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1 Effect of growth rate on the physical and mechanical properties of Douglas-fir in Western Europe

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Résumé

Afin de quantifier l'impact des modalités de gestion sylvicole, et donc de la vitesse de croissance des arbres sur les potentialités d'usage du Douglas, neuf propriétés physico-mécaniques ont été mesurées sur plus de 1250 éprouvettes standardisées. Celles-ci sont issues d'arbres prélevés dans 11 peuplements équiennes (6 arbres/peuplement) situés en Wallonie (Sud de la Belgique). L'âge des peuplements varie de 40 à 69 ans, tandis que la circonférence moyenne des arbres avoisine 150 cm. La largeur moyenne des cernes des 66 arbres varie ainsi de 3 à plus de 7 mm. Les analyses statistiques ont montré des effets significatifs mais faibles de la largeur des cernes sur les propriétés étudiées. Considérés ensemble, la largeur des cernes et l'âge cambial des éprouvettes n'expliquent que 28 à 40% de la variabilité des propriétés étudiées. D'autre part, lorsque la largeur des cernes augmente, ces propriétés diminuent davantage dans le bois juvénile que dans le bois mature. D'un point-de-vue technologique, limiter la largeur moyenne des cernes à 4 et 6 mm, respectivement dans le bois juvénile et mature, permet de maintenir les meilleures potentialités d'usages du bois. Cependant, étant donné que la densité apparaît comme le principal déterminant des propriétés mécaniques, nos résultats et la littérature corroborent l'importance de la sélection génétique en complément de la gestion sylvicole en vue d'améliorer ou de garantir les propriétés technologiques du bois de Douglas.

Mots clés (5) : Douglas, propriétés mécaniques, largeur de cerne, éprouvettes sans défaut, qualité du bois

1 **Abstract**

2 To quantify the impact of forest management practices and tree growth rate on the potential uses of
3 Douglas-fir wood, nine physico-mechanical properties were studied on more than 1250 standardized
4 clear specimens. These were collected from trees cut in 11 even-aged stands (6 trees/stand) located in
5 Wallonia (Southern Belgium). Stands were 40 to 69 years old and the mean tree girth was ca. 150 cm.
6 The mean ring width of the 66 trees ranged from 3 to more than 7 mm. Statistical analysis evidenced
7 significant but weak effects of ring width on the studied properties. Considered jointly, mean ring
8 width and cambial age of the test specimens only explain 28 to 40% of the variability of their
9 properties. Also, when ring width increases, these properties display higher decrease in juvenile than
10 in mature wood. From a technological standpoint, maintaining mean ring width under 4 mm in
11 juvenile wood and 6 mm in mature wood should allow all potential uses of Douglas-fir wood.
12 However considering that density appeared as the main driver of wood properties, our results and the
13 literature corroborate the importance of genetic selection as a complement of silvicultural measures to
14 improve or guarantee the technological properties of Douglas-fir wood.

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19 **Key words (5):** Douglas-fir, mechanical properties, ring width, clear wood specimen, wood quality

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1 Introduction

2 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was introduced in Belgium in 1871, in the
3 Ardenne region. It currently covers around 23 000 ha, i.e. slightly less than 10% of the Walloon
4 coniferous forest (Alderweireld et al. 2015). According to Perin et al. (2016), the total volume
5 production of mature Douglas-fir is around 30% higher than that of Norway spruce (*Picea abies* (L.)
6 Karst.). The excellent reputation of Douglas-fir wood is due to the exceptional quality of wood from
7 old-growth forests in Northwestern America, characterized by slow growth rates. However, the
8 properties of timber from more dynamically growing second-growth forests could be different. Shorter
9 rotations (<50 years) bring to the market smaller logs including higher proportions of juvenile wood
10 (Lauseberg et al. 1995; Vikram et al. 2011). The larger proportion of juvenile wood could be
11 problematic, as this wood has less favorable mechanical properties than mature wood (Barett and
12 Kellogg 1991).

13 In Belgium, the mean annual girth increment of mature Douglas-fir may vary from 2 to
14 5 cm/year, corresponding to a 3- to nearly 8-mm average ring width (mean radial growth measured
15 along the entire radius) (unpublished data). The properties of wood are influenced by many factors,
16 including site conditions, genetic provenance, forest management practices, and location in the tree.
17 Planting density and thinning modalities influence the ring width (RW), the proportion of juvenile
18 wood and sapwood, and the proportion of latewood. All these factors are also interrelated (Melin and
19 Riou-Nivert 1985). Several studies have shown an influence of mean ring width on some physical and
20 mechanical properties of Douglas-fir wood (Geldreich 1981; Melin and Riou-Nivert 1985; Nepveu
21 and Blachon 1989; Lauseberg et al. 1995; Leban and Mothe 1996; Todaro and Macchioni 2011;
22 Vikram et al. 2011) as well as wood of other species (Zobel and Van Buijtenen 1989; Zhang 1995).
23 These studies, however, rarely deal with properties other than density, modulus of elasticity, or
24 bending strength, and the stands studied are generally not mature. The trees are thus not representative
25 of the final product used in structural applications.

26 In most softwood species including Douglas-fir, wood density decreases with increasing ring
27 width (Geldreich 1981; Leban and Mothe 1996). On the basis of results obtained on clear specimens,
28 Melin (1984) showed that wide rings display less favourable mechanical properties. Melin and Riou-

Nivert (1985), however, consider that for common uses of Douglas-fir, timber from wide-spacing plantations should not be subject to discrimination. On the basis of modulus of elasticity and bending strength values measured on boards, Nepveu and Blachon (1989) recommend that to guarantee the best mechanical properties, at least for structural uses, a ring width of 5 mm should not be exceeded. To put this into perspective, one can mention that the maximum RW allowed by the Belgian and French Visual grading standards (NBN B16-520 and NF B52-001) for accessing the best grade class is 6 mm (and even 8 mm in some circumstances according to NF B52-001).

It is worth mentioning that few studies on Douglas-fir wood grown outside its native range were performed on small clear specimens. These tests however allow objective characterization of wood properties as well as inter-specific comparison of Douglas-fir with other species used for the same purposes - in this study larch (*Larix decidua* Mill.) and spruce (*Picea abies* (L.) Karst.). One should bear in mind, however, that the levels of the measured properties cannot describe full boards, whose properties are influenced also by defects such as knots, slope of grain, etc.

Given the range of potential Douglas-fir uses (structure, cladding, interior and exterior woodwork...), it is important to make sure that dynamic silvicultural practices do not compromise some uses. In this context, the main objective of this study was to test the effect of growth rate (expressed through ring width measured on test specimens, RW_s) on the physico-mechanical properties of Douglas-fir wood. As a corollary, the effect of wood density on the other properties was also studied. Finally, thorough analysis required assessing the potential effect of site, tree, and cambial age of the wood.

Material and methods

The experimental material was collected in 11 Douglas-fir stands distributed all over Wallonia (southern Belgium). At the time of felling, stand age ranged from 41 to 69 years whilst the mean girth of the trees was approximately 150 cm. The other main characteristics of the stands are presented in table 1. In each stand, six trees were cut, belonging to 10-cm girth categories (at 1.5 m height) between 120 cm and 180 cm. The trees were randomly chosen among well-formed trees assumed to belong to the final stand. Injured trees, bowed trees, border trees, and other trees showing abnormal development

were avoided. The sampling methodology was designed so that the stands involved in the study were representative of contrasting silvicultural management practices (although little information was available regarding the management practices in some stands). The mean annual radial increment of the trees, i.e. ring width (RW_t), calculated on disks located 2 m high in the standing tree, ranged from 3 to 7 mm (Fig. 1). Fig. 1 also presents the average of the six RW_t values within each stand, as an indicator of stand growth rate.

The cutting pattern of the test specimens was identical for all trees (Fig. 2). An 85-mm-thick central plank containing the pith was cut perpendicularly to the longest radius - in order to avoid the presence of reaction wood - within the 0.6- to 2-m-height logs of the 66 trees. This plank was longitudinally sawn, from the pith, into two half-planks, to avoid shrinkage cracks during drying. After natural drying, both half-planks were sawn parallel to the grain into 30-mm-thick battens starting from the bark. These were stored under a standard atmosphere of 20 ± 2 °C and $65 \pm 5\%$ relative humidity in order to stabilize the wood moisture content at $12 \pm 1\%$. The batten near the pith was numbered "0", and the remaining battens were numbered successively towards the bark. The battens were then cut into three chunks of 400 mm minimum length, optimizing the cut to discard knots and other defects.

These chunks were cut longitudinally into three bars ($400 \times 30 \times 26$ mm³). Among the nine bars produced from each batten (corresponding to one radial position), four were selected according to criteria defined in the standards used in this study, i.e. straight grain without knots or defects. These bars were then planed to a final thickness and width of 20×20 (± 0.2) mm² and the length needed for the mechanical tests. For each radial position two specimens were selected for the impact bending strength test ($300 \times 20 \times 20$ mm³) and two for determining the modulus of elasticity in static bending ($360 \times 20 \times 20$ mm³). The specimens (of shorter length) required for other qualification tests were taken from these four large samples after the impact and static bending tests were performed (Fig. 2).

Technological tests

The tests were performed on standardized specimens according to French and ISO standards.

Physical properties

Ring width (mm) and **density at 12% moisture** (kg m⁻³) are well known wood characteristics. According to ISO 4858, **total volumetric shrinkage** (%) corresponds to $(V_s - V_0)/V_s$,

1 where V_s and V_0 are the volume of the water-saturated and oven dry specimen, respectively. **Total**
2 **linear shrinkage** (%) equals $(L_s - L_0)/L_s$, where L_s is the length of the water-saturated sample in a given
3 direction (radial or tangential), whilst L_0 is the distance between the same points in the oven dry state
4 (ISO 4469). Shrinkage occurs when the water content decreases below the fibre saturation point. It is
5 important to consider this parameter because it partly determines the dimensional instability of the
6 wood, which is a major disadvantage of this material.

7 *Mechanical properties*

8 **Impact bending strength** or **resilience** (J cm^{-2}) (ISO 3348) measures the energy that must be
9 absorbed to cause breaking of the specimen in dynamic bending (shock). Measurements were
10 performed with a pendulum machine test where a hammer strikes the specimen at its center along the
11 direction tangential to the ring. This property is important for mobile uses (crates, sport articles, handle
12 tools...).

13 The following mechanical tests were performed with an Instron[®] 5500 series testing machine.

14 **Modulus of elasticity in static bending** (MPa) (ISO 3349) quantifies the wood rigidity using
15 the "4-point system". The force is applied parallel to the rings under gradually increasing load applied
16 at two points in the zone of pure bending of an elastic deformation. The distance between the support
17 points is 320 mm and loading points are located 80 mm from them. The deformation is measured
18 between a load of 200 N and 600 N reached within 30 s. **Static bending strength** (MPa) (ISO 3133) is
19 the maximum load that the wood can support momentarily before breaking, when the ends of the test
20 specimen are placed on a support and the sample is progressively loaded at two points, parallel to the
21 ring. The load is applied at a constant speed of 3000 N/min until breaking, reached within 1.5 ± 0.5
22 min. The measure of **Compression strength** (MPa) (NF B51-007) involves progressive crushing of
23 the specimen in the axial direction, in order to determine the maximum load applied prior to the
24 appearance of a break or crack. The load is applied at a speed of 1170 daN/min. **Hardness** (no unit)
25 (NF B51-013) is the resistance of the wood to the penetration of a hard body. Hardness is expressed as
26 the inverse of the penetration depth generated by a 3-cm-diameter steel cylinder with a load of 1000 N
27 per width centimeter of the specimen. Regarding Monnin hardness determinations, the depth of
28 penetration of the steel cylinder into the wood is calculated from the footprint width.

Distinction of juvenile and mature wood

In the analyses performed here, it is important to consider the effect of the nature of the wood, and thus to distinguish specimens taken from mature wood and those containing juvenile wood. The latter is characterized by less advantageous mechanical properties and wider ring width than mature wood (Hébert et al. 2002). On the basis of wood density, some authors mention relatively variable number of juvenile wood rings (in Akhter and Hale 2002): 12 rings according to Winandy and Morrell (1993), 15 to 20 rings for Hong and Morrell (1997). More recently, Drewett (2015) and Blohm et al. (2016) reported 10 to 20 rings of juvenile wood. We considered that the transition occurs around the 15th ring counted from the pith, a threshold adopted in several other studies (Wellwood and Smith 1962 in Zobel and Van Buijtenen 1989; Melin and Riou-Nivert 1985).

The cambial age of a specimen was defined as the age of the ring (counted from the pith) at which roughly 50% of the piece of wood is older and 50% is younger. It was considered that the test specimens having a cambial age ≥ 17 years contained only wood produced after the 15th year and were thus free, or almost, of juvenile wood. Conversely, the test specimens under 13 years old were considered to be pure juvenile wood.

Statistical analysis

As a first step, the statistical parameters of position and dispersion of the studied properties were measured for all specimens, with no distinction between juvenile and mature wood, and with distinction of these. Afterwards, the effect of ring width and density on the studied properties was assessed through regression analysis, separately for juvenile and mature wood. In order to have a finer and unbiased understanding of the relationships studied here, a hierarchical random model of analysis of variance with two random effects (site and tree (site)) was used to explain the variation of the physico-mechanical properties. Also, to quantify the influence of mean ring width and cambial age on the total variability of specimen properties, these fixed effects measured on the specimens were added to the model. Statistical analyses were performed with the Minitab software version 17.

1 **Results and discussion**

2 **Mean values**

3 Table 2 shows for all specimens (no distinction between juvenile and mature wood) the
4 statistical parameters of position and dispersion of the various properties measured in this study, along
5 with the values reported in the literature for Douglas-fir, Norway spruce, and European larch. The
6 comparisons below are only indicative, because the material and experimental conditions of the other
7 studies in this table may be different. Since our specimens were collected from the central plank of the
8 log (which constitutes, in fact, a transect through a circular area), juvenile wood is over-represented in
9 the samples. For instance, if three of ten equidistant specimens taken along a radius are made of
10 juvenile wood, they represent 30% of the sample, whereas the surface of juvenile wood represents
11 only 9% of the total area of the section. Hence, all values were weighted according to the radial
12 position of the specimens they were recorded on. The relative difference between weighted and non-
13 weighted values ranged from 2 to 5%, depending on the property. As expected, the mean unweighted
14 values were always lower than the weighted values.

15 Douglas-fir properties appear very similar to those of larch and more favourable than those of
16 spruce. The density (ρ_{12}) of Douglas-fir is lower than that of larch, but higher than that of spruce. The
17 volumetric (β_{vol}) and linear (β_{rad} , β_{tang}) shrinkages of Douglas-fir are comparable to those reported in
18 the literature for this species, and slightly lower than those of spruce and larch (except for the linear
19 shrinkage values reported in Kollmann 1951 and Rijdsdijk and Laming 1994, and the tangential
20 shrinkage values reported in Charron et al. 2003). The hardness (N) of Douglas-fir is comparable to
21 that of larch, spruce wood being much softer. The very good modulus of elasticity (E) and static
22 bending strength (σ_f) values observed in our study are higher than those mentioned in the literature for
23 the same species, and also higher than those of spruce and larch (except the mean value of σ_f obtained
24 by Charron et al. 2003 and Kollmann 1951 for larch). The axial compression strength (σ_c) and
25 resilience (K) are similar to those of larch and spruce.

26 Table 3 presents the statistical parameters of position and dispersion of the various properties
27 measured in this study when a distinction was made between mature and juvenile wood.

Whatever the property considered, juvenile wood shows values 10 to 30% lower than those observed in mature wood. Compared to the latter, juvenile wood has an 11% lower density (ρ_{12}), a 15% lower axial compression strength (σ_c), a 20% lower static bending strength (σ_f), a 22% lower modulus of elasticity (E), and nearly 30% lower hardness (N) and resilience (K) values. The weaker mechanical properties of the juvenile versus mature wood have been evidenced by many authors (Melin and Riou-Nivert 1985; Megraw 1986; Barrett and Kellogg 1991; Bawcombe 2012; Blohm 2015; Drewett 2015). They are due partly to the lower density and higher mean ring width of juvenile wood. At the anatomical level, thinner cell walls, shorter tracheids, and a larger microfibril angle explain the weaker properties of juvenile wood (Megraw 1986; Jozsa and Middleton 1994; Vikram et al. 2011). Note that, as mentioned by Charron et al. (2003) who report a similar trend in larch, the lower values of juvenile wood are an advantage when considering shrinkages.

Effect of density

The graphs of figure 3 illustrate the relationship between density (at 12% moisture content) and the various properties studied, distinguishing juvenile from mature wood.

The physical and mechanical properties increase with the density and the coefficients of determination vary approximately from 0.45 to 0.75 (Fig.3, graphs a to h), except for the shrinkages, whose variability is higher (R^2 from 0.19 to 0.45) (Fig. 3, graphs e to g). These results are in agreement with those of many authors, who have evidenced the preponderant influence of wood density on its mechanical characteristics (Jozsa and Middleton 1994; Kennedy 1995; Leban and Mothe 1996; Rozenberg et al. 1999; Drewett 2015). According to Todaro and Macchioni (2011), the density of the wood is the most important parameter explaining variations in bending strength in Douglas-fir wood. According to Megraw (1986), several studies on the heritability of density highlight the importance of genetics in determining this property. In Douglas-fir, it has generally been shown that the mean density is closely linked to the latewood percentage (Erikson and Harrison 1974; Dedeckel 1994; Jozsa and Middleton 1994). It is therefore not surprising that, according to Lachenbruch et al. (2010), latewood percentage and density make the largest contributions to the modulus of elasticity and bending strength.

Whatever the property considered, a given increase in density appears to have similar effects in juvenile and mature wood: in each graph, the slopes of the two regression lines are indeed very similar (Fig. 3, graphs a to h). One should note, however, that for a given density, the average value of the modulus of elasticity (E) is more than 1000 MPa higher in mature than in juvenile wood (Fig. 3, graph a).

On the basis of the regression equations presented in Fig. 3, the relative variations of the different properties induced by a 1% change in density were determined. For each property, the reference value corresponds to a density of 500 kg/m³. On average and whatever the nature of the wood, a 1% relative increase in density leads to:

- an approximately 1% increase in β_{tang} and β_{vol} and 1.3% increase in β_{rad} ;
- a 1.2% increase in σ_c ;
- a 1.4% increase in E and σ_f ;
- a more than 2% increase in K and N .

Effect of the mean ring width of the specimen (RW_s)

The graphs of figure 4 illustrate the relationship between the mean ring width measured on the test specimens (RW_s) and the properties studied, distinguishing juvenile from mature wood.

In mature wood, all the properties decrease significantly as the mean ring width increases (Fig. 4, graphs a to i). The coefficient of determination between these properties and RW_s is generally three times as high for juvenile wood ($R^2 \approx 0.30$) than for mature wood ($R^2 \approx 0.10$) (Fig. 4). In most softwoods species, the wood density decreases when the ring width increases (Geldreich 1981; Leban and Mothe 1996) but, in agreement with our results, other studies indicate a weak correlation between these two characteristics (Kennedy 1995; Lauseberg et al. 1995). Bawcombe (2012) also reports a significant but low impact of ring width on E , σ_f and σ_c . This suggests that factors other than growth rate (site, genetic provenance, anatomical characteristics...) determine the density of Douglas-fir wood and thus also its mechanical properties, given the influence of density on these properties reported by Zhang (1995) and observed here. According to Megraw (1986) and Rosenberg et al. (2001), most of the observed variability of the density-growth relationship in Douglas-fir may be genetic. This suggests that genetic selection, and thus the choice of tree provenance, could have a greater impact on

wood quality than silvicultural measures. Nevertheless, mean density being closely linked to latewood percentage, Geldreich (1981) advocates maintaining a regular ring width in order to minimize density variations (heterogeneity of wood). It is therefore important to limit juvenile growth (up to 20-30 years) and then carry out regular thinning, so as to ensure uniform growth.

Table 4 presents, for mature and juvenile wood, the proportion of test specimens (%) having a value higher than a reference value for each studied characteristic, in classes based on the specimen mean ring width (RW_s). For each characteristic, the reference value is the rounded average of the values observed in the data set. This table also shows, for mature and juvenile wood, the average values and relative differences in measured properties, distinguishing samples according to their RW_s (above or below 5 mm). The classes were defined so as to ensure a sufficient number of specimens in each class.

Up to 6 mm ring width, more than 50% of the mature wood specimens display a value above the reference value for all the properties studied. The exception is the resilience coefficient (K) for which this proportion already drops from 4 mm annual radial growth. Interestingly, the proportion of test specimens having a higher shrinkage than the reference value decreases with increasing RW_s . The radial shrinkage, however, seems practically unaffected by the growth rate: whatever the latter, at least 65% of the test specimens taken from mature wood have a higher value than the reference value. In the case of juvenile wood, the proportion of specimens showing values above the reference value is already lower in RW_s class [3; 4mm[for most of the properties.

In mature wood, the percentage difference in mean value between test specimens having a $RW_s < 5$ mm and those having a $RW_s > 5$ mm varies from 4 to 14%, depending on the property considered. In their article on the mechanical properties of Douglas-fir boards, Nepveu and Blachon (1989) propose 5 mm as the RW threshold that should not be exceeded in order to maintain the highest mechanical properties (in a structural use perspective). For most properties, the percentage differences for juvenile wood between $RW_s < 5$ mm and > 5 mm are about twice as high as those observed for mature wood. In other words, juvenile wood appears more sensitive to dynamic growth than mature wood.

1 **Statistical analysis of the different sources of variation**

2 Table 5 summarizes the results of a variance analysis performed to assess how physico-
3 mechanical properties are influenced by both site and tree (site) random effects, as well as two fixed
4 effects related to the test specimen: mean ring width and cambial age. To lighten the report, only the
5 regression equations and the significance levels of the variance analysis are shown in the table (with a
6 colour code).

7 The first equation shows the significant correlation between density on the one hand and ring
8 width and cambial age on the other hand. This observation confirms the results previously presented in
9 Fig. 4.a (considering that nature of the wood – juvenile or mature – is a rough expression of cambial
10 age). Hence, given that assessing the effect of ring width was the primary objective in this research,
11 the regression models were kept simple by introducing only ring width and cambial age as fixed
12 effects, and site and tree(site) as random effects.

13 Statistical analysis reveals a highly significant site effect only for the modulus of elasticity.
14 The random site effect (including genetic provenance and environmental factors) does not seem to be
15 a major source of variation, accounting for only 4-7% of the total variability, except for E. The random
16 tree effect appears much greater (14 to 33% of the total variability), and all properties studied show
17 very highly significant between-trees differences. Melin and Riou-Nivert (1985) also observed
18 considerable variability of properties between Douglas-fir individuals. Since the random tree effect
19 almost certainly includes a genetic component, our results still demonstrate the potential importance of
20 individual genetic heritage as explained previously.

21 The inclusion of fixed effects shows that mean ring width and cambial age account together
22 for 28 to 40% of the total variability of the specimens' properties; they are also very highly significant
23 for all properties. It should be noted that initial exploratory statistical analyses showed that when
24 density, mean ring width and cambial age are individually added to the model as covariates, density
25 appears as the main explanatory variable, accounting for 30 to 78% of the variability. These results
26 demonstrate that the influence of ring width and cambial age on the wood properties analyzed are
27 largely attributable to their correlation with wood density. Similar results are reported in Drewett
28 (2015).

The regression equations in Table 5 quantify the theoretical impact of ring width increase on the nine studied properties. As these properties and ring width depend on cambial age, specimens were classified into 10-yr cambial age categories between 1 to 60 years (six classes), and mean RW_s was calculated for each class. Then the theoretical properties of specimens with RW_s respectively 25% higher and 25% lower than the mean RW_s were calculated for each cambial age class. Based on the difference between both values, Fig. 5 presents the relative decrease of all properties across successively older cambial age classes, expressed as a percentage of the value corresponding to the lower ring width (i.e. mean $RW_s \cdot 0.75$). Proportional differences of mean ring width have a higher impact on the properties in the juvenile wood than in the mature wood. So, from the 30th-40th ring, the faster growth rate induced only a 5-10% decrease in wood properties (compared to slow growth rate); this difference even drops below 5% in specimens older than 50 years (except for E, K and β_{rad}).

Conclusion

The objective of these tests was to identify the factors influencing the physical and mechanical properties of Douglas-fir wood from Western Europe, with a special emphasis on ring width effect.

Although the impact of growth rate must also be quantified on boards (which notably integrate the impact of silviculture on knot size and abundance), the results of our tests on standard specimens are already very instructive. Not surprisingly, the mechanical properties of the test specimens increase significantly with density, which appeared as the most important parameter driving wood properties. However, a weaker but significant effect of growth rate on the properties was evidenced. This effect depends on wood cambial age, juvenile wood being more sensitive to ring width increase than mature wood.

Depending on the property, the difference between average values observed in juvenile and mature wood ranges from 10 to 30%. Forest management practices inducing excessive juvenile growth (low plantation density, early and strong thinning) should therefore be considered cautiously. From a purely mechanical standpoint, it seems that juvenile growth should be minimized or at least maintained at a relatively low level, near 4 mm/year. Naturally, other considerations such as profitability of the forest investment could lead to reconsidering this threshold. Concerning mature wood, the results are very encouraging: it seems that ring widths below 6 mm guarantee very high-

1 level mechanical properties in Douglas-fir wood. This is consistent with the values mentioned in the
2 visual grading standard for structural timber (NBN B16-520). Hence, although juvenile growth must
3 clearly be controlled, enhanced growth rates do not seem to cause substantial reduction in wood
4 density and associated wood properties. Lastly, as highlighted by Megraw (1986), the major
5 performances of Douglas-fir, like those of most other wood species, result directly from the micro-
6 structural characteristics of its wood. An anatomical analysis that is being conducted as part of our
7 research should thus help to address with more finesse the properties of Douglas-fir wood.

8

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Table 1: Main characteristics of the 11 stands at the time of the felling.

Stand	Forest district	number of rings on stump	Initial spacing (m)	Initial composition	Mean girth (cm)	Number of trees (n/ha)	Basal area (m ² /ha)	Mean annual Girth increment (cm/an)	Dominant height (m)	Site index*
SPA	Spa	69	1.5 X 1.5	Pure	163	174	-	2,3	36,3	4
BEAU	Beauraing	59	-	Mixture <i>Abies</i> sp.	160	175	36	2,7	38,3	3
VIEL	Vielsalm	57	-	Pure	139	188	30	2,8	35,9	3
LIB	Libin	53	1.5 X 1.5	Pure	155	175	35	3,0	37,0	2
FLA	Florenville	53	-	Mixture <i>Larix</i> sp.	155	225	45	3,0	36,0	2
BER	Bertrix	53	2.0 X 1.5	Pure	148	243	42	3,0	34,8	3
FLB	Florenville	49	2.0 X 2.0	Pure	153	211	40	3,3	36,0	2
DEL	Florenville	46	2.0 X 2.0	Pure	152	158	29	3,5	35,8	1
REI	Florenville	45	1.8 X 1.8	Mixture <i>Picea</i> sp.	150	170	31	3,6	34,3	2
PHB	Philippeville	44	2.0 X 2.3	Pure	157	142	28	3,7	32,0	2
PHA	Philippeville	41	2.0 X 2.3	Pure	143	140	23	4,0	33,1	1

*according to Perin et al. (2016)

Table 2: Physical and mechanical properties measured on standardized test specimens. The results are compared with values collected in the literature for Douglas-fir, spruce, and larch (n = number of samples, m = mean, min = minimum, max = maximum, CV = coefficient of variation, RW_s = mean ring width, ρ_{12} = density at 12% moisture, β_{vol} = total volume shrinkage, β_{rad} = total radial linear shrinkage, β_{tang} = total tangential linear shrinkage, N = hardness, E = modulus of elasticity in static bending, σ_f = static bending strength, σ_c = compression strength, K = resilience).

Characteristic	Present study, Douglas-fir						Literature		
	n	m	m*	min	max	CV	Douglas-fir (<i>Pseudotsuga menziesii</i> Franco)	Spruce (<i>Picea abies</i> (L.) KARST.)	Larch (<i>Larix decidua</i> Mill.)
RW_s (mm)	1254	4.8	-	1.7	10.8	32%	3-12 ^b ; 3-4 ^b	3.5 ^{b2}	4.1 ^{b1}
ρ_{12} (kg m ⁻³)	1254	506	514	376	653	10%	540 ⁿ ; 450-600 ^d ; 426 ^a ; 470 ^a ; 480 ^u	419 ^{b2} ; 450 ⁿ ; 430 ^d ; 430 ^a	642 ^{b1} ; 600 ^{n,d} ; 550 ^a
β_{vol} (%)	1370	11.7	12.1	6.9	17.5	14%	13 ^{n,d,b} ; 9.8 ^a ; 11.9 ^a ; 12.4 ^u	14 ⁿ ; 11.9 ^a	15 ^{b1} ; 14 ⁿ ; 11.4 ^a
β_{rad} (%)	1370	4.4	4.6	1.6	8.1	22%	4 ^{b3} ; 5.1 ⁿ ; 3.5 ^a ; 4.2 ^a ; 4.8 ^u	4.5 ^{b3} ; 5.1 ⁿ ; 3.6 ^a	4.7 ^{b1} ; 3.5 ^{b3}
β_{tang} (%)	1378	7.8	8.0	2.6	12.8	17%	7 ^{b3} ; 8.1 ⁿ ; 6.3 ^a ; 7.4 ^a ; 7.6 ^u	9.8 ^{b3} ; 9.3 ⁿ ; 7.8 ^a	7.5 ^{b1} ; 7 ^{b3} ; 9.2 ⁿ ; 7.8 ^a
N (-)	1388	2.4	2.5	0.8	5.2	28%	2.2 ⁿ	1.4 ⁿ	2.7 ⁿ
E (MPa)	1254	13966	14482	5834	21745	19%	12100 ⁿ ; 10900 ^b ; 8580 ^a ; 11500 ^a ; 13400 ^u	11663 ^{b2} ; 11000 ^{n,a}	12000 ^{b1} ; 12500 ⁿ¹ ; 13800 ^a
σ_f (MPa)	1253	97	100	32	142	19%	85 ⁿ ; 81 ^b ; 79 ^a ; 79 ^a ; 85 ^u	71 ⁿ ; 78 ^a	112 ^{b1} ; 93 ⁿ ; 99 ^a
σ_c (MPa)	1382	49	50.4	28	70	15%	55 ⁿ ; 46 ^b ; 46 ^a ; 47 ^a ; 50 ^u	45 ⁿ ; 50 ^a	55 ^{b1} ; 53 ⁿ ; 55 ^a
K (J cm ⁻²)	1157	5.7	6	1.2	12.5	31%	5 ⁿ	4.5 ⁿ	6 ^{b1,n}

* weighted values

Belgium: ^{b1}Charron et al. (2003), ^{b2}Jourez and Leclercq (1994), ^{b3}Rijsdijk and Laming (1994)

France: ⁿBenoit (2008), ^dCollardet and Besset (1988), ^aCTBA (1986), ^uMelin (1984)

Germany: ^aKollmann (1951)

USA: ^uWood Handbook (2010)

Table 3: Physical and mechanical properties measured on standardized test specimens, a distinction being made between juvenile and mature wood (n = number of samples, m = mean, min = minimum, max = maximum, CV = coefficient of variation, RW_s = mean ring width, ρ_{12} = density at 12% moisture, β_{vol} = total volume shrinkage, β_{rad} = total radial linear shrinkage, β_{tang} = total tangential linear shrinkage, N = hardness, E = modulus of elasticity in static bending, σ_f = static bending strength, σ_c = compression strength, K = resilience). Difference (%) is the relative difference between the average for the mature wood and that observed in the juvenile wood.

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Characteristic	Mature wood					Juvenile wood					Difference (%)
	n	m	min	max	CV	n	m	min	max	CV	
RW_s (mm)	884	4.6	1.7	9.8	30%	274	5.6	2.2	10.8	33%	-22
ρ_{12} (kg m ⁻³)	884	520	402	653	9%	274	465	376	570	9%	11
β_{vol} (%)	883	12.3	7.4	17.5	12%	389	10.6	6.9	14.7	13%	13
β_{rad} (%)	885	4.7	1.9	8.1	20%	387	3.9	1.6	7.1	22%	17
β_{tang} (%)	888	8.1	3.0	12.4	16%	393	7.0	2.6	12.8	17%	14
N (-)	888	2.6	1.3	5.2	23%	400	1.8	0.8	3.6	27%	30
E (MPa)	884	14807	7535	21745	15%	274	11514	5834	16452	20%	22
σ_f (MPa)	883	102	44	142	16%	274	82	32	118	20%	20
σ_c (MPa)	891	52	34	70	13%	391	44	28	63	14%	15
K (J cm ⁻²)	868	6	1.8	12.5	28%	202	4	1.2	10.2	34%	28

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Table 4. Proportion (%) of test specimens having a value higher than or equal to a reference value for each characteristic in each mean ring width (RW_s) class in mature and juvenile wood (classes with less than 10 measurements are not included in the table); mean values of the test specimens according to their RW_s (below or above 5 mm); observed difference (%) between these two groups in mature and juvenile wood (n = number of samples, ρ_{12} = density at 12% moisture, β_{vol} = total volume shrinkage, β_{rad} = total radial linear shrinkage, β_{tang} = total tangential linear shrinkage, N = hardness, E = modulus of elasticity in static bending, σ_f = static bending strength, σ_c = compression strength, K = resilience).

	Reference value	RWs class (mm)							RWs (mm)		Difference (%)	
		[2;3]	[3;4]	[4;5]	[5;6]	[6;7]	[7;8]	[8;9]	< 5mm	> 5mm		
Mature wood	ρ ₁₂ (kg/m ²)	500	80	80	61	64	47	24	-	529	505	5
	β _{voi} (%)	12	66	69	57	55	39	18	-	12.4	11.9	4
	β _{rad} (%)	4	88	89	78	66	70	68	-	4.9	4.4	10
	β _{tang} (%)	8	64	67	56	54	46	18	-	8.3	7.8	6
	N (-)	2.4	70	77	61	56	51	33	-	2.7	2.4	12
	E (MPa)	14000	76	78	66	63	42	14	-	15268	13970	9
	σ _f (MPa)	96	72	81	59	64	50	24	-	105	97	8
	σ _c (MPa)	50	66	76	53	51	57	24	-	53	49	7
	K (J cm ⁻²)	6	67	64	46	39	33	24	-	6.4	5.5	14
	n (min-max)		86-94	241-254	228-235	174-180	82-99	21-29	0	569-587	294-319	
Juvenile wood	ρ ₁₂ (kg/m ²)	500	60	48	35	20	6	7	0	491	446	9
	β _{voi} (%)	12	27	46	23	18	11	0	0	11.4	10.2	11
	β _{rad} (%)	4	77	69	43	48	31	16	0	4.4	3.6	17
	β _{tang} (%)	8	36	43	29	25	4	4	0	7.7	6.6	13
	N (-)	2.4	45	34	15	16	1	5	5	2.1	1.7	17
	E (MPa)	14000	20	28	25	20	8	0	0	12890	10519	18
	σ _f (MPa)	96	60	48	30	17	8	7	0	91	75	18
	σ _c (MPa)	50	39	27	29	15	6	0	0	47	41	12
	K (J cm ⁻²)	6	27	27	3	14	0	3	0	5	4	22
	n (min-max)		15-22	40-54	37-84	42-81	52-80	29-56	13-24	87-154	115-250	

Table 5: Equations of regression and coefficient of correlation from analysis of variance for each property according to mean ring width (RW_s) and cambial age (Age) of the specimens. Share of variability (%) related to each factor and co-variable (sequential sums of squares of the factor or co-variable considered) relative to the total variability of the model (total sequential sums of squares), and significance level of the statistical test with a color code (ρ_{12} = density at 12% moisture, E = modulus of elasticity in static bending, σ_f = static bending strength, σ_c = compression strength, K = resilience, N = hardness, β_{vol} = total volume shrinkage, β_{tang} = total tangential linear shrinkage, β_{rad} = total linear radial shrinkage).

Equation of regression					r^2	Share of variability (%)			
						Site	Tree	RW_s	Age
ρ_{12}	=	497 - 7,815 * RW_s + 1,963 * Age	76	6	33	22	15		
E	=	14375 - 621,8 * RW_s + 108,4 * Age	76	12	24	25	15		
σ_f	=	96 - 3,14 * RW_s + 0,665 * Age	67	6	27	20	14		
σ_c	=	51 - 1,5 * RW_s + 0,23 * Age	66	7	26	24	9		
K	=	5,16 - 0,299 * RW_s + 0,079 * Age	63	4	23	17	19		
N	=	1,32 - 0,054 * RW_s + 0,015 * Age	65	4	24	19	18		
β_{vol}	=	11,8 - 0,31 * RW_s + 0,065 * Age	64	5	21	21	17		
β_{tang}	=	7,8 - 0,217 * RW_s + 0,045 * Age	50	5	17	17	11		
β_{rad}	=	4,7 - 0,209 * RW_s + 0,029 * Age	48	4	14	21	9		
P>0,05 Not significant			NS						
P<0,05 Significant			*						
P<0,01 Highly significant			**						
P<0,001 Very highly significant			***						

1 **Figure 1:** Mean ring width (RW_t) of each of the 66 trees (squares), grouped according to the stand
2 from which they came. On the basis of the 6 individual values, an average RW_t was calculated for
3 each stand (circles).

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1 **Figure 2:** Cutting scheme from log to test specimens (dimensions in mm, β_{vol} = total volumetric
2 shrinkage, β_{tang} = total tangential linear shrinkage, β_{rad} = total radial linear shrinkage, N = hardness, E
3 = modulus of elasticity in static bending, σ_f = static bending strength, σ_c = compression strength, K =
4 resilience).
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Fig. 3. Relationship between physico-mechanical properties and wood density (ρ_{12}) for juvenile and mature wood from Douglas-fir small clears specimens: (a) Modulus of elasticity (E); (b) Static bending strength (σ_f); (c) Compression strength (σ_c); (d) Resilience (K); (e) Total volume shrinkage (β_{vol}); (f) Total tangential linear shrinkage (β_{tang}); (g) Total radial linear shrinkage (β_{rad}); (h) Hardness (N). Graphs created from 884 specimens taken from the mature wood (mean cambial age ≥ 17 ans, small grey squares) and 274 specimens taken from the juvenile wood (mean cambial age ≤ 13 years, small open circles). Seven density classes were defined (boundaries are the values on the X axis). Class values based on fewer than 10 observations appear as open symbols, the others are represented by full squares (mature wood) or circles (juvenile wood). The regression line and the corresponding equation and coefficient of determination are represented above and below the scatter plot, for mature and juvenile wood respectively.

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Fig. 4. Relationship between physico-mechanical properties and ring width (RW_s) for juvenile and mature wood from Douglas-fir small clears specimens: (a) Density at 12% moisture (ρ_{12}), (b) Modulus of elasticity (E), (c) Static bending strength (σ_f), (d) Compression strength (σ_c), (e) Resilience (K), (f) Total volume shrinkage (β_{vol}), (g) Total tangential linear shrinkage (β_{tang}), (h) Total radial linear shrinkage (β_{rad}), (i) Hardness (N). Graphs created from 884 specimens taken from the mature wood (mean cambial age ≥ 17 years, small grey squares) and 274 specimens taken from the juvenile wood (mean cambial age ≤ 13 years, small open circles). Ten RW_s classes were defined (boundaries are the values on the X axis). Class values based on fewer than 10 observations appear as open symbols, others are represented by full squares (mature wood) and circles (juvenile wood). The regression line and the corresponding equation and the coefficient of determination are represented above and below the scatter plot, for mature and juvenile wood respectively.

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Fig. 5. Decline in nine physico-mechanical properties induced by increasing ring width for six 10-yr cambial age classes. Ring width increase was calculated as the difference between the RW_s values respectively 25% higher and 25% lower than the mean RW_s , for each cambial age class. The two RW_s values for each cambial age class are introduced in the regression equations (Table 5). Based on both values obtained, the property decrease is represented for each cambial age class as a percentage of the property value corresponding to the lower RW_s . Mathematically, the loss of a given property is a function of specimens' ring width (RW_s) and cambial age (Age), which can be expressed as follows:

$$\text{Loss (\%)} = [\text{Property (Age, } 0.75 * \text{mean } RW_s \text{ (Age))} - \text{Property (Age, } 1.25 * \text{mean } RW_s \text{ (Age))}] / \text{Property (Age, } 0.75 * \text{mean } RW_s \text{ (Age))}.$$

See Fig. 3 & 4 caption for symbols signification.

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