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Impact of Tree Growth Rate on the Mechanical Properties of Douglas Fir Lumber in Belgium

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Abstract: In the context of questioning the relevance of making Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) silviculture more dynamic in Wallonia, we evaluated the influence of growth rate on the potential of Douglas-fir lumber for structural uses. Therefore, six trees 120 to 180 cm in circumference at 1.5 m were felled in 11 stands whose age varied from 40 to 69 years (mean circumference of the trees ≈150 cm; initial planting density from ≈2200 to 4400 seedlings/ha). In total, 706 boards (38 × 100 mm^2 and 70 × 180 mm^2 in cross section) were cut from these trees, whose average ring width ranged between 3 and 7 mm. The density of the wood (ρ) always appeared compatible with the mechanical class C30, regardless of the growth rate of the trees from which the lumber originated. The modulus of elasticity (E) and the modulus of rupture (f_m) displayed by the 38 × 100 mm^2 boards cut from corewood were respectively 30% and 41% lower than those observed in outerwood. The latter did not seem affected by growth rate: E and f_m characteristic values remained compatible with structural use, regardless of the mean ring width. Growth rate considerably affects the characteristic values of these mechanical properties when boards are made from corewood. Juvenile growth should therefore be limited.

Keywords: *Pseudotsuga menziesii* (Mirb.) Franco; strength grading; ring width; silviculture; corewood; outerwood

1. Introduction

Within the forest landscape of Wallonia (Southern Belgium), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) has experienced a notable progression in recent decades [1]. Introduced to Belgium during the second half of the 19th century, it is currently one of the main reforestation species in Wallonia: the area covered with Douglas fir in Wallonia in the early 2000s (i.e., slightly more than 20,000 ha) had increased tenfold compared to its 1960 levels [2]. This increase is the consequence of the advantageous properties of its wood [3,4], which are associated with a growth potential significantly higher than that of other resinous species [5–7], as well as with significant ecological plasticity. The latter makes it relatively well adapted to the soil and climatic conditions of Wallonia [8]. The above figures underlie the limited experience of Walloon foresters regarding the silvicultural management of Douglas fir. In these circumstances, the silviculture of this species in Wallonia has so far been substantially inspired by that applied to Norway spruce (in terms of spacing at planting, intensity, timing of thinning, etc.). As reported hereafter, initial planting densities of more than 3000 or even 4000 seedlings/ha have been adopted in the past. Present planting guidelines are 2000–2500 seedlings/ha [7], which is approximately double the densities in the leading production countries of France [9] and Germany [10]. This situation has probably implied an under-exploitation of the production potential of the North

American species, as shown by data from the Walloon Permanent Forest Inventory (WPFI) according to which the mean annual circumference increment (MACI) in Walloon Douglas fir stands is about 3.2 cm/year (Lecomte, 2010, pers. com.), while with ad hoc silvicultural management, periodic increments of up to 4 cm/year can easily be achieved, at least in young stands [11]. As recent research in Germany [12,13] or in the United Kingdom [14,15] has shown, European forest managers are therefore questioning the impact of silviculture on the characteristics of the Douglas fir resource. In France, research on this issue has been carried out longer ago [16–18]. Moved by the same questions, the Public Service of Wallonia has therefore subsidized a vast study in order to assess to what extent it would be opportune to boost Douglas fir silviculture in Wallonia while ensuring the production of a material that offers the widest potential of uses. Hence, the influence of growth rate was evaluated on certain morphological characteristics (bark thickness, taper, branchiness, etc.), on the natural durability of the wood [19], on the physico-mechanical properties of clear wood specimens [20], as well as on the mechanical and visual characteristics of lumber destined for structural applications or cladding [21,22]. In addition to the intrinsic mechanical properties of clear wood, it is also important to ensure that the final product does not suffer excessively from an increase in the growth rate of the trees. Indeed, lumber presents features (knots, resin pockets, etc.) which, despite the valuable properties of the material per se, can prove to be prohibitive in a particular context of use. Moreover, although it is known that a higher growth rate determines lower mechanical properties of Douglas fir wood [12–14,17,20], this trend is less pronounced than in other softwood species [17].

Additionally, given the differences in mechanical properties of core- and outerwood (As defined in [23]) [13,15,20,24], the type of wood should also be taken into account as much as possible in the analysis of the impact of tree growth rate. In this respect, it is important to note that the age at which wood exhibits its maturity characteristics notably relies on the property considered [14]: for example, microfibril angle, tracheid length, or density do not necessarily stabilize from the same growth ring [25]. Moreover, even considering only one property (e.g., specific gravity), the age of transition can vary significantly between trees and provenances [26], this age being under "appreciable genetic control" [27]. It should also be noted that a slightly earlier transition to maturity in slower-growing trees has been reported [14]. However, if significant at 1.3 m, this impact is no longer significant at 8 m height. In fact, if outerwood is characterized by relatively stable properties, those of corewood evolve from the pith to the levels specific to outerwood: the transition between core- and outerwood is therefore gradual. According to [15,28], who respectively studied British and German Douglas fir, the mature character of wood is generally observed at an age between 10 and 20 years (although full maturity can only be observed beyond the 30th growth ring).

Finally, the Construction Products Regulation CPR 305/2011 has for some years imposed upon European sawmillers the grading of lumber intended for structural applications, which in Western Europe remains the main outlets of Douglas fir.

In this context, the research presented here aims at evaluating, from the perspective of lumber grading, to what extent growth rate (assumed to be representative of silviculture) influences the potential use of Douglas fir boards for structural applications.

2. Materials and Methods

2.1. Material

The experimental material was collected from 11 even-aged stands where the average Douglas fir circumference was about 150 cm at the time the trees were felled. These plantations were then between 40 and 69 years old. General and dendrometric stand characteristics are presented in Table 1.

Table 1. General characteristics of the 11 sampled Douglas fir plantations. C_{mean}: mean circumference of the Douglas firs; N_{ha}: number of trees per hectare at the time of tree cutting; MACI: mean annual circumference increment; H_{dom}: dominant height.

Stand	Forest District	N° of Rings on Stump	Initial Spacing (m)	Initial Composition	C_{mean} (cm)	N_{ha}	Basal Area (m^2/ha)	MACI (cm/year)	H_{dom} (m)
SPA	Spa	69	1.5 × 1.5	Pure	163	174	unknown	2.3	36.3
BEAU	Beauraing	59	unknown	Mixt. with *Abies* sp.	160	175	36	2.7	38.3
VIEL	Vielsalm	57	unknown	Pure	139	188	30	2.8	35.9
LIB	Libin	53	1.5 × 1.5	Pure	155	175	35	3.0	37.0
FLA	Florenville	53	unknown	Mixt. with *Larix* sp.	155	225	45	3.0	36.0
BER	Bertrix	53	2.0 × 1.5	Pure	148	243	42	3.0	34.8
FLB	Florenville	49	2.0 × 2.0	Pure	153	211	40	3.3	36.0
DEL	Florenville	46	2.0 × 2.0	Pure	152	158	29	3.5	35.8
REI	Florenville	45	1.8 × 1.8	Mixt. with *Picea* sp.	150	170	31	3.6	34.3
PHB	Philippeville	44	2.0 × 2.3	Pure	157	142	28	3.7	32.0
PHA	Philippeville	41	2.0 × 2.3	Pure	143	140	23	4.0	33.1

It should be noted that although planting densities varied by a factor of two (±4400 in Spa and Libin, vs. ±2200 in Philippeville), they were all relatively high in absolute terms—much higher than those characterizing stands studied for a similar objective by, among others, [29]—1000 seedlings/ha, [30]—400 seedlings/ha, or [10]—100 seedlings/ha.

Six trees were collected from within each stand, belonging to circumference classes at 1.5 m height [120 cm; 129 cm], [130 cm; 139 cm], [140 cm; 149 cm], [150 cm; 159 cm], [160 cm; 169 cm] and [170 cm; 179 cm]. These trees were randomly selected among those supposed to be final crop trees (i.e., they were well shaped, straight grain, displayed well-balanced crown, no apparent curvature of the foot log, etc.). The 66 trees in the sample thus had contrasting individual growth rates: their average ring width (RW_{tree}) measured on a disk taken at 2 m height varied from barely 3 mm (smallest tree of the oldest stand) to more than 7 mm (largest tree of the youngest stand). The sample broadly covered the range of RW_{tree} encountered within the Walloon Douglas fir stands. However, due to the structure of the sample, it should be noted that 60% of the trees had a RW between 4 and 5.5 mm (Figure 1).

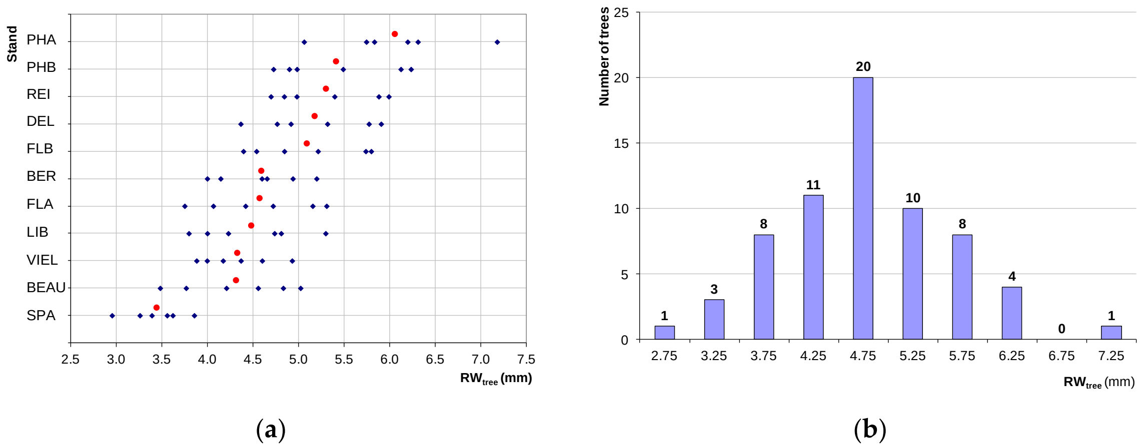


Figure 1. (**a**) Mean ring widths of the 66 trees (RW_{tree}—squares), measured at 2 m height. For each of the 11 stands, an average RW_{tree} was calculated (circles) on the basis of the six individual values; (**b**) Frequency distribution of RW_{tree} in classes of 0.5 mm, from [2.5 mm; 3.0 mm] to [7.0 mm; 7.5 mm].

In order to provide the material for the various tests, the 66 trees were cut according to a common protocol (for more details, see [21]). The boards studied here originated from three log types, as described in Table 2.

Table 2. Characteristics of the analyzed boards.

Cross Section (mm^2)	Origin	Length (m)	Height in Standing Tree (m)	Number
38 × 100	Log n°2 of 33 trees ([120; 129], [140; 149] and [160; 169])	2.2	[2.2–4.4]	238
38 × 100	Log n°3 of 33 trees ([120; 129], [140; 149] and [160; 169])	2.2	[6.0–8.2]	207
70 × 180	Log n°5 of 65 trees [1]	4.3	[11–15.3]	261

[1] The smallest tree of stand PHB broke at 13 m height when it was cut.

Logs n°5 were entirely cut into 70 × 180 mm^2 boards, producing as many wane-free pieces as possible. On the other hand, the 38 × 100 mm^2 boards taken from logs n°2 and n°3 resulted from the edging of the 110 mm thick transverse slice centered on the pith and perpendicular to the largest radius of the section (in order to minimize the presence of reaction wood). No 38 × 100 mm^2 boards were taken out of the transverse slice.

These cutting schemes do not necessarily correspond to what would have been done in sawmills. They were underpinned by the carried out visual and mechanical strength grading of the boards (remembering that boards of different sections are not affected equally by the presence of knots of a given size, for example). The fact remains that the boards analyzed here allowed an objective evaluation of the impact of tree growth rate on the mechanical properties of the lumber.

With regard to the 445 38 × 100 mm^2 boards, the proportion of the section of the log that they represent increases with the distance that separated them from the pith. For some evaluations, it may therefore be suitable to weight the importance of each board in the sample according to its radial position.

2.2. Methods

2.2.1. Measurement of the Boards' Properties

Before the mechanical trials, a visual strength-grading was carried out on all boards at a moisture content of around 20%, obtained through natural seasoning [21]. Within the framework of this grading, the average ring width observed on each board (RW_{board}) as well as the marginal and total knot area ratios (KAR_m and KAR_t) were determined in accordance with the methodology presented in NBN B 16-520 [31].

Although it has been mentioned that the transition between core- and outerwood is progressive, it was necessary for the purposes of this study to distinguish sub-samples of boards according to the nature of the wood they were made of, which made it necessary for us to fix a transition age. The compromise adopted in the present study was to consider that the transition between core- and outerwood occurs when the cambial age is 15 years; this is also the compromise adopted by [16,24,26,32]. The average cambial age of the 38 × 100 mm^2 boards (Age_{camb}) was defined as the age of the ring (counted from the pith) for which roughly 50% of the wood of the board is older, and 50% is younger. This characteristic was not determined on the 70 × 180 mm^2 boards. The 38 × 100 mm^2 boards were considered to be exclusively (or almost) made of corewood when their average cambial age was 10 years or less; if Age_{camb} was 20 years or more, they were considered as mainly composed of outerwood; between these two values, the nature of the boards was considered as mixed.

The physico-mechanical properties considered to determine the potential of wood in structural uses were the density at 12% humidity ($\rho_{12\%}$), the modulus of elasticity in static bending ($E_{m,g}$, which we will generally call E or stiffness), and the static bending strength (f_m). The characteristic values required in the different mechanical strength classes are defined in EN 338 [33]. These values are the percentile 5% for $\rho_{12\%}$ ($\rho_{12\%,k}$) and f_m ($f_{m,k}$), and the mean for E (E_{mean}).

The physico-mechanical properties of the 38 × 100 mm^2 and 70 × 180 mm^2 boards were measured within the facilities of the TERRA Teaching and Research Center (Gembloux Agro-Bio Tech, University of Liège, Liège, Belgium) and of the FCBA Institute of Technology (Bordeaux, France), respectively. Stiffness was determined in accordance with EN 408 [34]. When the boards' moisture content was different from 12%, $E_{m,g}$ values were adjusted according to the methodology described in EN 384 [35].

After stiffness measurement, the boards were again kept in a conditioned atmosphere and their average moisture content reached the expected 12%. The boards were broken on a test stand and the f_m value was determined in accordance with EN 408 [34]. According to EN 384 [35], these values were divided by $(150/h)^{0.2}$, where h is the height of the boards in mm.

2.2.2. Analysis of the Results

The statistical parameters of position and dispersion of the different board populations considered were calculated using Minitab 17 software (Minitab Inc., State College, PA, USA). Subsequently, the sensitivity of the physical and mechanical properties of boards to tree growth rate is presented graphically and discussed in light of the characteristic values of the mechanical strength classes defined in EN 338 [33].

3. Results and Discussion

3.1. General Statistics

The main descriptive statistics of both lumber populations (depending on their cross section) are presented in Table 3.

Table 3. Physical and mechanical properties measured on the 445 38 × 100 mm^2 and 261 70 × 180 mm^2 boards studied. The averages for the lowest cross section (38 × 100 mm^2) were calculated on the basis of both the raw values (i.e., not weighted according to the radial position of the boards) and the weighted values; the values for the largest cross section (70 × 180 mm^2) did not require weighting.

Cross Section (mm^2)	Property	Mean	Weighted Mean	Standard Deviation	Min.	Max.	1st Quartile	3rd Quartile
38 × 100	E (MPa)	11,412	11,892	2547	5870	18,695	9533	13,256
	f_m (MPa)	41.3	44.1	15.5	11.1	77.9	29.1	53.2
	$\rho_{12\%}$ (kg/m^3)	497	505	46	401	631	463	531
70 × 180	E (MPa)	13,047	-	2359	7353	18,517	11,247	14,690
	f_m (MPa)	36.1	-	10.6	10.6	64.9	28.2	42.4
	$\rho_{12\%}$ (kg/m^3)	449	-	32	359	527	427	471

Regardless of cross-sectional area, the mean values of E determined on Walloon boards were similar to the values reported in [36] for American lumber (these values varied between 10 and 13 GPa) as well as with the values measured on German Douglas fir lumber [29] (stiffness values of 15,000 MPa are reported in [37], but this author studied much older trees (around 100 years old)). Although [17] do not provide a global average value for their sample of French boards, the E and f_m values they present seem—by comparing the means by RW$_{board}$ class—slightly higher than those we observed. In contrast, [38] report slightly lower values. Finally, the E values measured by [15] on British Douglas fir (i.e., slightly over 9 GPa) are significantly lower than the values measured on other European resources, while the average f_m value (34 MPa) is comparable to that measured on Walloon 70 × 180 mm^2 boards.

At the level of height at which the central area of the 70 × 180 mm^2 boards was located (i.e., approximately 13 m), it was estimated that there were on average 7–11 fewer growth rings of outerwood compared to the level at which the central area of the 38 × 100 mm^2 boards from logs three and two was located—respectively cut 6 m or even 10 m lower in the trunk. The lower density values presented by the 70 × 180 mm^2 boards are therefore logical since, for a given ring width, corewood density is ca. 10% lower than that of outerwood [13,20].

If the values presented in Table 3 are compared to those relating to clear wood specimens taken from the basal log of the same trees (see [20]), E and $\rho_{12\%}$ mean values were relatively similar and hardly affected by the material on which the property was measured. Conversely, f_m values measured on structural dimensions boards were less than half those observed on clear specimens (on average 97 MPa). The higher sensitivity of f_m to features (compared to E) relies on the fact that, as reported in previous studies (e.g., [15]) and as it appeared in the present one, stiffness principally depends on density, whilst strength is mainly driven by knottiness.

Finally, it should be noted that the weighted values of E and f_m were respectively 4% and 7% higher than the raw values, which confirms the slight underestimation of the properties induced by taking into account only the transverse slice in the case of the 38 × 100 mm^2 boards. Concerning $\rho_{12\%}$, the underestimation was less than 2%.

3.2. Impact of the Wood Type

The physico-mechanical properties of corewood, outerwood, and mixed 38 × 100 mm^2 boards are presented in Table 4.

Table 4. Physico-mechanical properties measured on three types of 38 × 100 mm^2 boards: corewood (Age$_{camb}$ ≤10 years; *n* = 168), outerwood (Age$_{camb}$ ≥20 years; *n* = 184), or mixed (*n* = 93).

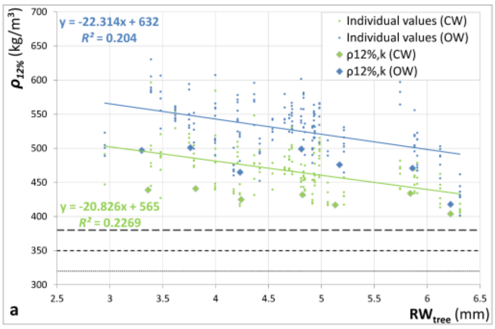
Property	Type of Wood	Mean	Standard Deviation	Min.	Max.	Percentile 5%	1st Quartile	3rd Quartile
$\rho_{12\%}$ (kg/m^3)	Corewood	466	34	401	597	417	442	488
	Mixed	492	38	404	565	429	469	514
	Outerwood	528	39	402	631	462	504	556
E (MPa)	Corewood	9410	1758	5870	16,102	6653	8067	10,699
	Mixed	11,146	1771	6983	14,441	7887	9992	12415
	Outerwood	13,375	1938	8422	18,695	10,109	12,030	14,691
f_m (MPa)	Corewood	30.7	9.9	11.1	58.3	16.0	24.5	37.3
	Mixed	38.6	12.5	12.7	67.9	16.7	29.9	47.1
	Outerwood	52.4	13.5	16.2	77.9	29.7	42.9	63.8

Compared to the values observed on boards cut from outerwood, the mean E values observed on mixed and corewood boards were 17% and 30% lower, respectively. Regarding f_m, these decreases reached 26% and 41%, while they were only 7% and 12% for density. Logically, a one-way ANOVA indicated a very highly significant impact of the type of wood on the boards' physico-mechanical properties (p = 0.000 for $\rho_{12\%}$, E and f_m), confirming the bibliographical information and the relevance of taking into account, where possible, the proportion of corewood and outerwood. Moreover, whether considering E or f_m, it appears that more than 75% of the boards taken from outerwood (those of the 2nd, 3rd, and 4th quartiles) had more advantageous properties than those offered by 75% of those taken from corewood (i.e., the first three quartiles). It should also be noted that a 1% increase of $f_{m,k}$ would allow the 184 boards taken from outerwood to be assigned to class C30; this once again demonstrates the excellent mechanical properties of the outerwood of this species.

In this context, corewood proportion should be minimized by maintaining relatively high stocking in the initial phase of stand growth. This underlies the interest of natural regeneration, which seems relatively easy to achieve [39,40]. In addition to improving the intrinsic properties of clear wood, this strategy would also generate, through the beneficial effect of competition observed on the branchiness of the trees studied in this research [21] and in many others (e.g., [10,41,42]), lumber with lower knottiness. In this perspective, however, it would be important to ensure that the maturation dynamics (i.e., the age at which wood acquires its mature characteristics) of relatively dense natural seedlings are similar to those observed in plantations where the individuals are exposed to competition much later. It should also be stressed that natural regeneration should obviously only be considered when the genotype of the stand to be regenerated offers the necessary guarantees in terms of the quality of the resource.

3.3. Impact of the Trees' Growth Rate—RW_{tree}

Figure 2 illustrates the decrease in density and mechanical performances of the boards due to the increase in growth rate of the trees from which they originated. These decreases were compared with the normative requirements defined in standard EN 338 [33].



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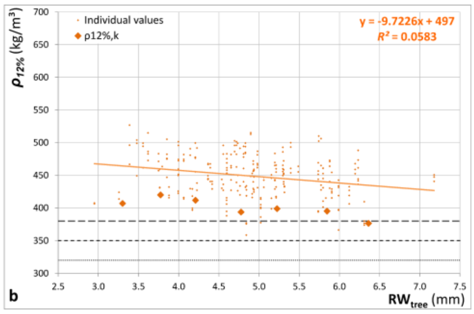

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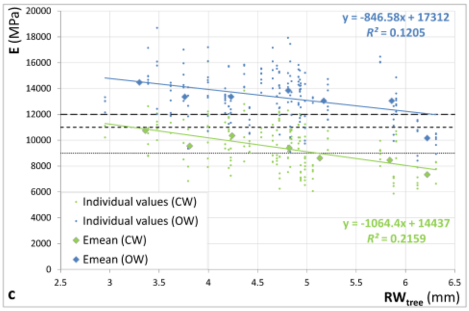

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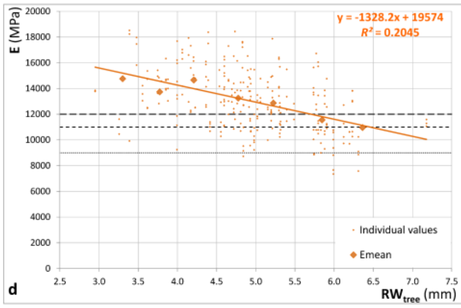

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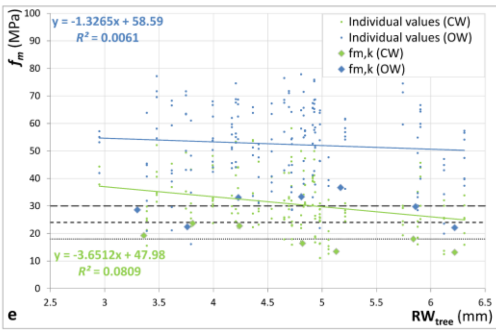

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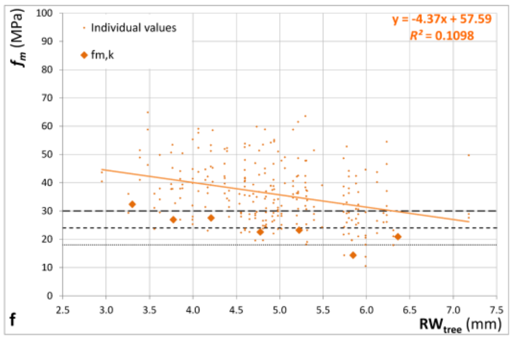

(**f**)

Figure 2. Density (ρ: a and b), modulus of elasticity (E: c and d), and static bending strength (f_m: e and f) at 12% moisture content of the 445 38 $\times$ 100 mm^2 (**left**) and 261 70 $\times$ 180 mm^2 (**right**) boards, depending on the growth rate of the trees (RW_{tree}) from which the boards originated. The seven RW_{tree} classes (namely: <3.5 mm; [3.5–4 mm]; [4–4.5 mm]; [4.5–5 mm]; [5–5.5 mm]; [5.5–6 mm] and $\geq$6 mm) were defined so that each of them contained at least 10 boards. For each property, the dotted lines represent the characteristic values required to comply with (from bottom to the top) strength classes C18, C24 and C30. CW: corewood; OW: outerwood.

As a preamble to the in-depth examination of each graph, the following observations can already be made:

- individual values of E and f_m within each class of RW_{tree} exhibited a large dispersion;
- the coefficients of determination (r^2) between the studied properties and the radial growth rate of the trees were relatively low, being at best around 20%. Considering the same properties

measured on clear specimens taken from the same 66 trees, r^2 values mentioned by [20] were around 10% in outerwood and from 28% to 41% in corewood;

- density is never a limiting parameter for the use of Douglas fir in structural applications: all the marginal characteristic values (i.e., percentile 5% per RW_{tree} class) observed—except that of the 70×180 mm^2 boards from trees whose $RW_{tree} \geq 6$ mm—allowed access to strength class C30. This acknowledgement is not surprising given the relatively high density of Douglas fir (compared to spruce in particular), the fact this property is predominantly under genetic control [43,44] and only slightly sensitive to growth rate [20,25], and finally because identical density characteristic values define the strength classes of Norway spruce and Douglas fir.

3.3.1. Observations on 38 × 100 mm^2 Boards

For the seven batches defined according to RW_{tree} and cut from outerwood, only the batch from trees with a RW exceeding 6 mm had an average E value incompatible with C30 grading. As far as f_m is concerned, the results can be considered identical after a critical examination of the data. Indeed, the surprisingly low $f_{m,k}$ values of the two lowest RW_{tree} classes were each due to a single board (for which f_m was 20.9 and 16.2 MPa, in ascending order of RW_{tree}). These boards were characterized by an average cambial age of 26 and 23 years (which therefore does not formally exclude the presence of corewood) and by very high KAR values, which would even induce the exclusion of one of them according to NBN B 16-520 [31] visual grading. Consequently, in the absence of these two boards, $f_{m,k}$ would increase by more than 30% in the first two classes of RW_{tree} (mean f_m values increased by only 3% and 4% if these boards were removed from the sub-sample. This illustrates the very high sensitivity of the 5th percentile to extreme values, especially on small sub-samples such as those considered here), reaching values higher than 30 MPa. Moreover, it should also be noted that if the mechanical properties of the batch of "outerboards" from trees whose RW_{tree} exceeds 6 mm are clearly lower than those of the other batches, the former nevertheless meets the requirements of C18 strength class.

Considering the batches of boards taken from corewood, the characteristic values of the mechanical properties (E_{mean} and $f_{m,k}$) best met the requirements of strength class C18; these requirements were no longer met beyond an average growth rate of 4.5 to 5 mm (depending on whether f_m or E was considered).

The results observed on the 38×100 mm^2 boards corroborate the observations made on clear specimens taken from the same trees [20]: both approaches demonstrated the different sensitivity of core- and outerwood mechanical properties to growth rate. In more practical terms, the results show that enhancing growth mainly affects corewood mechanical properties, with little impact on those of outerwood.

3.3.2. Observations on 70 × 180 mm^2 Boards

From a qualitative point of view, the trends observed on 70×180 mm^2 boards were identical to those made on the boards with smaller cross-sectional area: the three properties studied here decreased as RW_{tree} increased.

The lower average density of the 70×180 mm^2 boards (compared to that of the 38×100 mm^2 boards) due to an increased proportion of corewood was already discussed in Table 4. If logically it also appears by considering the characteristic values per RW_{tree} class, this decrease in density does not compromise the possibilities of using the wood in construction.

Up to RW_{tree} of 6 mm, E_{mean} values complied with the requirements of the C24 strength class (and even of C30 if RW_{tree} < 5.5 mm). Concerning the batch from the highest RW_{tree} class (>6 mm), excluding the only board with a value of E < 8000 MPa (which according to a visual grading would have been excluded from structural uses because of its knottiness) would be sufficient to raise E_{mean} to over 11,000 MPa—a value which would allow the batch to be assigned to the C24 class.

Finally, if we examine $f_{m,k}$, six of the seven batches defined on the basis of RW_{tree} were suitable for structural uses. The batch from class [5.5; 6 mm] was heavily penalized by three boards exhibiting

f_m of less than 15 MPa. Because of their knottiness, two of these boards would have been rejected as part of a visual grading, which would have led to an increase in $f_{m,k}$ above 18 MPa.

3.3.3. Structural Use Ability

Table 5 concludes the analysis of these data by allowing an overview of the structural use potential of the boards as a function of tree growth rate. It is based on the observations made in Figure 2—namely that, for the 21 combinations studied (three types of boards × seven RW_{tree} classes), $f_{m,k}$ was always more limiting than E_{mean} (remembering that, in practice, density never impedes accessing the highest mechanical class). It should however be noted that E is often more important than f_m in the dimensioning of structures: The cross sections imposed by the project managers are indeed calculated above all to maintain the deformations of the structure below a given level, which is obviously much lower than that required to break the components of this structure. Table 5 is only valid for the samples studied here and was drawn up on the basis of the "reasoned values" (i.e., taking into account the critical interpretation of the trends observed as carried out in Sections 3.3.1 and 3.3.2).

Table 5. Structural use ability of the studied board batches according to the characteristic values of E and f_m and of the growth rate of the trees from which the boards originate.

70 × 180mm²		C30	E and f_m	E	E	E	E	None	None
		C24	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	E	E
		C18	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m
38 × 100mm²	Outerwood	C30	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	None
		C24	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	None
		C18	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m	E and f_m
	Corewood	C30	None	None	None	None	None	None	None
		C24	E	E	E	None	None	None	None
		C18	E and f_m	E and f_m	E and f_m	E	None	None	None
		RW_{tree} (mm)	3.5	4	4.5	5	5.5	6	

Mechanical property(ies) whose characteristic value enables grading in the corresponding strength class
E and f_m
E
None

Table 5 shows that the batches of 38 × 100 mm² boards taken from corewood had generally poor properties which, with the exception of those from trees with RW_{tree} <4.5 mm (with the exception of the SPA stand, where all individuals displayed a RW_{tree} <4.5 mm, the latter value was exceeded for all dominant trees in the other 10 stands), require individual grading of these boards. In contrast, it appears that, up to a 5.5 mm RW_{tree}, batches of 38 × 100 mm² boards taken from outerwood and batches of 70 × 180 mm² boards could be assigned to strength class C24 or even C30.

4. Conclusions

This research aimed to identify as precisely as possible the influence of growth rate on the physico-mechanical properties of Douglas fir boards—in particular on their suitability for structural use with respect to normative characteristic values.

Remembering that planting densities in the studied stands were relatively high compared to those observed in neighboring countries, it is reassuring to note that in the range of growth rates and cross sections tested, lumber from outerwood offered very good properties, even in trees and stands with the highest growth rates. Conversely, lumber taken from corewood appeared to be rather sensitive to growth rate, and its suitability for structural uses decreased significantly as ring width increased.

Hence, by minimizing both the proportion of corewood and sapwood, increasing rotation length only has advantages from a purely technological point of view. The extent to which these must be subordinated to increased health and climate risks, to the negative impact on the profitability of longer investments, or to the reduction in the adaptation of logs to current industrial tools must now be determined.

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