (Becker & Beimgraben 2001) will be
55 exploited to characterize the patterns of radial variation of wood properties. The study will be
56 preceded by the presentation of typical patterns observed in trees according to the literature.

57 **2. State of the art on the spatial variations of wood properties**

58 **2.1 Secondary growth descriptors and mechanical parameters**

59 Secondary growth performed by living wood cells (Raven et al 2007, Savidge 2003, Thibaut
60 2019) consists of the following successive steps: division of the cambium stem cells into
61 daughter cells; expansion of daughter cells until the end of primary wall formation; thickening
62 of the fibre (or tracheid) cell walls until the end of secondary wall formation; lignification of
63 the whole cell wall, including the compound middle lamella; programmed cell death.

64 During this living period of wood cells, basic wood features are achieved. They can be described
65 by ring width (RW in m), result of combined cell division and expansion, density (D in kg/m^3)
66 expressing cell wall thickening, specific modulus (SM in Mm^2/s^2) determined by the cellulose
67 micro-fibril organisation in the cell wall, and maturation strain (α_m , no unit) resulting from the
68 final polymerization of lignin and other macromolecular processes (Thibaut & Gril 2021).

69 Some useful mechanical parameters can be calculated from these basic growth descriptors for
70 an elementary growth unit (Fig. 1):

71 RW (mm): local ring width, used as secondary growth layer width Δr ;

72 $RS = 10 \cdot \Delta\theta \cdot R \cdot RW$ (in cm^2): ring portion surface for a distance to pith R and angular sector $\Delta\theta$;

73 $RM = RS \cdot D$ (in kg/m): mass per unit length of the ring portion;

74 $MOE = SM \cdot D$ (in GPa): longitudinal modulus of elasticity;

75 $\sigma_m = MOE \cdot \alpha_m$ (in MPa): maturation stress, the pre-stressing of the peripheral layer in the
76 sapwood, mostly made of dead fibres or tracheids;

77 $RF = 100 \cdot RS \cdot \sigma_m$ (RF in N): local ring force.

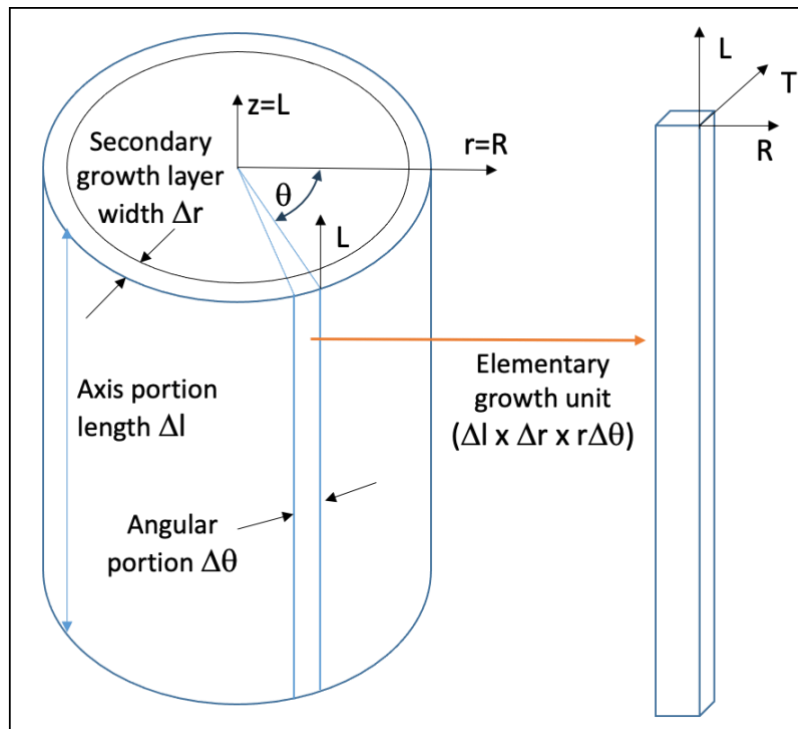


Fig. 1: Local elementary growth unit in a trunk.

(L, r, θ) : cylindrical coordinate system associated to the trunk

(L, R, T): Cartesian coordinate system associated to the elementary growth unit

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83 2.2. Secondary growth variations within a trunk section.

84 All secondary growth descriptors display spatial variation within a portion of trunk, in the 3
85 cylindrical directions: transversely across radii (Tar), around the perimeter (Ap) and
86 longitudinally along the stem (Las), called variation “TarApLas” within the tree by Savidge
87 (Savidge 2003). These variations are linked either to the effect of tree age (called juvenility) or
88 to the adaption of the wood growth to external conditions (climate, light availability, accidental
89 leaning ...).

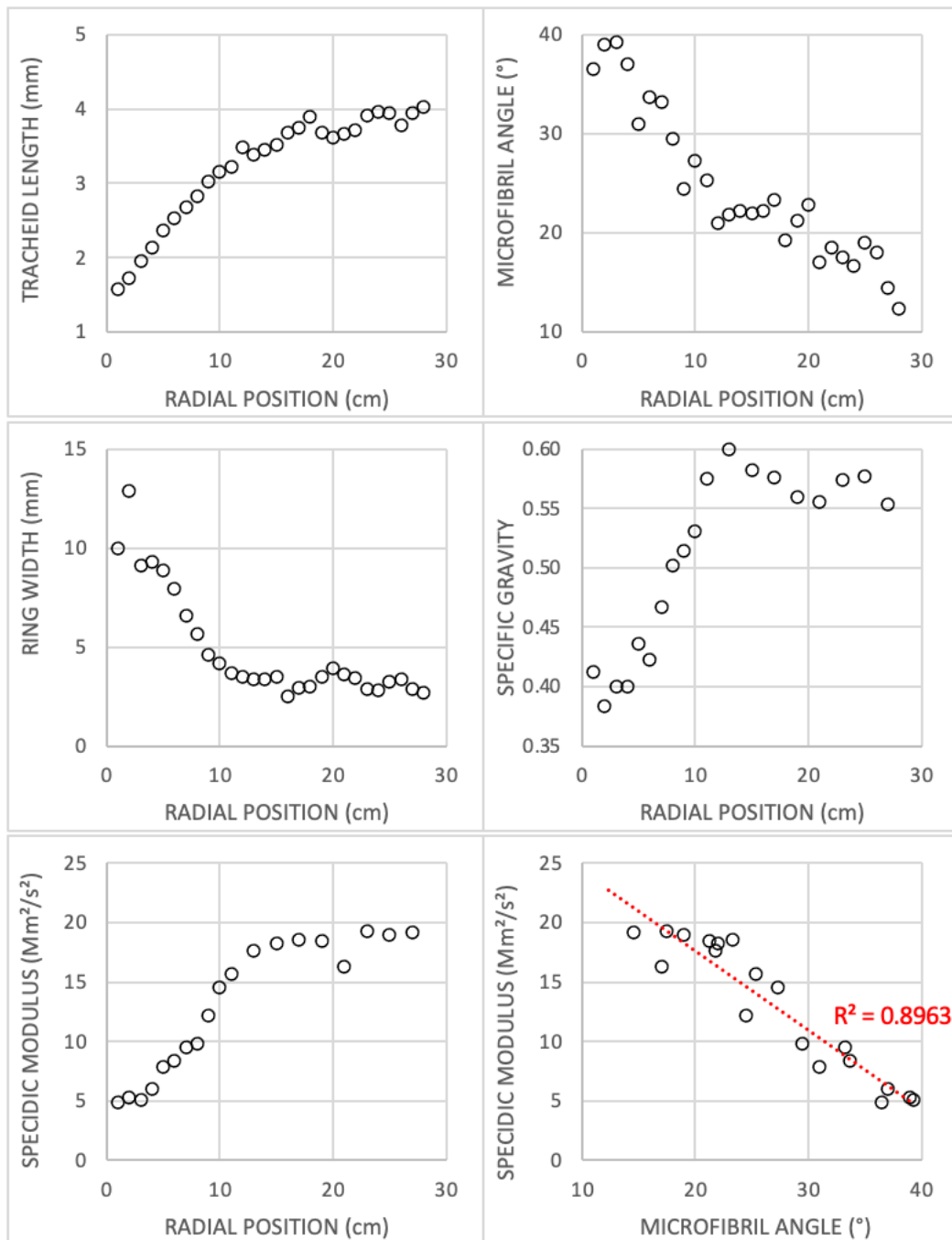
90 Variations around the perimeter in a given ring are related to a mechanical adaption in the
91 control of posture, i.e. oblique growth in a given direction (in the case of coppice or for the
92 search of light) or progressive change of axis curvature, either to restore verticality after
93 accidental inclination of the tree (Alm eras et al 2009) or to change the orientation of the
94 branches after the death of the apex (Fournier et al 1994). Maturation strain asymmetry is the
95 growth parameter most involved in posture regulation (Alm eras et al 2005) and there are often
96 large variations between the two sides of the axis (Thibaut & Gril 2021).

97 The variations along the stem deals with primary growth: i) succession of connected zones and
98 free-from-branching portions of the axis and ii) ageing of the terminal bud in the successive
99 growth unit. Apart from the vicinity of the branching zones, the variations are rather slow
100 (Savidge 2003).

101 Radial variations, from pith to bark at a given height level can be divided in two types: i) intra-
102 ring short distance changes mostly due to intra-annual climatic changes and ii) variations of
103 mean intra-ring properties linked both to cambium ageing (juvenility) and to the adaption of
104 secondary wood growth to tree mechanics at each growth step (gravity and wind forces
105 depending on tree slenderness and crown development). It is not easy to separate the effects of
106 age per se (time since birth of cambium in the growth unit) and of the mechanical situation of
107 the tree at different growth ages (light availability, wind protection).

108 The biggest variations in dimensions and environment for a given tree over time occur during
 109 the young ages, and so are the variations of wood properties showing higher radial gradients in
 110 the inner part of the axis. This inner part, where gradients are monotonously higher (in algebraic
 111 value), is called juvenile wood or core wood depending on the authors (Lachenbruch 2011) and
 112 their opinion concerning the main factor (juvility or adaptation).

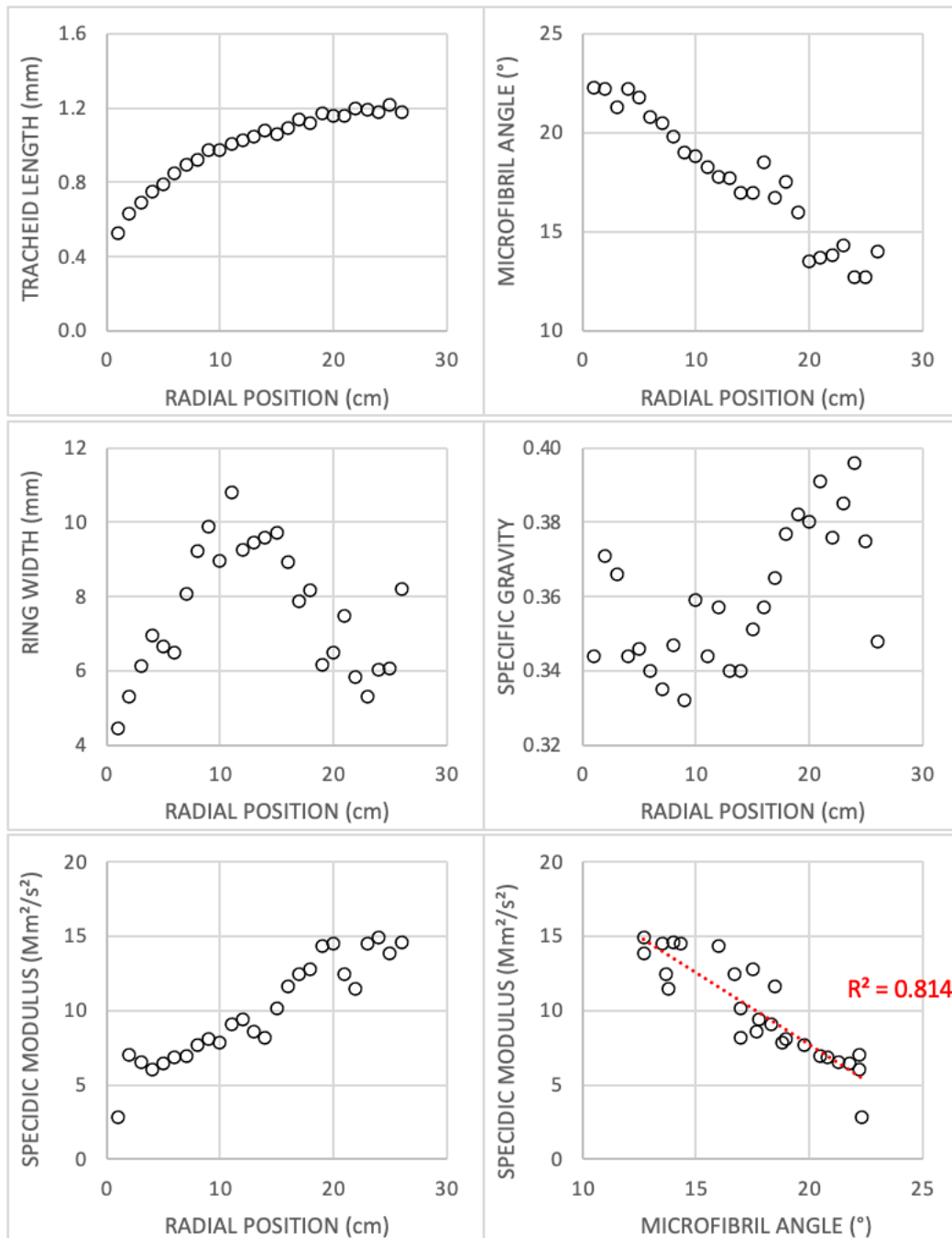
113 A good description is given in (Bendtsen & Senft 1986) for a softwood and a hardwood.
 114 Loblolly pine (Fig. 2) is an example of the typical radial pattern (TRP) of juvenility
 115 (Lachenbruch et al 2011): i) initial increase of tracheid length, specific gravity and specific
 116 modulus, initial decrease of ring width and microfibril angle (*MFA*); *MFA* variations are
 117 closely, negatively related to those of *SM*. This is the general case in softwood plantation trees
 118 (Crown & Dowling 2015, Larson et al 2001).



119
 120

Fig. 2: Radial variations for Loblolly pine, after Bendtsen & Senft (1986).

121 For Eastern cottonwood (Fig. 3), the ring width initially increases and there is no variation in
 122 specific gravity. The variations in fibre length and specific modulus are similar to those of TRP.
 123 There is again a highly significant, negative relationship between *MFA* and *SM*.



124 Fig. 3: Radial variations for Eastern cottonwood, after Bendtsen & Senft (1986).
 125
 126

127 Variations in tracheid or fibre length always share the same initial positive gradient for all trees,
 128 whether softwood or hardwood (Koubaa et al 1998, Larson et al 2001, Bhat et al 2001, Bao et
 129 al 2001, Kojima et al 2009). This parameter is important for the paper industry (Koubaa et al
 130 1998) but is not cited as a factor influencing the mechanical properties of wood (Kollmann &
 131 Côté 1968, Kretschman 2010). The results of initial variations of *RW*, *SG* and *SM* can vary
 132 considerably from tree to tree, with flat, positive or negative initial gradients (Bhat et al 2001,
 133 Mc Lean et al 2011).

134 There is very little data on the variation of the average maturation strain within a ring as a
135 function of cambium age or radial position in a log. It has been suggested that the maturation
136 strain can change from positive values (compression stress) in the most juvenile rings compared
137 to negative values (usual tension stress) in older rings, for softwoods (Fournier et al 1990). For
138 hardwoods (Eucalyptus and poplar), plantations of clones at different ages (3 trees per age) for
139 the same clone in the same environment have been used for in-situ measurements of maturation
140 strains (Baillères 1994, Gérard 1994, Thibaut et al. 1996). No clear influence of age was found
141 (see data for poplar).

142 In order to know, a-posteriori, the values of the maturation strains for each ring of a log, the
143 relationships between local maturation strain and wood parameters at trunk periphery were
144 investigated (Thibaut & Gril 2021). Longitudinal shrinkage is a good parameter in case of
145 reaction wood (compression or tension wood). But, until now, no relationship has been
146 established to estimate the maturation strains from wood parameters (cell wall structure of
147 chemical composition) for normal wood, although there are important variations of maturation
148 strain within normal wood around the periphery of the trunk (Jullien et al 2013).

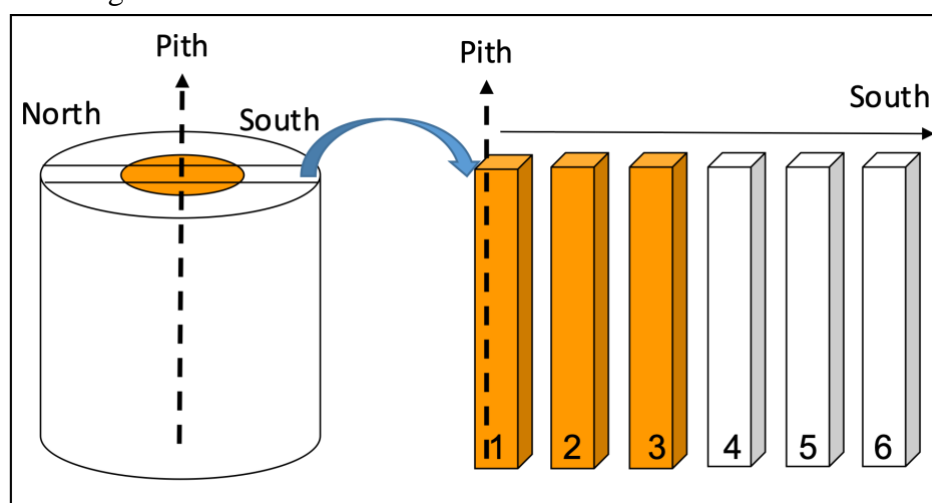
149 It can be hypothesized that initial fibre length gradient is mainly related to age per se (true
150 juvenility) while adaption is often the dominant causality for *RW*, *SG* and *SM*, and probably
151 also for maturation strain.

152 3. Material and methods

153 3.1. Material

154 Within the framework of a European collaborative programme called “Stresses in beech”, nine
155 beech forests, representative of European forest management, were selected in 5 countries
156 (Austria, Denmark, France, Germany and Switzerland) (Becker & Beimgraben 2001). The age
157 of the selected trees varied from 70 to 200 years. Maturation strain at 8 peripheral positions was
158 measured on 440 standing beech trees from the 9 plots (Jullien et al 2013).

159 In each plot, 10 trees (86 in total) were selected for the measurement of wood properties. One
160 small log of 50 cm length was cut at a height of 4 m for each tree. Each small log was cut into
161 radial boards, through the pith, from North to South. These boards were air-dried to an average
162 moisture content of 13.5 % (equilibrium at 20°C and 65% RH) and cut into 1259 rods of 20
163 mm in radial, 20 mm tangential and 360 mm longitudinal direction, from the pith outwards (Fig.
164 4). Those with irregularities or cracks were discarded.



165
166 Fig. 4: Diagram of the sawing of the rod after the sawing of a North-South diametrical board.
167 Numbering both for Northern and Southern parts of the board start with pith position. The coloured
168 parts evoke the case of redheart occurrence.

169 The rods were numbered according to their position in the board and their distance to pith (DP)
 170 was measured. At the same time, the number of rings at both ends of the samples was recorded
 171 and the mean annual ring width of the rod (RW) was calculated as the ratio of the mean radial
 172 dimension to the number of rings. The presence of red heartwood was also noted for the rods
 173 located in the core, in relation to a previously published work (Liu et al 2005).

174 **3.2. Measurement of density and specific modulus.**

175 All measurements were done in a regulated room at a temperature of 20°C and a relative
 176 humidity of 65%.

177 The density (D) was calculated by measuring the weight (W) and the dimensions R, T, L of the
 178 rod in direction R, T, L, respectively: $D = W/(R.T.L)$. The specific gravity (SG) is the ratio
 179 between D and water density.

180 To measure the specific modulus ($SM, 10^6m^2/s^2$), each rod is positioned on fine wires and set in
 181 free vibration by a hammer stroke. The analysis of the sound vibration by fast Fourier transform
 182 gives the values of the three highest resonance frequencies which are interpreted using
 183 Timoshenko solution (Brancheriau & Baillères 2002, Brancheriau 2006). The modulus of
 184 elasticity (MOE) can be calculated as: $MOE = D.SM$.

185 **3.3. Statistical analysis**

186 Basic statistical analyses were performed using XLSTAT software. The data description table
 187 includes the number of data, the minimum, maximum and mean values for each parameter, as
 188 well as the coefficient of variation (CV). The normality of the distribution is verified by Shapiro-
 189 Wilk test. A Pearson correlation analysis is used in the case of a normal distribution, and a
 190 Spearman correlation analysis in the case of a non-normal distribution, which is the majority of
 191 cases.

192 **4. Results and discussion**

193 **4.1. Radial variations of properties**

194 By giving positive values for the distance to the pith on the North side and negative values on
 195 the South side, it is possible to draw the South-North profile of each parameter ($RW, SG, SM,$
 196 MOE) for each tree, as a function of the diametrical position (DP). If there was an increase of
 197 the parameter from pith position, the profile is noted “Up”, “Down” for the reverse case and
 198 “Flat” when the variation was not clearly up or down. In case of clear asymmetry between the
 199 Southern and Northern parts by visual observation, the sample was noted as asymmetric (Fig.
 200 5).

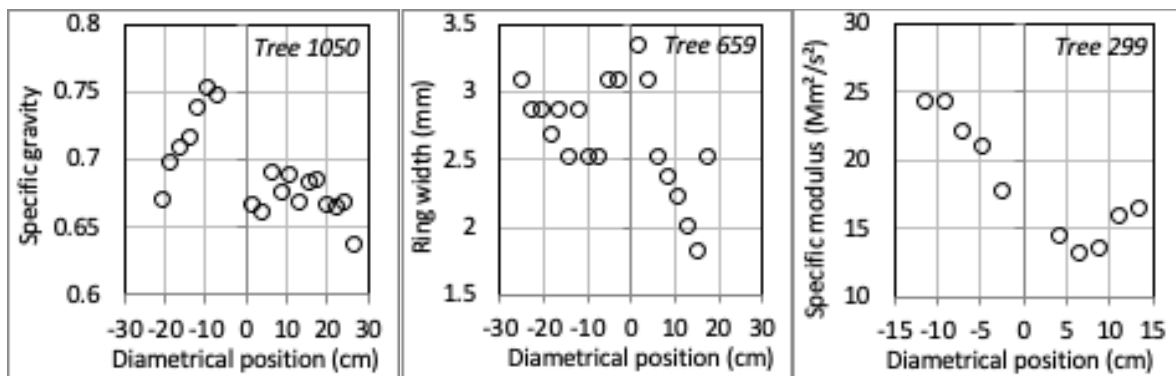


Fig. 5 Examples of clearly asymmetric North-South profiles.

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There was a large majority of symmetrical patterns (Table 1).

Table 1 Percentage of profile types per plot within each or wood parameter.

Para.	Ring width				Density				Specific modulus			
PLOT	Up	Down	Flat	Sym	Up	Down	Flat	Sym	PLOT	Up	Down	Flat
1	57%	43%	0%	70%	0%	25%	75%	40%	1	57%	43%	0%
2	67%	11%	22%	90%	11%	0%	89%	90%	2	67%	11%	22%
3	63%	0%	38%	80%	30%	0%	70%	100%	3	63%	0%	38%
4	70%	10%	20%	100%	20%	0%	80%	50%	4	70%	10%	20%
5	43%	14%	43%	70%	100%	0%	0%	60%	5	43%	14%	43%
6	86%	0%	14%	88%	50%	0%	50%	100%	6	86%	0%	14%
7	22%	56%	22%	90%	43%	14%	43%	70%	7	22%	56%	22%
8	67%	17%	17%	60%	100%	0%	0%	70%	8	67%	17%	17%
9	14%	57%	29%	88%	40%	0%	60%	63%	9	14%	57%	29%
Mean	54%	23%	23%	82%	44%	4%	52%	71%	Mean	54%	23%	23%

207 Para.: Wood parameter; Up: initial increase of the parameter from pith to bark; Down: initial decrease
 208 of the parameter from pith to bark; Flat: no clear initial increase or decrease; Sym: proportion of
 209 globally symmetrical profiles between North and South directions.
 210

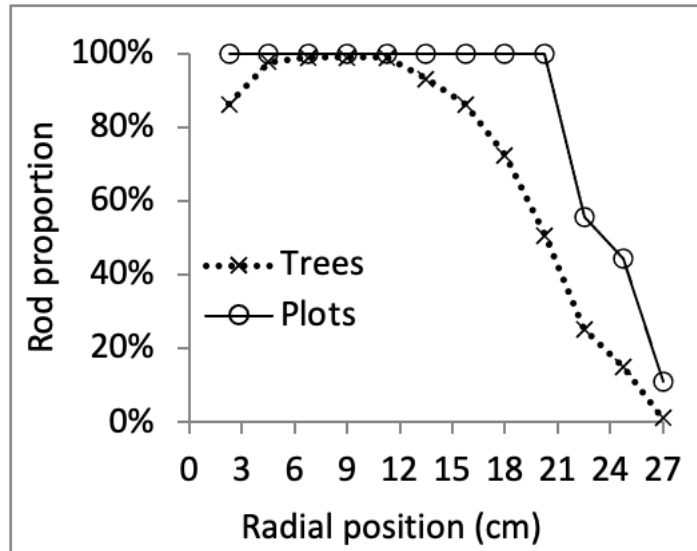
211 Globally there were no noteworthy difference between the Northern and Southern samples
 212 (Table 2).
 213

Table 2 Comparison of parameter values North and South.

Position (Nb)	RW (mm)	SG (kg/m ³)	SM (10 ⁶ m ² /s ²)	MOE (GPa)
North (637)	2.32	0.695	22.06	15.33
South (622)	2.28	0.694	22.39	15.54
% Sym.	82%	71%	76%	70%

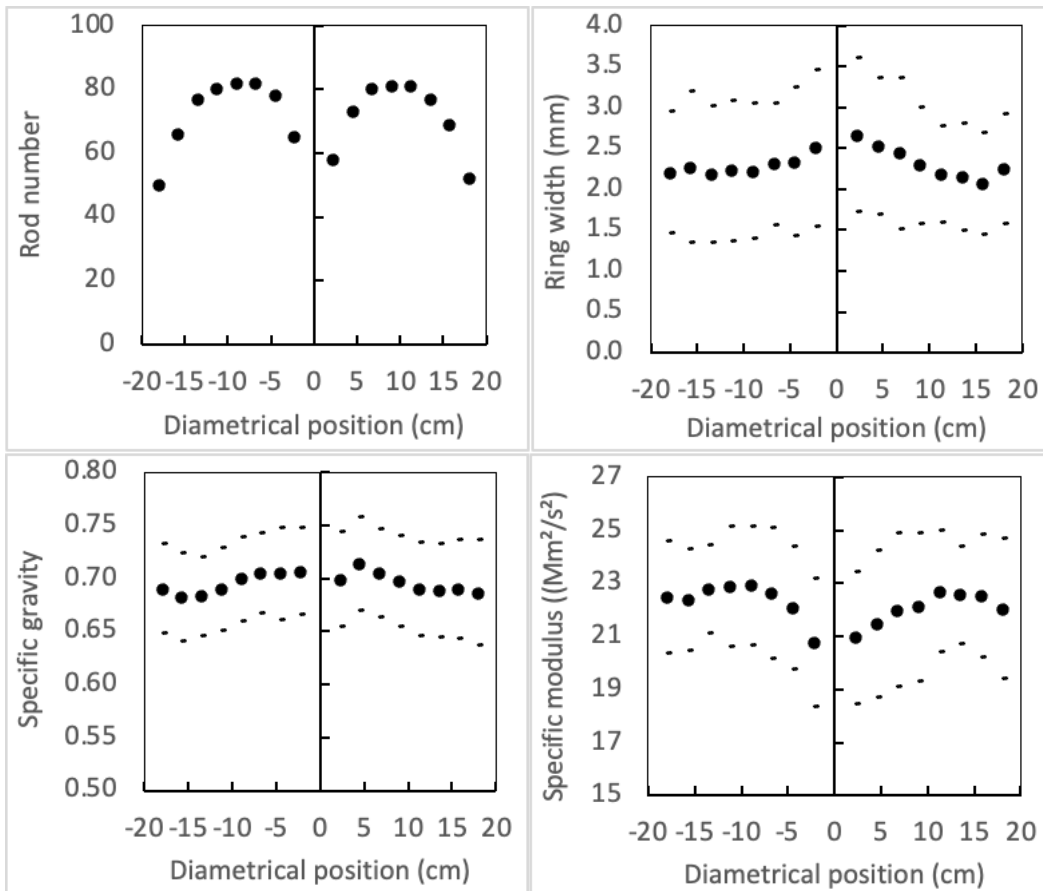
214 RW: mean ring width; SG: mean specific gravity; SM: mean specific modulus;
 215 MOE: mean longitudinal modulus of elasticity; Nb: number of rods;
 216 %Sym: proportion of diametrical patterns considered symmetrical for each parameter.
 217

218 In each case, the occurrence of rods for each successive radial position within the trees or plots
 219 was examined (Fig. 6). Up to 18 cm from the pith, all the plots are concerned and there are
 220 always more than 70% of the trees concerned, values lower than 100% being due to defect
 221 occurrence close to the pith. This proportion decreases rapidly for larger distances from the
 222 pith, due to variable log size. It is therefore preferable not to use rods with a radial distance of
 223 more than 18 cm to calculate the mean values of the parameters at the global scale.
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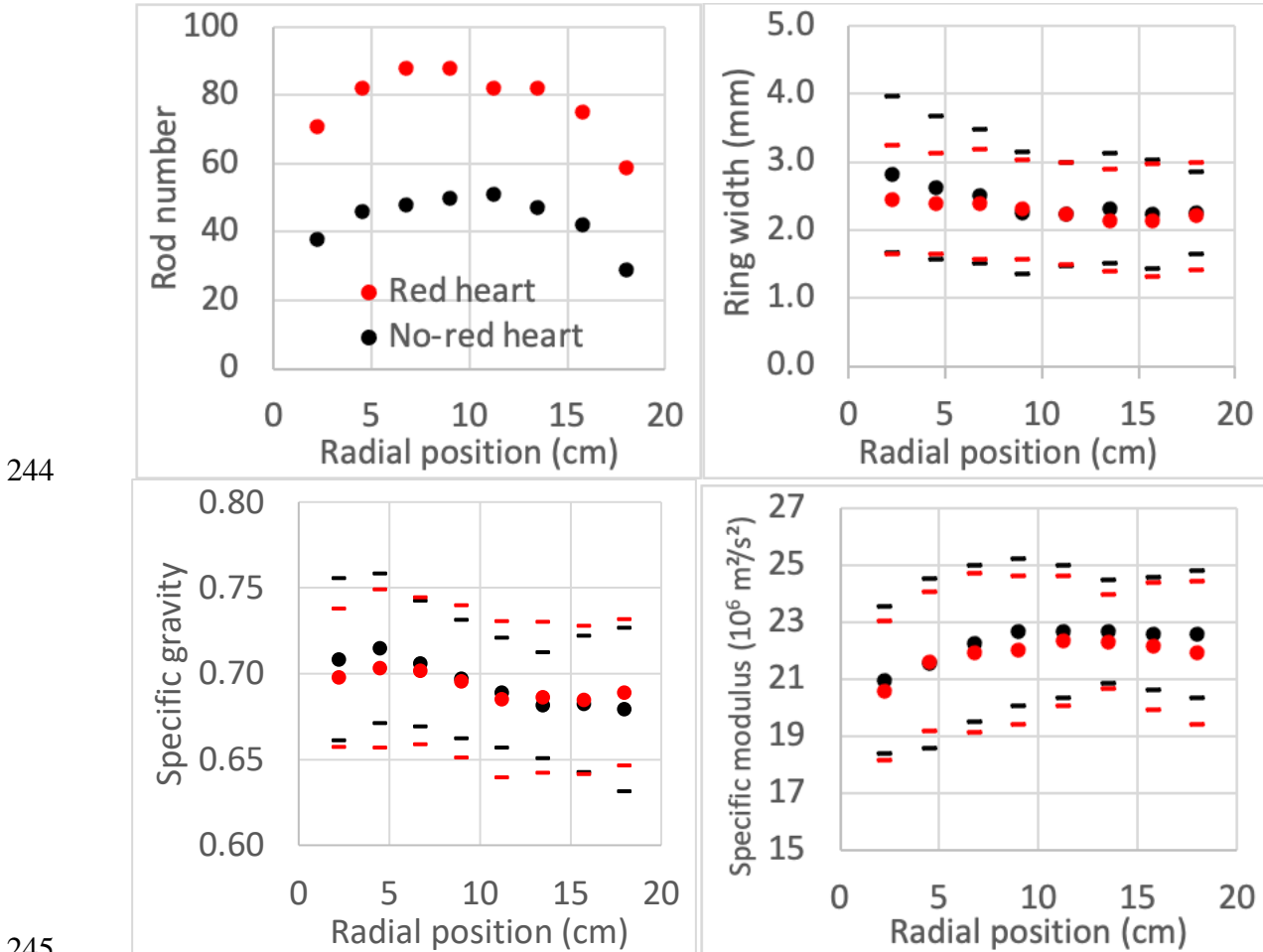
225 Fig. 6 Percentage occurrence of rods for each successive radial position within trees or plots
 226 100% means that there are used rods at a given radial position in every tree or every plot.
 227
 228

229 There are notable differences between trees for each parameter, both in value and in pattern.
 230 Globally, there is no significant difference between the Northern and Southern samples (Fig.
 231 7). It is thus allowable to mix the beech rods of the Northern and Southern specimens for further
 232 analysis of the mean radial variation patterns at the global or plot level.



233
 234 Fig. 7 Number of rods and parameter values for all trees as a function of diametrical position (DP)
 235 Bolt dots: mean value; thin dashes: mean value + or - standard deviation.
 236
 237

238 Moreover, some trees have a part of red core-wood portion and the effect it may have on
 239 properties was investigated. All trees (25) without any red rod (except sometimes one near the
 240 pith) were considered as white beech while all trees with more than two red rods were
 241 considered as red beech. The mean radial variations for red and white beech trees were
 242 calculated (Fig. 8). Due to the variability between the trees, no clear difference could be
 243 observed between the mechanical properties of red and white beech wood.



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Fig. 8 Values of parameter for all red and no-red hearted trees as a function of radial position.
 Bolt dots: mean value; thin dashes: mean value + or - standard deviation.
 Red dots: red heartwood; black dots white heartwood

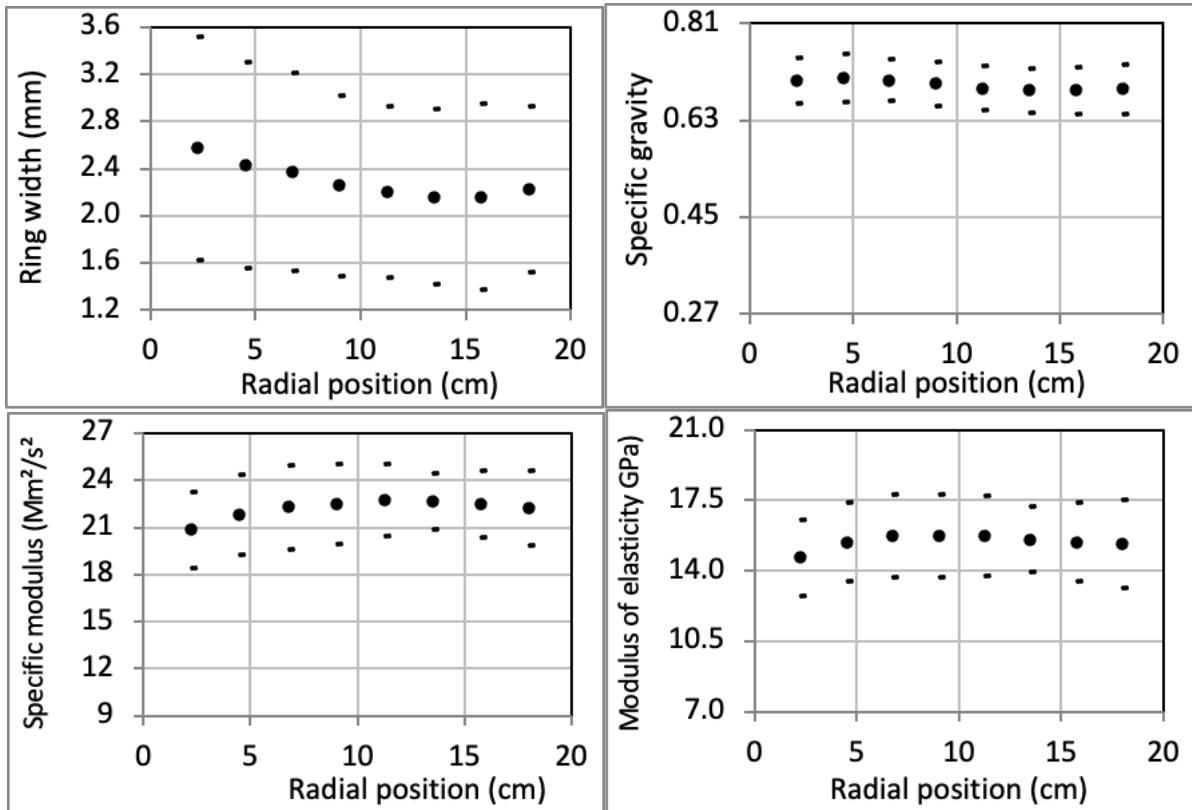
250 It is thus allowable to mix Northern and Southern specimens of red and white beech rods for
 251 further analysis of the mean radial variation patterns at the global or plot level.

252 The global mean radial patterns for these beech trees were as follows (Fig. 9):

- 253 - *RW* decreases regularly (2.6 to 2.2 mm) from pith to bark;
- 254 - *SG* increases a little (0.703 to 0.709) at the beginning (up to about 4 cm radius) and
 255 decreases thereafter (0.709 to 0.686), but the variations are small;
- 256 - *SM* increases (20.8 to 22.8 m²/s) for a rather long time (up to about 12 cm radius) and then
 257 decreases (22.8 to 22.2 m²/s²) regularly;
- 258 - the *MOE* pattern is very similar to the *SM* pattern.

259

260



261

262 Fig. 9 Mean radial distribution of indicators and modulus of elasticity for all rods.

263

264 Bolt dots: mean value; thin dashes: mean value + or - standard deviation.

265

A ratio of 3 has been set for all graphs between maximum and minimum values of the ordinate axis.

266

267 The variability between trees (standard deviation values) is high for *RW* but low for *SG*. It is slightly higher for *SM* and *MOE* (Table 6).

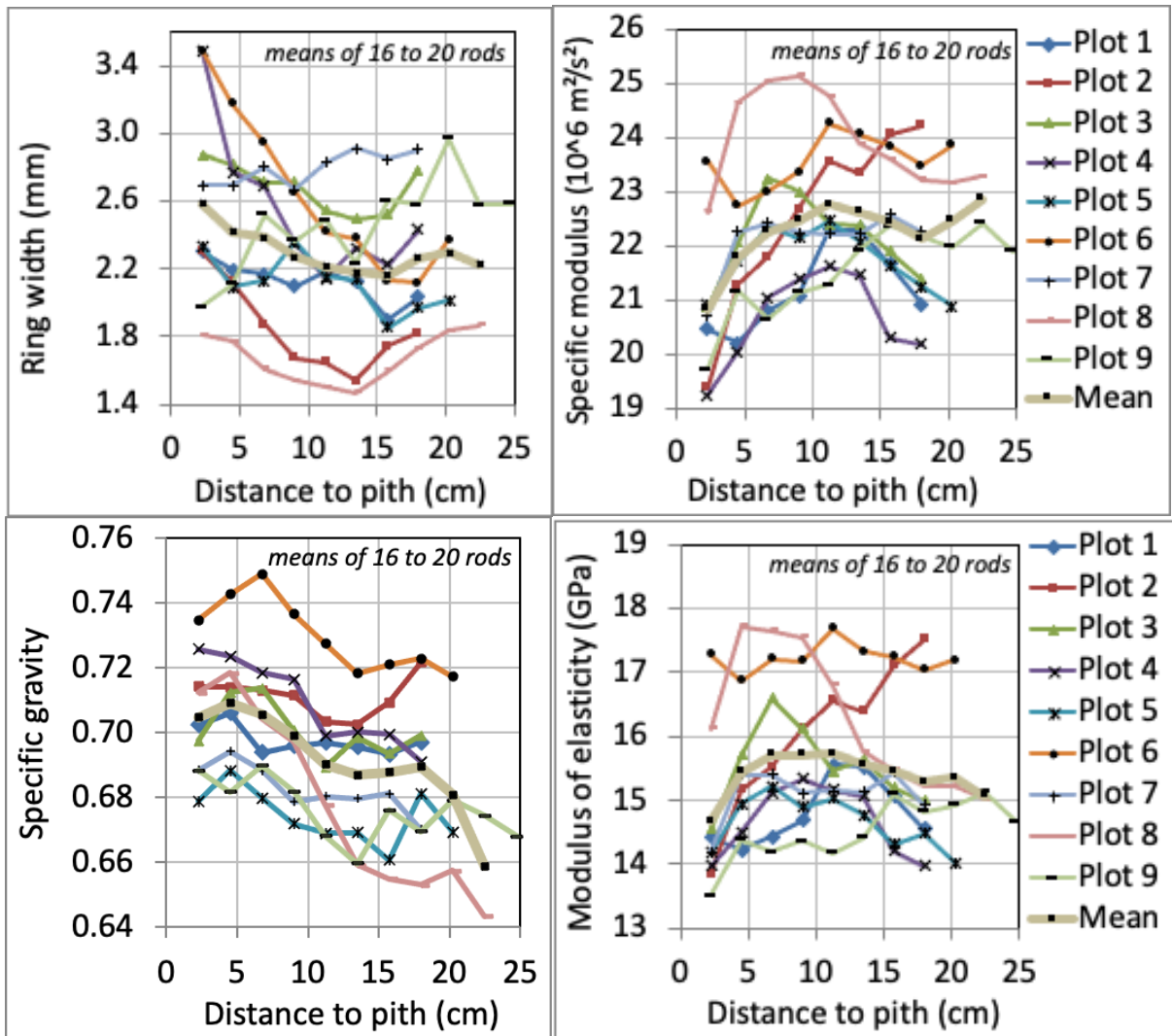
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269 The mean patterns of the plots (Fig. 10) are more irregular due to the smaller number of rods, but, more or less, the global mean pattern is the most frequent. There are differences between plots, in the mean level of properties and sometimes in the pattern, mainly for *RW*, with some plots having increasing *RW* (plot 7 and 9).

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Fig. 10 Mean radial variations of properties at the plot level
Mean: mean values for all rods at each radial position.

277 It is interesting to look at the evolution of the ring surface from pith to bark, using the radial
278 position ($PoRa$) and the mean ring width of each rod:

279 $RSra = 2\pi.PoRa.RW$

280 The evolution of the mean values of all $RSra$ at the same radial position for all trees in a plot,
281 from pith to bark (Fig. 11), is a signature of the trunk surface growth for the plot. For these
282 beech plots, the ring surface can be considered proportional to the distance from the pith with
283 a regression coefficient (R^2) always above 0.96 (Table 3):

284 $RSra = K.PoRa$

285 K has a mean value of 1.43 cm^2/cm , and ranges from 1.09 to 1.88. This kind of linear growth
286 quasi proportional to distance to pith together with K values can be considered as a result of
287 forest management in these European plots.

288

Table 3 Proportional coefficient (K) and R^2 values for linear regressions

Plot	1	2	3	4	5	6	7	8	9	Mean
K	1.25	1.14	1.69	1.47	1.28	1.44	1.88	1.09	1.63	1.43
R^2	0.98	0.96	0.99	0.98	0.98	0.96	0.98	0.98	0.98	0.99

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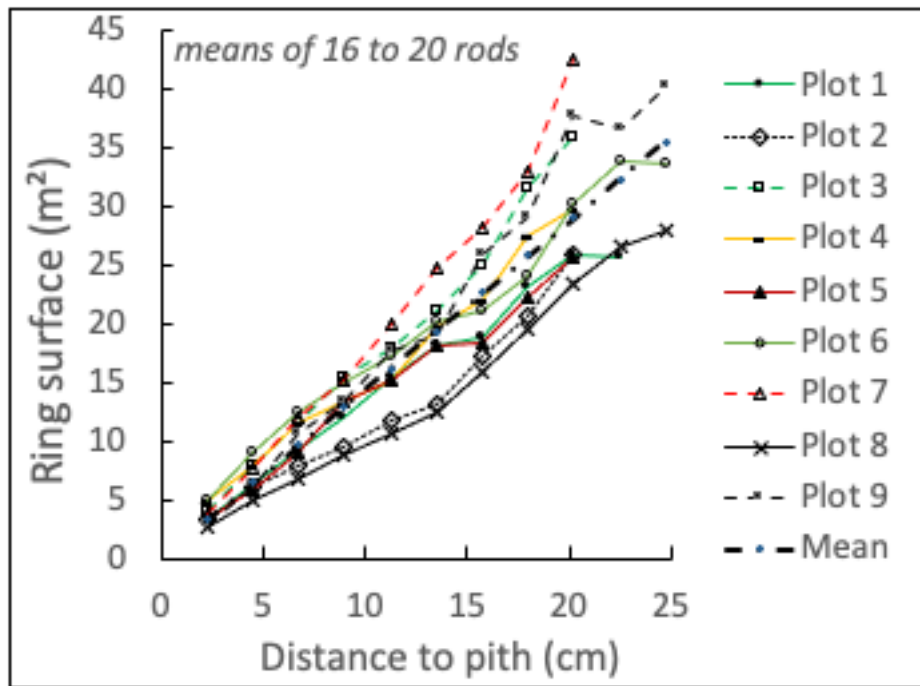


Fig. 11 Variation of ring surface (cm²) with distance to pith (cm) for each plot.
Mean: regression for mean values

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294 4.2. Global results

295 4.2.1. Global results at rod level

296 Table 4 and 5 give global description and correlation within the data for all samples (1259 rods).

297

Table 4 Parameter description for all rods

1259 rods	RW	SG	SM	MOE
Minimum	0.67	0.55	11.08	8.00
Maximum	6.67	0.83	27.49	21.30
Mean	2.30	0.69	22.22	15.44
Max/min	10.00	1.51	2.48	2.66
C. V.	35.0%	6.2%	10.9%	13.0%

RW (mm): ring width; *SG*: specific gravity; *SM* (10⁶m²/s²): specific modulus;
MOE (GPa): longitudinal modulus of elasticity.

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300

301 The variations of *SG* between samples are very low (coefficient of variation 6%).

302

Table 5 Correlation table for all rods

1259 rods	RW	SG	SM	MOE
RW	1	0.215	-0.313	-0.167
SG	0.215	1	0.047	0.506
SM	-0.313	0.047	1	0.884
MOE	-0.167	0.506	0.884	1

RW: ring width; *SG*: specific gravity; *SM*: specific modulus; *MOE*: longitudinal modulus of elasticity.

Bold numbers: correlation significant at 0.1% level.

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306 There is no significant correlation (at the 5% level) between *SG* and *SM*. *RW* has a very
 307 significant correlation (at the 0.1% level) positively with *SG* and negatively with *SM*. Thus, the
 308 correlation between *RW* and *MOE* is negative with a lower coefficient of determination (3%).
 309 In the determination of *MOE* from *SM* and *SG*, the coefficient of determination (square of the
 310 correlation coefficient given in Table 5) is three times higher for *SM* (78%) than for *SG* (26%).

311 4.2.2. Global results at tree level

312 Tables 6 and 7 give the description and correlation table for tree dimension and mean per tree.
 313 Variability of parameters is significantly lower for tree mean values, and notably low for *SG*.

314 Table 6 Parameter description for tree mean values

86 trees	RW	D	SM	MOE
Minimum	1.29	0.63	17.6	12.0
Maximum	4.78	0.78	25.6	19.3
Mean	2.28	0.70	22.4	15.6
Max/min	3.70	1.24	1.46	1.60
C.V.	24.9%	4.8%	7.6%	9.5%

315 *RW* (mm): ring width; *SG*: specific gravity; *SM* ($10^6\text{m}^2/\text{s}^2$): specific modulus;
 316 *MOE* (GPa): longitudinal modulus of elasticity.
 317

318 Except for *RW*, the mean wood properties per tree show rather low variations between trees
 319 (very low for *SG*).

320 Table 7 Correlation table for all trees

86 Trees	RW	D	SM	MOE
RW	1	0.122	-0.388	-0.252
D	0.122	1	0.140	0.602
SM	-0.388	0.140	1	0.874
MOE	-0.252	0.602	0.874	1

321 *RW*: ring width; *SG*: specific gravity; *SM*: specific modulus; *MOE*: longitudinal modulus of elasticity.
 322 Bold numbers: correlation significant at 0.1% level.
 323

324 Among the wood properties, *RW* and *SM*, *SM* and *MOE*, *SG* and *MOE* remain highly
 325 significantly correlated (0.1% level) at the tree level.

326 4.2.3. Global results at plot level

327 Table 8 gives the description of tree dimensions and mean wood properties per tree for the 9
 328 forest plots and Table 9 the correlation table for all plots. Except for *RW*, the mean wood
 329 properties per plot all show very little variation between plots.

330 Table 8 Parameter description for the 9 plots mean values

Plot	Nb trees	RW	D	SM	MOE
1	10	2.06	0.70	21.5	15.0
2	10	1.80	0.71	23.1	16.4
3	10	2.63	0.70	22.2	15.6
4	10	2.50	0.71	21.2	15.1
5	10	2.12	0.68	21.9	14.8
6	8	2.57	0.73	23.7	17.3

7	10	2.84	0.68	22.0	15.1
8	10	1.63	0.68	24.1	16.4
9	8	2.50	0.67	21.7	14.6
Max		2.8	0.7	24.1	17.3
Min		1.6	0.7	21.2	14.6
Mean		2.29	0.70	22.4	15.6
Max/min		1.74	1.08	1.14	1.18
CV		16.9%	2.6%	4.2%	5.5%

RW (mm): ring width; *SG*: specific gravity; *SM* ($10^6\text{m}^2/\text{s}^2$): specific modulus;
MOE (GPa): longitudinal modulus of elasticity.

331
332
333

334 At the plot mean level, only the causal relationship between *MOE* and *SG* or between *MOE* and
335 *SM* remains significant at the 0.1% level (Table 9).

336

Table 9 Correlation table for all plots

9 Plots	RW	D	SM	MOE
RW	1	0.154	-0.446	-0.266
D	0.154	1	0.252	0.671
SM	-0.446	0.252	1	0.886
MOE	-0.266	0.671	0.886	1

337 *RW*: ring width; *SG*: specific gravity; *SM*: specific modulus; *MOE*: longitudinal modulus of elasticity.

338
339

Bold numbers: correlation significant at 0.1% level.

340 4.3. Pre-stressing and growth forces

341 In situ measurements on standing trees give values of *GSI* for North and South sides at breast
342 height for each tree (Jullien et al 2013). *RW*, *SG* and *SM* values are measured in laboratory for
343 the last rods (farthest away from pith) at North and South positions and 4 m high in the tree.
344 We can expect that these 3 wood parameters are good estimations for the values at breast height
345 level.

346 All the North and South values labelled with the subscript _{last} for wood parameters were
347 gathered in the same sheet (Maturation): distance to pith (DP_{last} in cm), ring width (RW_{last} in
348 mm), specific modulus (SM_{last} in $10^6\text{m}^2/\text{s}^2$), longitudinal modulus of elasticity (MOE_{last} in GPa)
349 of the last rod (North & South), *GSI* (North & South) for the 86 trees.

350 Firstly, the calculation of maturation stress (pre-stressing value) and growth force needs green
351 wood values for parameters such as *DP*, *RW* and *MOE*. In the literature (Cirad 2015) we can
352 find a mean value for radial shrinkage ($RS=5.7\%$) and fibre saturation point ($FSP=32\%$) of
353 beech wood. The moisture content of the rods was 13.5%, which is 18.5% below *FSP*. The
354 increase in radial dimension between the air-dry and green state of the wood can be estimated
355 by the shrinkage proportion (*PS*):

$$356 \quad PS = 5.7\% \times 18.5\% / 32\% = 3.3\%$$

357 Thus the width of the green ring (RW_g) and green distance to pith (DP_g) can be obtained from
358 the air dry values (*RW* and *DP*) by the formulas:

$$359 \quad RW_g = 1.033 RW : DP_g = 1.033 DP$$

360 and ring portion surface (RS_g) is calculated as $RS_g = \Delta\theta \times DP_g \times RW_g$, where the angular sector
361 $\Delta\theta$ corresponding to a given *GSI* value is taken as $\pi/4$.

362 Air dry (MOE) and green (MOE_g) longitudinal modulus of elasticity are proportional according
 363 to the formula (Thibaut & Gril 2021):

364
$$MOE_g = 0.8943 \times MOE$$

365 It is also necessary to convert GSI values into maturation strains (α_m) using the conversion
 366 factor FI (Thibaut & Gril 2021):

367
$$\alpha_m = FI \times GSI$$

368 FI can be calculated from the formula:

369
$$FI = -0.475 \times SM_b + 25.24$$

370 SM_b is the basic specific modulus which is proportional to the specific modulus SM (Thibaut &
 371 Gril 2021):

372
$$SM_b = 1.1068 \times SM; \text{ so } FI = -0.5257 \times SM + 25.24$$

373 Using the values of the maturation strain α_m and green MOE , the value of the maturation stress
 374 (which is the value of the tensile pre-stress at the periphery of the trunk) can be calculated:

375
$$\sigma_m = MOE_g \times \alpha_m$$

376 Then, the local force generated on the unit ring portion (ΔF in N) by the maturation process can
 377 be calculated:

378
$$\Delta F = RS_g \times \sigma_m$$

379 For the 3 explaining factors (RS_g , MOE_g , GSI), the variability is rather low for MOE , high for
 380 local ring surface and very high for GSI . Thus it is also very high for local maturation strain,
 381 maturation stress (pre-stressing value) and growth force (Table 10).

382

383

Table 10 Statistical description of maturation parameters

	ΔS_g	MOE_g	GSI	FI	α_m	σ_m	ΔF
Mean	4.04	13.7	83	13.6	1109	15.4	6025
Median	3.60	13.9	70	13.4	941	12.3	4335
Minimum	0.77	8.4	0	10.8	0	0.0	0
Maximum	10.80	19.1	251	18.6	3103	47.6	23342
CV	45%	15%	68%	10%	66%	70%	79%

384 RS_g (cm^2): local ring surface; MOE_g (GPa): longitudinal modulus of elasticity of the last ring;

385 GSI (μm) growth stress indicator measured in situ on standing tree;

386 FI conversion factor between GSI and maturation strain; α_m : maturation strain (10^{-6});

387 σ_m (MPa): maturation stress; ΔF (N): local growth force. CV: coefficient of variation.

388

389 Both pre-stressing and growth force are strongly related to maturation strain ($R^2 = 92\%$ and
 390 62% respectively) through proportional laws. Growth force and pre-stressing are very
 391 significantly correlated but 35% of growth forces variations are not explained by pre-stressing
 392 variations (Fig. 12).

393

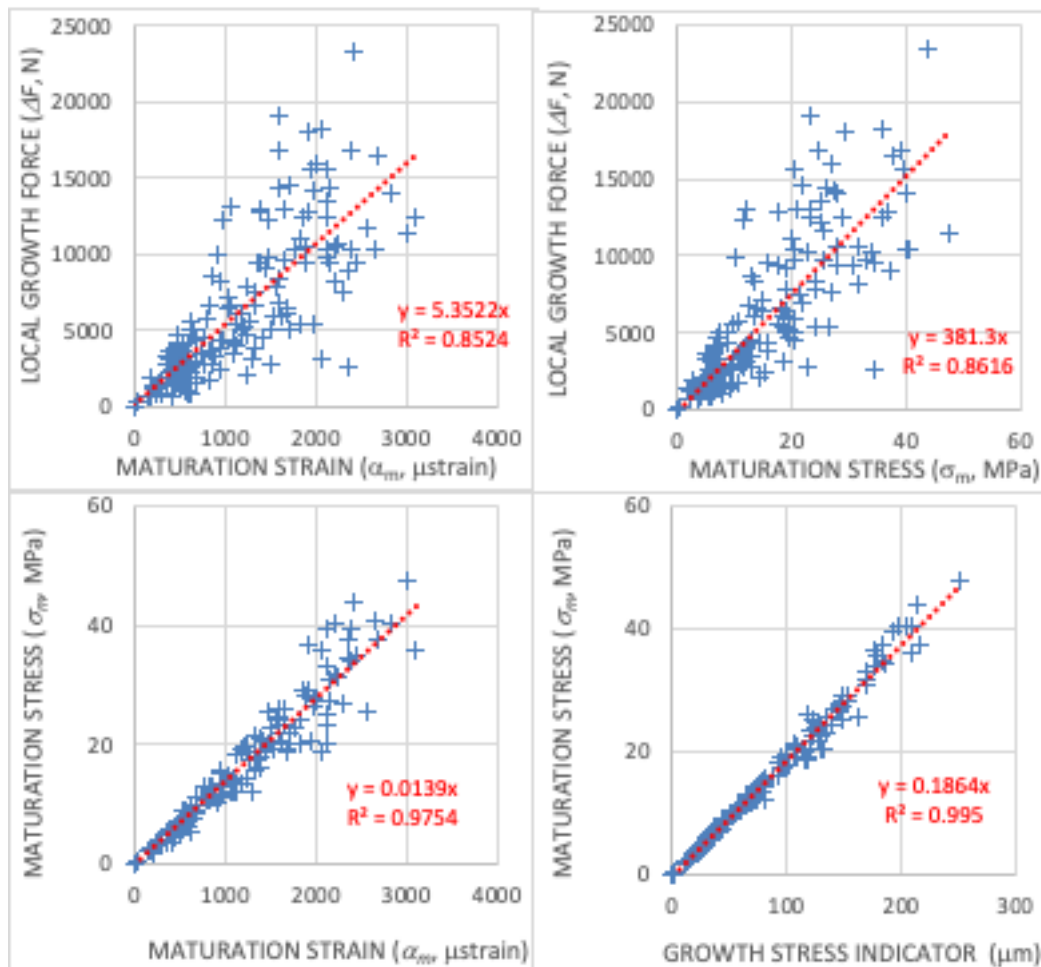


Fig 12: Relationships between growth forces, maturation strain or growth stress indicator, and maturation stress.

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398 4.4. Discussion and conclusion

399 There are few published results relating to radial variations of mechanical parameters in large
400 trees of high forests that are not the result of plantation. In Europe, old growth beech forests
401 can have different forest origins: i) even-aged (France or Germany) or uneven-aged high forest
402 (Switzerland), coppicing with standards (France) or conversion of coppice forest into high
403 forest (Ciancio et al 2006) (Germany, France) but are very rarely the result of plantations (none
404 in the 9 plots). *Fagus* is known for its shade tolerance and ability to grow very slowly under a
405 closed canopy (Collet et al 2011) and most forest plots undergo more or less severe thinning
406 before final harvesting, which leads to an increase of *RW* due to better access to light (Noyer et
407 al 2017). This is reflected in the different mean *RW* radial patterns for the 9 plots (Fig. 10). For
408 plots 7 and 9, a clear increase of *RW* is observed in the young ages, while the reverse and
409 classical pattern is true for plots 2, 4 and 6. Similar results were found on younger beech trees
410 (Bouriaud et al 2004).

411 As a mean for these high forest beech trees, the radial patterns of variations are partly similar
412 to the typical radial pattern for *RW* and *SM*. *SG* has a very small decreasing variation. But
413 looking tree by tree, there are all types of patterns (increasing or decreasing at the beginning)
414 for all parameters (*RW*, *SG* and *SM*). This supports the hypothesis of an “adaptation” for
415 “mechanical” juvenility.

416 Due to the very low variability of the *SG* of beech wood, the variations of *SM* are much more
417 important than those of *SG* in order to explain the variations of *MOE*.

418 The high level of inter-tree variability (CV=66%) for pre-stressing (σ_m) is massively due to
 419 variations in maturation strains combined with variations in *MOE*, while for growth forces (ΔF),
 420 the high level of variability between trees (CV=79%) is also mainly linked to variations in
 421 maturation strains combined with variations in local ring surface and *MOE* (Table 11).
 422 Although growth force and maturation stress are very significantly linked ($R^2 = 64\%$) due to
 423 the influence of the maturation strain, the ring width has no influence on pre-stressing and
 424 appears to be a possible trade-off parameter between the two mechanical functions of growth
 425 forces: pre-stressing of trunk periphery and posture control of axis position.

426

427 Table 11 Contribution of several factors to the variance of local growth force and maturation stress

R^2	α_m	MOE_g	DP_{last}	RW_{last}	RS_g
ΔF	61.8%	5.0%	9.4%	11.7%	17.2%
σ_m	92.5%	11.6%	0.4%	0.6%	0.9%

428 R^2 : coefficient of determination; ΔF : local growth force; σ_m : maturation stress; α_m : maturation strain;
 429 MOE_g : modulus of elasticity in green state; DP_{last} : distance to pith of last ring;
 430 RW_{last} : width of last ring; RS_g : ring portion surface.

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435 Data

436 The original data used in this paper are available at: <https://zenodo.org/record/8103568>.

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