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Original article

Hardness and basic density variation in the juvenile wood of maritime pine

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Abstract – This paper investigates the within- and between-tree variability of hardness and basic density in two stands of 11-year-old and 20-year-old maritime pine trees grown in the south-west of France. A slight increase was found in the inner core hardness of the 11-year-old trees (+13.9 %) and in basic density of the 20-year-old pines (6.5 %) with decreasing tree height. Between the 1st and 13th annual rings of the 20-year-old trees, hardness increased by +49.8 % and basic density by +18.7 % on average. These variations were strongly tree-dependent. A significant correlation was found between hardness and basic density, even when each sampling position was considered independently. (© Inra/Elsevier, Paris.)

variability / juvenile wood / hardness / basic density / maritime pine

Résumé – Variations de densité et de dureté dans le bois juvénile de pin maritime (*Pinus pinaster*). Cet article traite de la variabilité intra- et inter-arbres de la dureté et de l'infradensité. L'échantillon étudié est composé de 17 pins maritimes de 11 ans et de 20 pins maritimes de 20 ans. Ces arbres sont issus de deux parcelles situées sur le site du Centre de recherches forestières de L'Inra de Pierroton en France. Pour les pins de 11 ans, une légère augmentation de la dureté (13,9 %) a été mise en évidence lorsque la hauteur dans l'arbre diminue. L'infradensité augmente également (6,5 %) dans les mêmes conditions sur les arbres de 20 ans. Les variations du cœur vers l'écorce sont respectivement de +49,8 % pour la dureté et de +18,7 % pour l'infradensité pour les arbres de 20 ans. Ces gradients ont été mesurés entre le premier et le treizième cerne et sont fortement dépendant de l'arbre dans lequel ils ont été mesurés. La relation dureté - infradensité a également été étudiée. Une forte corrélation a été trouvée entre les deux variables, même lorsque chaque position de prélèvement a été étudiée séparément. (© Inra/Elsevier, Paris.)

variabilité / bois juvénile / dureté / infradensité / pin maritime

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1. INTRODUCTION

It has been widely accepted that products sawn from the juvenile zone of plantation-grown pines show significantly different properties than those sawn from the mature zone. Strength and density have been found to decrease in the fibre direction, both of which affect potential utilization in load bearing. The dimensional stability of beams has also been shown to be affected by the presence of juvenile wood [3], leading to distortions during drying (twist, warp and bow) and service.

Extensive research has been carried out to upgrade the quality of timber from fast-grown species, e.g. Radiata pine and Loblolly pine, especially through genetic selection of trees, process adjustment and the design of new products. However, little is known about the juvenile wood of maritime pine though intensive forest management (use of genetically improved material, fertilization and dynamic silvicultural treatments) results in a reduction of stand rotation from 70 to 40 years. Timber and wood products marketed from maritime pine fast-grown logs contain a larger proportion of juvenile wood than ever before, and the quality, strength and stability of floors, boards and plywood made from maritime pine wood (around 30 % of the maritime pine wood production) will probably suffer from this increase in juvenile wood percentage.

This paper presents some results concerning basic density and hardness in young maritime pine trees. Effect of height and radial patterns are shown as well as the between-tree variation of these gradients. The main objective is to complete a database on maritime pine wood variability which can be used in modelling wood and wood-based products.

Variation patterns in basic density have been found for many fast-grown species [13, 21]. Wilkes [19] found a radial gradient of approximately 40 % (based on the value measured in the first two annual rings) between the pith and the 20th annual ring at breast height in Radiata pine. This variation was similar to that shown by Bendtsen and Senft [3] on Loblolly pine. In the inner rings of the same species, Megraw [13] measured an increase of 15 % in basic density when the height in the tree decreased from 5 to 0.3 m. However, these within-tree patterns cannot easily be described by a general model, since they are dependent on the species and often on the tree itself [1, 10]. Dumail [8] found a decrease in wood density of maritime pine from the pith to the sixth annual ring, followed by an increase of about 20 %. These variations in density are related to those of several determinants. As stated by Boyd [4] “Density is determined by a series of interacting factors, which may be widely and independently variable. These include cell shape, wall thickness, relative amounts of earlywood and latewood in the annual growth rings, mean intensity of lignification for radial and tangential walls, and total extractive content.”.

One can suppose that hardness variability is very dependent on that of density, since these properties are strongly related. Doyle and Walker [7] found a strong increase in the wedge hardness when air-dry density increased from 0.141 to 1.274 (*figure 1*). Ylinen [20] suggested a linear relationship between Brinell hardness (H_b) and air-dry density (AD) ($H_b = -14.54 + 66.42\,AD$) for species whose density was ranging from 0.3 to 0.8. But according to Doyle and Walker [7], the anatomical structure is also responsible for variations in hardness. The special anatomy of juvenile wood could thus lead to a special hardness–density relationship in this zone.

Generally, the other determinants are thought to be dependent on the parameters of the hardness test itself (shape of the indentation tool, speed of loading and depth of penetration) and especially the way in which wood failure is induced during testing. Numerous hardness tests are commonly used. Monnin test (AFNOR) is performed

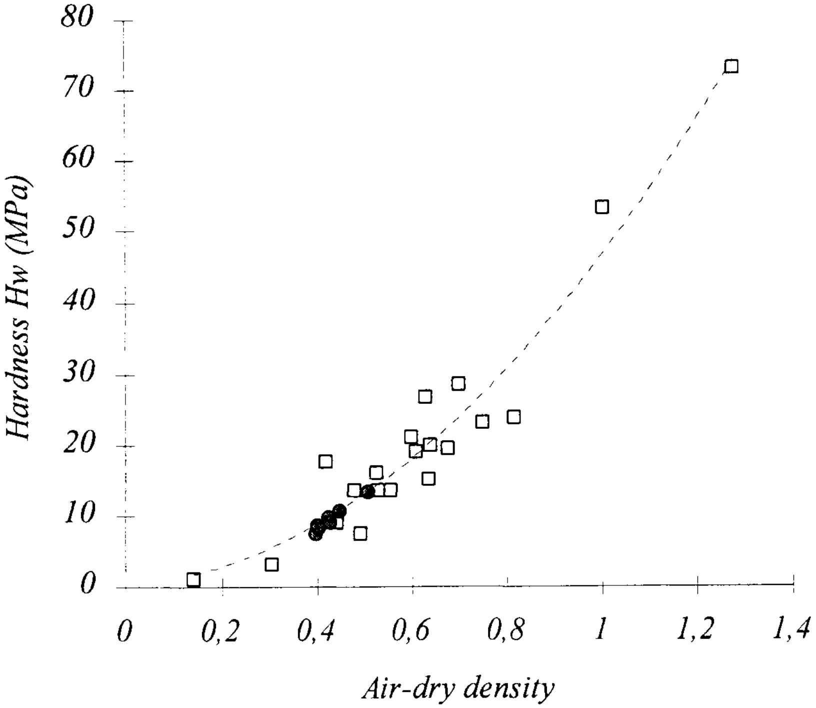

Figure 1. Relationship between wedge hardness and air-dry density. Based on Doyle (1980) values: each square point represents approximately ten specimens of the same species. Doyle and Walker [7] have given the following relationships based on these values: $H_w = -18.288 + 0.0701$ AD, $r^2 = 0.89$ or $H_w = -1.545 + 0.0122$ AD $+ 4E^{-5}$ AD^2, $r^2 = 0.94$. Means from this study are represented by filled circles.

by pressing a 30-mm diameter cylinder under a constant load of 1 960 N. ASTM [2] suggests the measure of the hardness modulus (Equivalent Janka Ball test). A ball (ϕ11.28 mm) is indented in the specimen until the penetration has reached 2.5 mm. The slope of the force–penetration curve is defined as the hardness modulus. The Brinell hardness is measured in Japan (JIS) with a 10-mm diameter ball indented until the penetration has reached $1/\pi$ mm. Doyle and Walker [6, 7] designed a test using a wedge with an angle of 136° (*figure 2a*). This method has numerous advantages and was chosen for the following study. Furthermore, the wedge hardness H_w value can be roughly related to the Janka Hardness H_j by using the relation $H_w = 9.834 + 0.054\ H_j + 0.0016\ H_j^2$, $r^2 = 0.83$.

2. MATERIALS AND METHODS

2.1. Preparation of the specimens

This study has been carried out on two samples of maritime pine trees: the first sample was composed of seventeen 11-year-old trees collected in a stand managed by AFOCEL (Association Forêt Cellulose). These trees were harvested during the first thinning of the stand. The second sample consisted of twenty 20-year-old trees which were chosen in an experimental stand of Inra (Institut national de la recherche agronomique), and would therefore be repre-

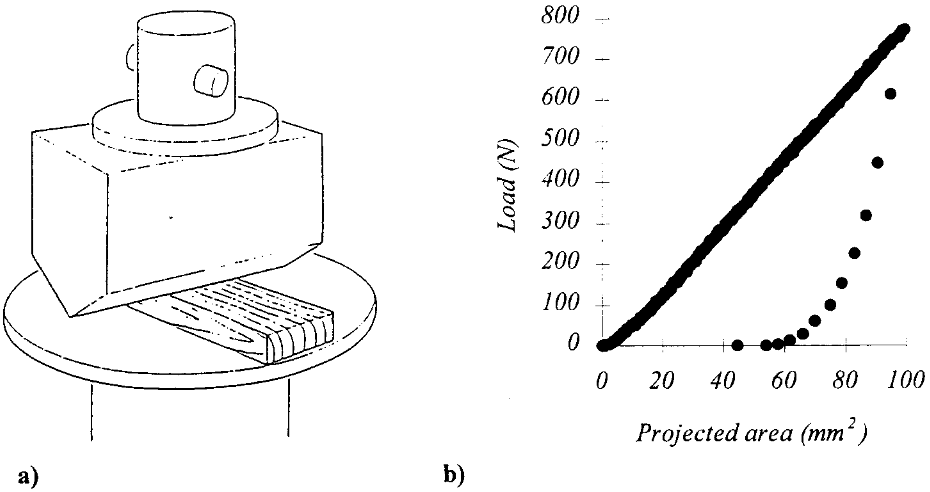

Figure 2. Principle of the wedge hardness test. a) Indentation of the sample by the wedge. b) Typical load–projected area curve.

sentative of the second thinning in current management practices. Both stands were located at the Forest research centre of Inra Pierroton in the south-west of France, so that the soils were similar. The criteria for the choice of the trees were straightness, verticality and diameter at breast height (DBH). Leaning maritime pine trees usually have large amounts of compression wood and thus were not chosen. The trees in both samples were selected randomly in the lower, average and upper diameter classes of the respective stands. Therefore, a variability in growth rate was introduced as a possible source of variation in wood properties in the juvenile core.

Two logs were cut from each tree, one in the crown and one near the base of the stem. In the 11-year-old trees, the top log was the third growth unit from the apical bud (approximately 6 m from the ground), whereas the butt log was the sixth growth unit (approximately 2 m high). In the 20-year-old trees the top and butt logs were chosen in the fourth and fourteenth growth units from the apical bud (approximately 14 and 5 m from the ground, respectively). The logs were cut into slabs from bark to bark (in a way that minimizes the occurrence of visually detected compression wood) and kept in green condition. Due to their small diameter, the top log slabs only provided two specimens at symmetrical positions from the pith, corresponding to the first growth rings. The same specimens were cut from the butt log slabs, plus two extra samples in the outer rings (rings 4–6) for the 11-year-old trees. Four extra samples in the medium and outer positions (rings 4–6 and rings 9–13) were cut from the 20-year-old butt slabs. The different sampling positions were referenced as follows:

C_1 for top log position in 11-year-old trees,
C_2 for butt log position in 11-year-old trees (inner rings),
C_3 for butt log position in 11-year-old trees (outer rings),
C_4 for top log position in 20-year-old trees,
C_5 for butt log position in 20-year-old trees (inner rings),
C_6 for butt log position in 20-year-old trees (medium rings),
C_7 for butt log position in 20-year-old trees (outer rings).

The specimens were sanded before being measured in the fully-saturated state (V_S: volume in the saturated state) with a digital sliding calliper to the nearest 0.01 mm. The dimensions were approximately 20 mm along the cross directions and 100 mm along the longitudinal direction. The specimens were then stabilized at 23 °C and 65 % HR and weighed as soon as the moisture content equilibrium was reached (W_{AD}: air-dry weight). After testing, the samples were dried at 105 °C before being weighed again (W_D: oven-dry weight). The basic density (BD) of the specimens was then calculated (W_D/V_S) and their moisture content controlled ($MC_{(\%)} = (W_{AD} - W_D)/W_D$).

The specimens were cut in a zone where the ring curvature was important. This was considered to have no great influence on our measurements and was neglected.

2.2. Hardness parameters

The hardness test was based on the studies by Doyle and Walker [6, 7] (*figure 2a*). The indentation was made in the tangential direction with a wedge with an angle of 136°. The width of the wedge was greater than that of the sample. The depth of penetration was 1 mm. This was sufficient for deducing the slope of the load–area curve which was defined as the wedge hardness H_w (*figure 2b*). Since the indentations were not very deep, two of them were performed on the same sample. The smallest distance between two indentations or between an indentation and the wedge of the sample was 25 mm. The tests were performed using an ADAMEL DY26 test equipment. The speed of the cross-head was 0.5 mm per minute. The displacement of the cross-head was used as the measure of the depth of penetration. Load and displacement were recorded during testing and the load–area curves were used for calculating the wedge hardness H_w (formula 1).

$$H_w = \frac{\Delta L}{\Delta A} \qquad A = \frac{2wd}{\mathrm{Tan}\, 22^\circ} \tag{1}$$

where H_w is the wedge hardness in MPa, L the load in N, A the projected area in mm^2, d the depth of penetration in mm and w the width of the sample in mm.

A parameter called energy release rate $W_{\%}$ was also measured in order to estimate the recovery properties of the samples (*figure 2b*). After reaching 1 mm of penetration, the sample was unloaded to the zero load level (5 mm/min). The area under the unloading curve gave the energy released by the sample W_r. The energy release rate $W_{\%}$ (formula 2) was then defined by the ratio between the released energy W_r and the total energy of compression W_t (area below the loading curve).

$$W_{\%} = \frac{W_r}{W_t} * 100 \tag{2}$$

2.3. Statistical methods

The within-tree variations were estimated by calculating the effects between the different positions in the tree. For example, the effect between the classes C_1 and C_2 was noted E_{12} and calculated as follows:

$$E_{12} = \frac{M_2 - M_1}{M_1} * 100 \tag{3}$$

where M_1 is the mean value for the class 1 based on 101 specimens and M_2 is the mean value for the class 2 based on 64 specimens.

The effect E_{12} was felt to be representative of the variations with height in the 11-year-old trees' inner rings, while E_{45} was the 'height' effect for the same growth rings in the 20-year-old trees. The effect E_{23} was defined as the 'cambial age' effect on the lower part of the 11-year-old logs, while the gradient of the property in the butt log of the 20-year-old trees was described by the effects E_{56}, E_{67} and E_{57} (*table I*).

Formula 3 was also used to calculate the effects in each tree, by using the means in the tree instead of the means in the whole class, so that, finally, the mean effect for all the trees, noted A_{ij}, could be calculated, as well as the scattering around this mean (*table III*).

The relationships between basic density, hardness and the energy release rate were calculated by using two different kinds of regressions between two variables:

> total correlation (R_c values in *table IV*): this method provided a general predictive model for the studied variable based on basic density;
>
> between-tree mean correlation (R_i values in *table IV*): this method was carried out to investigate the relationship between two variables between trees (e.g. if a tree has a high basic density, is the wood very hard?).

Between-effect correlations were also performed to answer the question: if a tree has a strong radial gradient, will this tree also have a strong height gradient?

The significance at the 5 % level was calculated for all the variations.

3. RESULTS

The significance of the position effect was tested for each variable by using a Kruskal-Wallis one way analysis of vari-

Table I. Description of the different effects.

Effect	Tree age	Description of the effect
E_{12}	11	height gradient (6–2 m) in the inner rings (1st–3rd)
E_{23}	11	radial variations (1st–6th ring) in the butt log (2 m high)
E_{45}	20	height gradient (14–5 m) in the inner rings (1st–3rd)
E_{56}	20	radial variations (1st–6th ring) in the butt log (5 m high)
E_{67}	20	radial variations (4th–13th ring) in the butt log (5 m high)
E_{57}	20	radial variations (1st–13th ring) in the butt log (5 m high)

Table II. Mean value and coefficient of variation (CV) for the different classes. *n* is the number of specimens in the class.

Tree age	Position	*n*		H_w (MPa)	$W_{\%}$ (%)	BD
Mean, C_1	11	top	101	7.42	28.97	0.333
CV, C_1			–	0.09	0.05	0.057
Mean, C_2	11	base	64	8.45	25.99	0.338
CV, C_2			–	0.12	0.07	0.059
Mean, C_3	11	base	40	9.8	30.27	0.356
CV, C_3			–	0.15	0.05	0.079
Mean, C_4	20	top	67	8.59	25.98	0.336
CV, C_4			–	0.12	0.06	0.054
Mean, C_5	20	base	128	8.99	26.34	0.358
CV, C_5			–	0.11	0.06	0.070
Mean, C_6	20	base	126	10.66	31.27	0.375
CV, C_6			–	0.13	0.05	0.056
Mean, C_7	20	base	95	13.47	32.98	0.425
CV, C_7			–	0.12	0.05	0.061

ance on ranks. This test can be applied when the normality test or the equal variance test has failed as was the case for the total distributions of hardness and basic density (*figure 3*). As the effect was significant (at the 5 % level) for all the variables, the mean values were calculated for each class and each variable (*table II*), as well as the mean effects between classes (E_{12} ... E_{57}). No significant changes in basic density were found with increasing stem height in the core of the 11-year-old trees (E_{12}). However, hardness and energy release rate varied greatly with decreasing tree height (H_w: $E_{12} = +13.9$ % ; $W_{\%}$: $E_{12} = -10.3$ %). In the inner rings of the 20-year-old trees, basic density increased from the apex to the butt ($E_{34} = +6.5$ %) and no variation was found in hardness and energy release rate.

Large radial variations were found from the pith to the bark in hardness ($E_{57} = +49.8$ %), in basic density ($E_{57} = +18.7$ %)

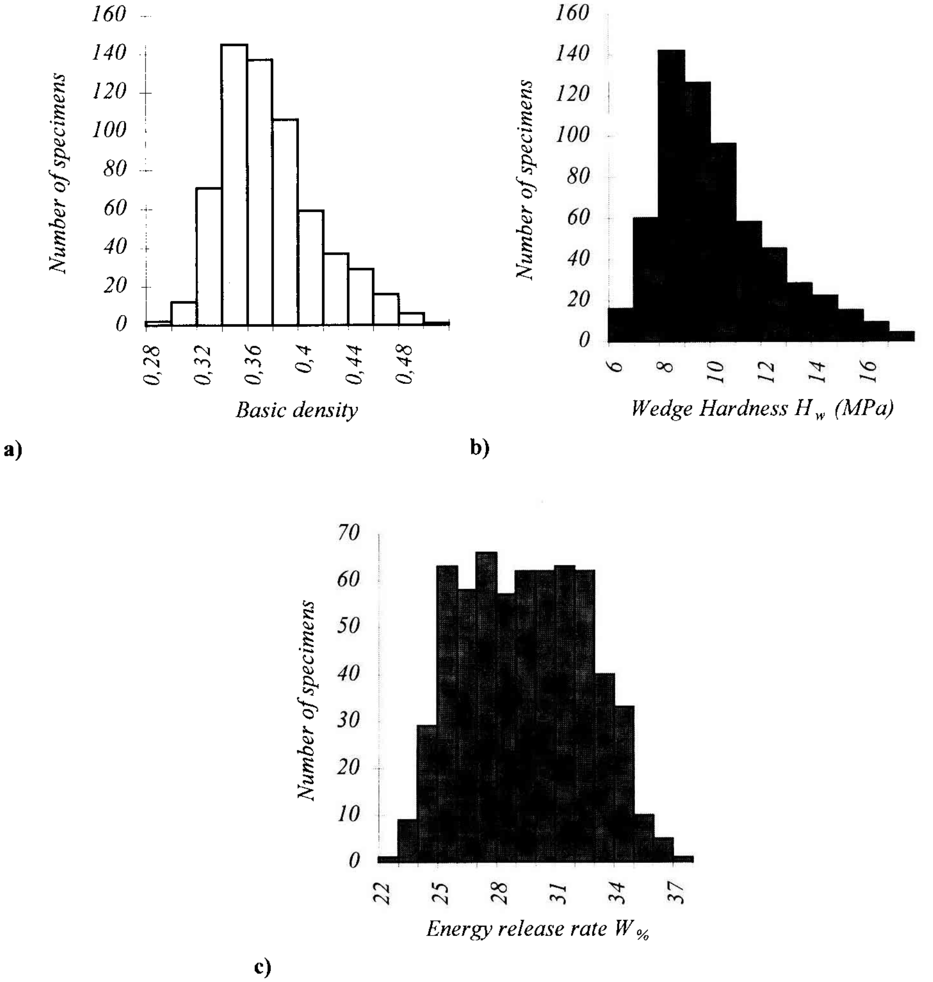

Figure 3. Distribution of basic density (a), hardness (b) and energy release rate (c). Number of specimens: $n = 621$.

and in the energy release rate (E_{57} = +25.2 %). Between the 1st and the 6th ring from the pith (E_{56}), hardness, basic density and the energy release rate increased by 16, 5.3 and 16.5 %, respectively. Between the 4th and the 13th ring from the pith (E_{67}), basic density increased by 13.3 %, hardness by 26.4 % and the energy release rate by 5.5 %. In the 11-year-old trees, a similar trend was found. All the variables increased with distance from the pith (BD: E_{23} = +5.3 %; H_w: E_{23} = +16 %; $W_{\%}$: E_{23} = +16.5 %).

Table III gives the mean values, the coefficients of variation, the minimum and maximum of the effects calculated with the mean value for each tree ($A_{12} \dots A_{57}$). The within-tree variation appeared to be strongly depen-

Table III. Mean values, coefficients of variation (CV), minimum and maximum values of effects, using the means of each tree.

		A_{12} (%)	A_{23} (%)	A_{45} (%)	A_{56} (%)	A_{67} (%)	A_{57} (%)
H_w	mean	15.10	13.60	2.50	19.30	27.60	52.30
	CV	0.90	1.00	3.67	0.70	0.44	0.36
	min.	–10.40	-13.00	–14.00	–0.30	10.10	10.00
	max.	38.90	33.30	19.80	44.90	49.30	78.50
$W_{\%}$	mean	–9.30	16.90	2.20	18.70	6.10	25.60
	CV	–0.48	0.43	2.08	0.25	0.57	0.22
	min.	–2.20	6.60	–6.20	9.50	–1.70	14.40
	max.	–15.30	34.50	8.40	25.80	14.50	39.20
BD	mean	2.30	4.30	5.20	5.40	13.90	20.00
	CV	3.23	1.51	0.90	1.26	0.39	0.45
	min.	–9.30	-7.20	-2.40	–5.40	4.20	-1.50
	max.	17.80	11.90	13.50	19.90	22.60	37.30

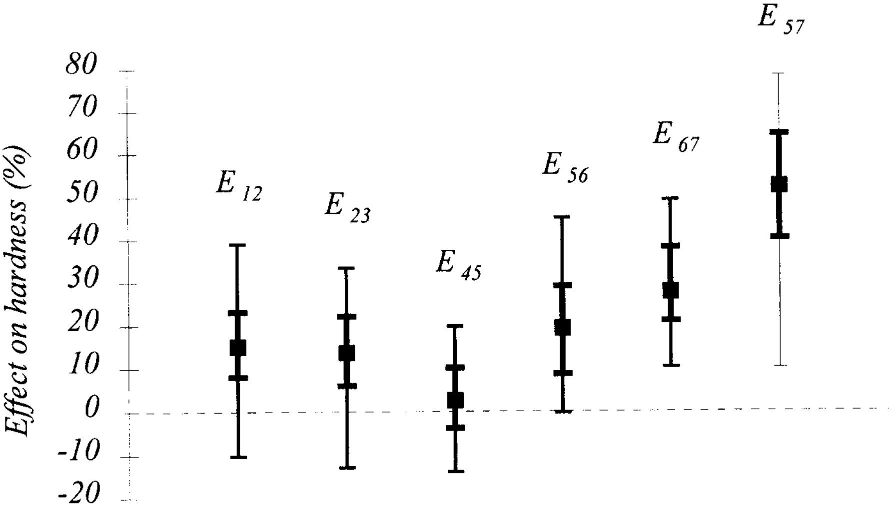

Figure 4. Variability of the position effects for hardness. Means are represented by squares. The minima and the maxima are shown by thin lines and first and third quartiles by thick lines.

dent on the tree for all variables since the variability of the effects was very large (no statistical test has been performed owing to non-balanced sampling and missing values) (*figures 4, 5* and *6*).

The overall correlation between hardness and basic density was significant at the 5 % level: $H_w = 55.80\,BD - 10.60$ with $R = 0.94$ and $n = 621$ (*figure 7* and *table IV* and *V*). The relationship between basic density and

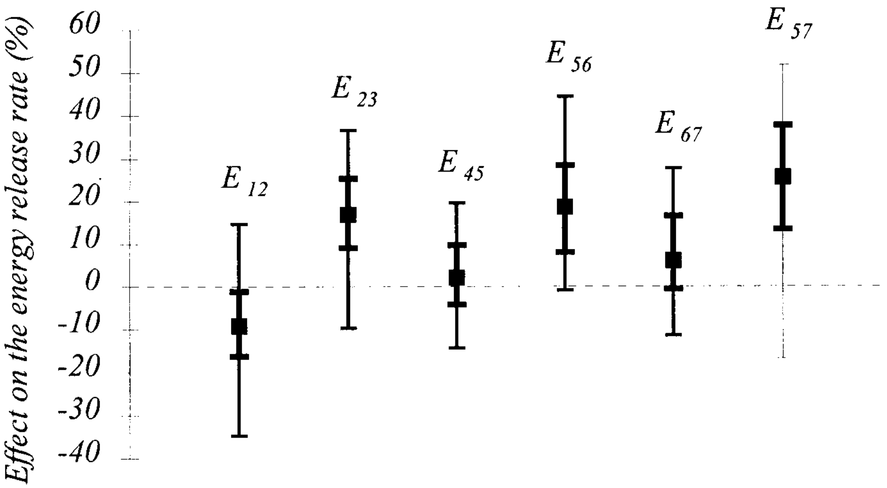

Figure 5. Variability of the position effects for the energy release rate. Means are represented by squares. The minima and the maxima are shown by thin lines and first and third quartiles by thick lines.

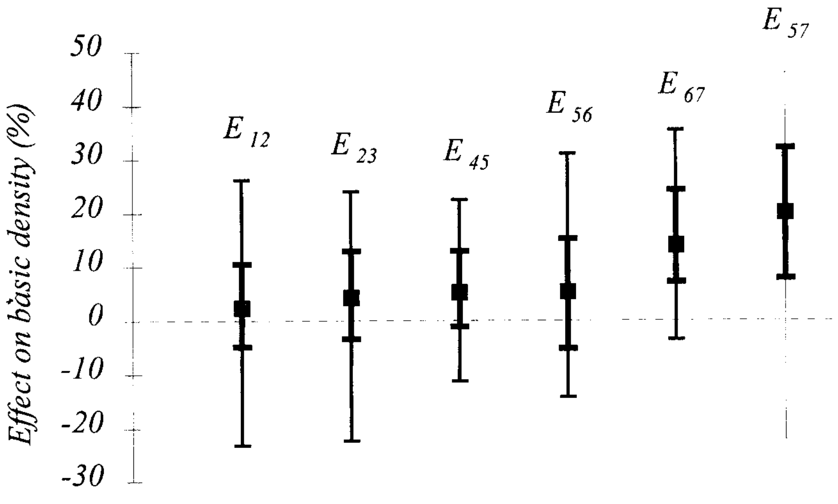

Figure 6. Variability of the position effects for basic density. Means are represented by squares. The minima and the maxima are shown by thin lines and first and third quartiles by thick lines.

hardness within each class was also highly significant (R_c in *table IV*). However, classes 1, 2 and 5 (inner growth rings below 6 m) had a slightly lower coefficient of correlation than the other classes. The regression coefficients a and b were also lower for C_1 and C_5 (*table V*). Calculating the regressions with the mean value of each tree in each

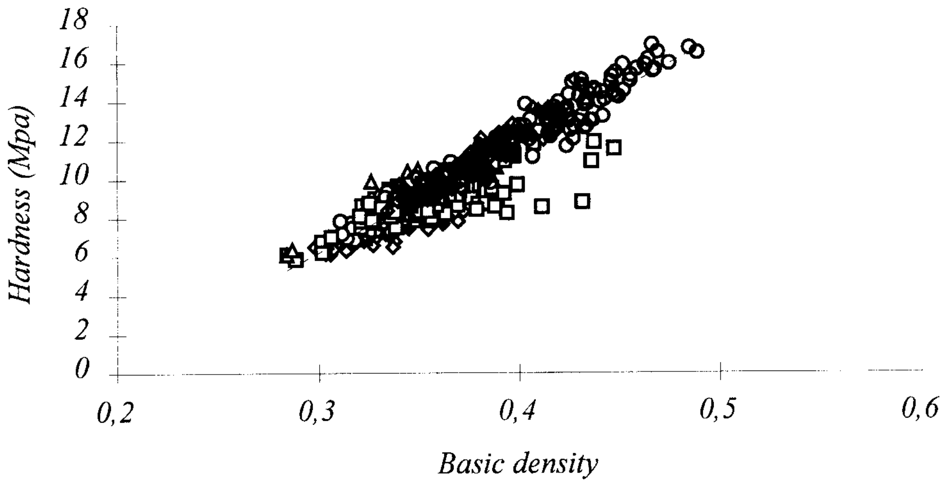

Figure 7. Relationship between basic density and hardness.
$H_w = 55.80\,BD - 10.60$, $R^2 = 0.88$ and $n = 621$

Table IV. Coefficients of correlation between basic density and hardness, and basic density and the energy release rate for the different classes. N is the number of specimen in the class. R_c is the coefficient of correlation within the class. R_i is the coefficient of correlation calculated with the mean value of each tree in the class. The coefficients are shown if they are significant at the 5 % level. The sign – means that the relationship is non-significant.

	n	H_w – BD:R_c	H_w – BD:R_i	$W_{\%}$ – BD:R_c	$W_{\%}$ – BD:R_i
Total	621	0.94		0.59	
C1	101	0.86	0.97	0.46	0.68
C2	64	0.83	0.86	–	–
C3	40	0.92	0.97	0.41	–
C4	67	0.89	0.95	0.30	–
C5	128	0.73	0.86	–	–
C6	126	0.93	0.95	0.18	–
C7	95	0.91	0.96	0.27	0.45

class also gave high correlation coefficients (R_i in *table IV*), except for classes 2 and 5 which were still particularly low.

In spite of this strong relation between hardness and basic density, it can be seen that a mean increase of 6.5 % in basic density (height effect E_{45}) had no effect on hardness. This result also occurred for E_{12}: hardness increased by 13.9 % while no significant change was observed in basic density.

The energy release rate was generally poorly explained by basic density, once again especially for C_2 and C_5 (*table IV*). The regressions between energy release rate and hardness were not significant at all when considering each specific class, but the over-

Table V. Best regressions between basic density and hardness within the classes. n is the number of specimens in the class. R^2 is the coefficient of determination. The coefficient are shown if they are significant at the 5 % level.

	n	Regression	R^2
Total	621	$H_w = 55.8BD - 10.6$	0.88
C1	101	$H_w = 31.67BD - 3.14$	0.74
C2	64	$H_w = 42.32BD - 5.88$	0.68
C3	40	$H_w = 46.76BD - 6.83$	0.85
C4	67	$H_w = 51.75BD - 8.81$	0.79
C5	128	$H_w = 29.07BD - 1.42$	0.53
C6	126	$H_w = 62.4BD - 12.75$	0.86
C7	95	$H_w = 52.28BD - 10.02$	0.82

Table VI. Coefficients of correlation R_i between the different effects in the tree for hardness, energy release rate and basic density. n is the number of trees in the class. R_i is calculated with the effect for each tree. The coefficients are shown if they are significant at the 5 % level. The sign – means that the relationship is non-significant.

R_i	n	H_w (MPa)	$W_{\%}$ (%)	BD
E_{45}–E_{56}	17	–	0.49	0.59
E_{45}–E_{57}	16	–	–	–
E_{45}–E_{67}	16	–	–	–
E_{67}–E_{57}	19	0.51	0.56	0.51
E_{56}–E_{57}	19	0.70	0.68	0.79
E_{56}–E_{67}	19	–	–	–

all relationship $H_w = 0.425W_{\%} - 3.39$, $r^2 = 0.39$ tended to show that both properties increased in the same time. This was observed when studying the variations with distance from the pith but not when considering the height effect: $E_{57} = +49.8$ % for hardness while $E_{57} = +25.2$ % for the energy release rate, but $E_{12} = +13.9$ % for hardness while $E_{12} = -10.3$ % for the energy release rate.

Regressions between the effects in each tree (*table VI*) were calculated in the 20-year-old trees. The relations were significant between E_{67} and E_{57} and between E_{56} and E_{57} for all variables. Variations with height E_{45} were related to E_{56} for the energy release rate and basic density only. Concerning the 11-year-old trees, only nine trees were available for this analysis owing to missing values. Therefore, regressions were not carried out.

4. DISCUSSION

The occurrence of the height gradient in the tree is usually explained by the influence of root growth on wood properties of the butt log, the increase in physiological age of the apical bud and the variation in growth unit length with tree height. Consequently, it would be expected that the value of the height gradient was dependent on the position of the studied log (from the base or from the apex) and on the position of the studied growth ring from the pith. Megraw [13] observed such behaviour in Loblolly pine. Dumail and Castéra [9] found that basic density increased by 6 % when height decreased from 13 to 4 m in the inner growth rings of 20-year-old trees, but no difference was found in the inner growth rings of 11-year-old trees at a height of 1.8–5 m. In this study, similar results were found for basic density.

The basic density variations from pith to bark were significantly lower for maritime pine than for other hard pines, e.g. Radiata pine (increase of approximately +30 % in the first ten rings at 1.30 m [19]) or Loblolly pine (+50 % in the same zone [3]) but quite comparable to those found by Dumail and Castéra [9] on other growth units of the same trees (+17.3 %). However, there was, in these studies on maritime pine, no evidence that the variations did not continue beyond the thirteenth ring. Polge [17] and Radi [18] suggested a limit of about 12 years between juvenile and mature wood for maritime pine, but no information was available on the variability of this limit for this species. It was felt on the basis of studies on other species that the scattering could be important [1, 11].

The high variability of the variations with tree height or with distance from the pith suggested that the effects, as well as the shape of the gradients, were genetically controlled. Such a possibility would enable a tree to be selected not only on the basis of the property itself, but also by considering its radial and height gradient. A similar result was found for the cambial age effect on density by Dumail and Castéra [9]. Nevertheless, this selection would only be relevant if the property and its radial gradient were inheritable. A narrow-sense heritability of 0.44 for basic density values in the juvenile zone of maritime pine (from the pith to the 12th growth ring) was reported in Nepveu [14]. Similar results have been found by Matziris and Zobel [12] on juvenile wood of Loblolly pine, Nicholls et al. [16] on 14-year-old Radiata pines and Nicholls et al. [15] on maritime pine. Burdon and Harris [5] found significant repeatabilities for pith to bark density gradients but not for height gradients in 12-year-old Radiata pine.

The hardness–density relationship is known to be highly significant when density varies in a wide range [7, 20]. This was verified in this study though the range was not as wide as that considered by these authors. The relationship within a specific class, and consequently on a lower range of density, was also highly significant though it was not as strong. Furthermore, the relationships were also valid between trees. Density was therefore a dominant determinant of hardness, but it was thought that the relationships could have been improved by considering other determinants. In the inner rings below 6 m (classes 1, 2 and 5), the relationships were slightly poorer than in the other positions and in C_1 and C_5, the coefficients *a* and *b* of the regressions were quite low. This suggested that, within these classes, the hardness was not as sensitive to density variations as within other classes, perhaps due to the particular structure of this wood, known to differ from that of normal wood (a high percentage of earlywood, no real latewood and a higher intra-ring homogeneity) and which can induce a different behaviour during the indentation of the tool. It was again in these inner rings that one could observe a mean variation in hardness without any change in density and vice-versa.

The relationship between hardness and the energy release rate was not significant when each class was considered separately. However, when studying the total sample, a significant linear relation was found ($r^2 = 0.39$). Therefore, in a sufficiently wide range of hardness, it could be supposed that the energy release rate increased with hardness (even if this increase was controlled by other parameters which varied with hardness). Thus permanent damages would increase if hardness decreased.

Finally, hardness decreased from 13.5 to 9 MPa between the eleventh and the second ring. Since all parts of the tree are generally used for making boards and floors, it can be supposed that the variability in the production is very high and that it is quite difficult to give a correct value of the hardness of the product. With the decrease of the stand rotations from 70 to 40 years, it also seems that a significant decrease in the overall mean value of hardness will be added to the problem of homogeneity in wood production.

5. CONCLUSION

The within-tree variations were shown to be significant for hardness, energy release rate and basic density for all variables when considering the 'radial position' effect. The amplitude of the effects was strongly variable either for the 'height effect' or for the 'cambial age' effect; the data were very scattered around the mean effect. The relationship between hardness and basic density was strongly significant, even when considering each class independently. Basic density provided a good prediction of hardness, even on a narrow range of density. However, the relationships were particularly poor in the inner rings below 6 m.

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