ARTÍCULO DE INVESTIGACIÓN

Variation throughout the tree stem in the physical-mechanical properties of the wood of *Abies alba* Mill. from the Spanish Pyrenees

Variación de las propiedades físico-mecánicas de la madera de *Abies alba* Mill. de los Pirineos españoles, a lo largo del tronco del árbol

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ABSTRACT

This study analyses the variation of main physical-mechanical properties of wood along the longitudinal and radial directions of the tree for *Abies alba* Mill. growing in the Spanish Pyrenees. Small clear specimens were used to study the properties of volumetric shrinkage (VS), density (□), hardness (H), bending strength (MOR), modulus of elasticity (MOE), maximum compressive strength parallel to the grain (MCS) and impact strength (K). Several models of properties variation in the longitudinal and radial directions were analyzed. Main trends of variation of properties throughout the tree stem were identified although none of them could be fitted to predictive statistical models. Along the longitudinal direction, the properties studied followed a downward trend from the base to the crown, which was not significant in all cases, indicating that no differences in quality existed. Throughout the radial direction the trend is upward for the first 40-50 growth rings, after which it slopes downwards, more gently at first until rings 70-75 and then more steeply. This behaviour is related to variation in wood structure from the pith to the bark, depending on whether the wood is juvenile, sapwood or heartwood, and to wood maturity and microfibril angle. Authors encourage carrying further studies on other populations of *A. alba* in the Spanish Pyrenees to check if the trends found in this study apply to other provenances.

KEY WORDS.
Fir, longitudinal direction, mechanical properties, physical properties, radial direction.

RESUMEN

En este trabajo se han estudiado las propiedades físico-mecánicas de la madera, para establecer la variación de la misma a lo largo de los ejes axial y radial del árbol. Haciendo uso de pequeñas probetas libres de defectos, se ha estudiado la contracción volumétrica (VS), densidad (ρ), dureza (H), módulo de ruptura a flexión (MOR), módulo de elasticidad longitudinal (MOE), máxima resistencia a la compresión paralela a la fibra (MCS) y al impacto (K) de la madera de *Abies alba* Mill. procedente del Pirineo español, y se han analizado los modelos de variación de dichas propiedades en los ejes axial y radial. No se han obtenido modelos que permitan determinar la variación de las propiedades a lo largo del fuste, aunque sí se han identificado tendencias que se repiten para todas las propiedades. A lo

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largo del eje axial las propiedades estudiadas siguen una tendencia decreciente de la base al ápice, no en todos los casos significativa, lo que permite concluir que no existen diferencias en la calidad. A lo largo del eje radial, la tendencia es creciente en los primeros 40-50 anillos de crecimiento y posteriormente decreciente, primero con pendiente más suave hasta el anillo 70-75 y de forma más acusada a partir de este punto. Este comportamiento está relacionado con la variación que experimenta la estructura de la madera desde la médula hasta la corteza, madera juvenil, madera de albura o de duramen, con el grado de madurez de la misma y con el ángulo microfibrilar.

PALABRAS CLAVE:
Abeto, eje axial, propiedades mecánicas, propiedades físicas, eje radial.

INTRODUCTION

Phenotypic and genotypic factors cause high variability in the physical-mechanical properties of wood, not only between populations of the same species but also in individual trees. Variation in an individual is not immediately apparent (Panshin and De Zeeuw, 1980), but is the result of a complex system of interrelated factors that modify the physiological processes involved in wood formation. Studies by Palka (1973), Olesen (1978), Panshin and de Zeeuw (1980), Dinwoodie (1981), Fukazawa (1984), Niklas (1992), McDonald *et al.* (1995), De Palacios *et al.* (2006) and De Palacios *et al.* (2008) showed considerable variation throughout the radial and longitudinal directions of the tree. It has even been questioned whether the wood of a single individual can be considered a homogeneous material. Tree stem has the structural function of supporting loads that will be acting during its lifetime. The variation of stresses along the stem influences the internal structure and mechanical properties of wood.

Most studies to date have focused on variation in wood anatomy and physical properties (particularly density) throughout the tree (Zobel and Van Buijtenen, 1989; Giménez and López, 2002; Medina *et al.,* 2013). However, fewer studies have analysed the variation in mechanical properties (Machado and Cruz, 2005).

Density has traditionally been associated with the various physical-mechanical properties (Mitchell, 1963; Wilson and Ifju, 1965; Panshin and De Zeeuw, 1980; Lewark, 1979; Van Buijtenen, 1982; Bamber and Burley 1983; Esteban *et al*, 2009) and variation in density is thought to affect the other properties. Studies on fir (*Abies alba* Mill.) have shown that this association exists, although it can be slight (R^2<50%) (Mazet and Nepveu, 1991). Behaviour of the various physical-mechanical properties must therefore be determined individually in order to identify the factors that affect each property.

Wood property variation throughout the longitudinal direction has been studied less than in the radial direction. For various species and genera, Heger (1974) determined that variation in conifer wood structure is more dependent on the location of the sample studied in terms of height from the base of the tree than on species or tree size.

Variation in density throughout the longitudinal direction depends on the species and its provenance (Zobel and Van Buijtenen, 1989). Panshin and de Zeeuw (1980) stated that density decreases uniformly with height in conifers. In the genus *Pinus*, the behaviour established by these authors is followed in most species. In fact, it is common to find a decrease in density at increased height (Jayne, 1958; Brown, 1972; Pronin, 1971), although this variation can be very slight (Jeffers, 1959; Pronin, 1971; Taylor *et al.,* 1982). Species such as *Chamaecyparis obtusa* Siebold & Zucc. (Hirai, 1958) and *Tsuga heterophylla* Sarg. (Krahmer, 1966) have very heavy wood at the base, but towards the middle of the stem the wood becomes lighter and at the top of the stem density increases again.

Variation in wood shrinkage in the longitudinal direction has been studied in *Pinus taeda* L. (Yao, 1969) and *Pinus echinata* Mill. (Choong and Fogg, 1989). In both cases, radial, tangential and volumetric shrinkage decreased with height in the tree.

Earlier studies indicated that variation in MOR and MOE does not follow a fixed pattern along the longitudinal direction for different species, which means that results must be extrapolated with caution. Hui and Smith (1991) maintained that the wood of *Picea glauca* Voss decreases in strength from the base to the high part of the stem, which is contrary to the finding of Pearson and Gilmore (1971) for *P. taeda*. Tsehaye *et al*. (1995) concluded that non-significant variation in MOE exists in *Pinus radiata* D. Don. Johansson and Kliger (2002) maintained that *Picea abies* (L.) H. Karst. shows greater MOR and MOE at the base of the stem. Castéra *et al*. (1999) and Machado and Cruz (2005) observed a decrease in MOR from the base to mid-stem, followed by an increase from this point to the crown in *Pinus pinaster* Aiton. According to Machado and Cruz (2005), compressive strength parallel to the grain decreases throughout the longitudinal direction. This behaviour is more pronounced in test pieces further from the pith.

Wood property variation throughout the radial direction similarly does not follow a single pattern. Panshin and de Zeeuw (1980) considered that variation in conifer wood density along the radial direction increases from the pith to the bark. This behaviour has been found in most species of the genus *Pinus* and in *Pseudotsuga menziesii* (Mirb.) Franco (Domec and Gardner, 2002). In contrast, Hirai (1958) observed that Cupressaceae normally have high density near the centre of the stem, which decreases in the first growth rings and then increases again towards the bark. Jeffers (1959) and Krahmer (1966) studied the behaviour of the genera *Abies*, *Picea* and *Tsuga* and concluded that a very slight difference occurred in the radial direction in most cases. *Larix* and *Pseudotsuga* normally show low density in the centre, a rapid increase in the first rings and greater stability towards the bark (McKimmy, 1959; Wellwood and Smith, 1962; Isebrands and Hunt, 1975).

In terms of mechanical properties, Machado and Cruz (2005) found a clear increase in MOR and MOE throughout the radial direction, from the pith to the bark. This increase is closely associated with the transition from juvenile to mature wood (Pearson and Gilmore, 1971; Bendtsen, 1978; Bendtsen and Senft, 1986; Barrett and Kellogg, 1991; Kretschmann and Bendtsen, 1992; Kennedy, 1995; Bao *et al*, 2001; Beaulieu, 2006)). Pearson and Gilmore (1980) studied the variation in mechanical properties throughout the radial direction in *P. taeda* and found that the mean increase was more than 40% for trees aged 41 years and that the increase was greater the younger the tree was. In *P. abies* Kliger *et al.* (1998) observed an increase of more than 30% in MOE and MOR between wood near the pith and mature wood.

Pearson (1988) analysed the compressive strength parallel to the grain in inner and outer test pieces of *P. taeda*, observing an increase in this property of nearly 30% towards the bark. Machado and Cruz (2005) conducted a study to determine the variation in compressive strength in *P. pinaster*. They showed that juvenile wood has an influence of more than 40% and concluded that the increase in this property along the radial direction is greater in the first half of the stem.

OBJECTIVES

In the absence of a common behaviour pattern for the physical-mechanical properties of conifer wood in the radial and longitudinal directions of the tree, the present study analyses variation in the properties of volumetric shrinkage, density, hardness, MOR, MOE, MCS and impact strength, in both directions, of the wood of *Abies alba* from the Spanish Pyrenees, and establishes models of the behaviour of each property. *Abies alba* wood was traditionally used in the Spanish Pyrenees where small relict forest masses subsist nowadays under protection.

METHODOLOGY

The research team selected five trees, representative of the forest in Mount Montinier, province of Huesca (Spain) (region of provenance the Midi- Pyrenees (Martín *et al*, 1998) (Fig. 1), in coordination with the Regional Authorities. The sample was large enough for the physical-mechanical study to be representative of the species in this site as referred in the literature (Anon, 1961; Brown *et al.*, 1952). Aged 70-100 years, the trees had normal diameters larger than 30 cm and straight stems with no bifurcations and were in good phyto-sanitary condition. They were growing on a slope of less than 15% and were not subjected to edge effect.

The stems were cut into 2-m logs, from which 40-mm thick radial planks were obtained at a sawmill. The planks were air dried to 18% moisture content and then machine cut into strips 35 mm x 35 mm, which were conditioned to constant weight in a chamber at 20 ºC ± 2 ºC and 65 % ± 5 % relative humidity. The final small clear specimens, with a cross section of 20 mm x 20 mm, were prepared by identifying them according to location in the tree, both in height (m) and in relation to the pith (number of growth rings). The test pieces were divided over the various tests conducted to ensure appropriate dispersion of the data (Fig. 2). Table 1 shows the tests conducted and the corresponding standard,

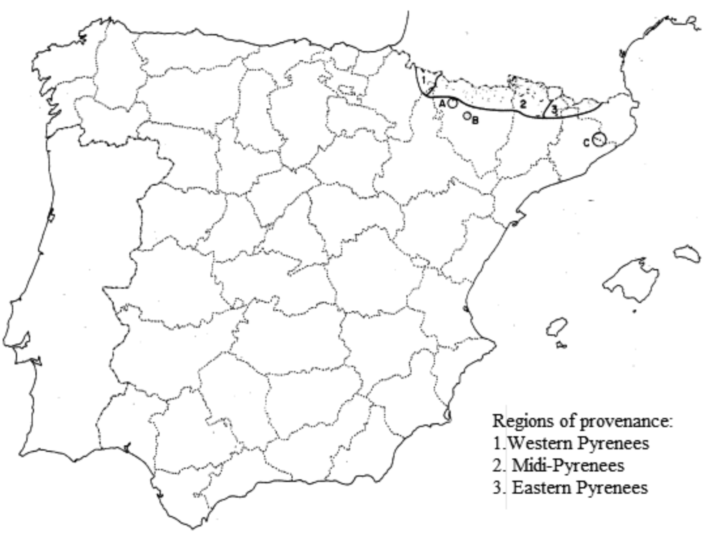

Figure 1. Fir region of provenance in the Iberian Peninsula. Source: Martín *et al.*, 1998.

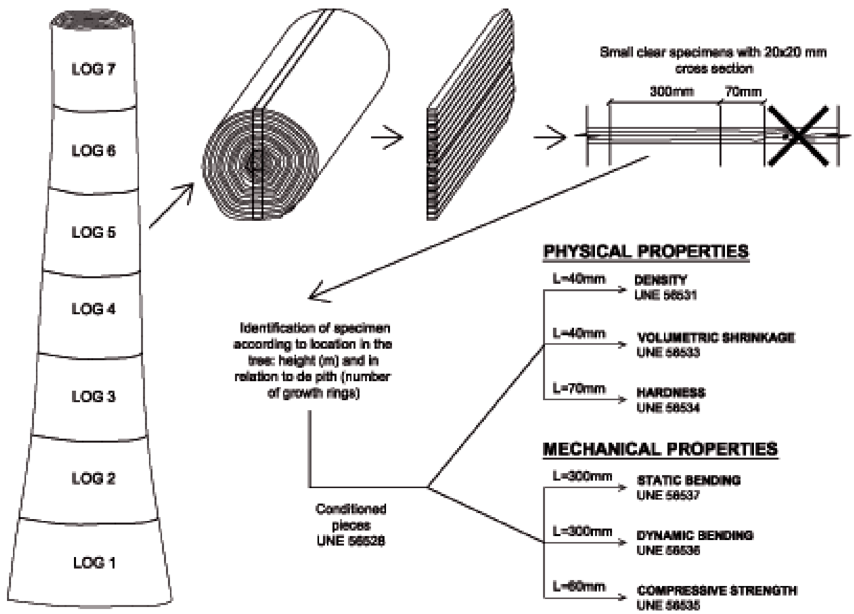

Figure 2. Diagram of the protocol followed for the physical and mechanical tests.

number of test pieces and test piece size for each test. The moisture content of the wood was calculated after each test, following the standard UNE-EN 13183-1 (AENOR, 2002), to confirm conditioning.

A Microtest universal testing machine with two load cells of 5000 N and 75000 N, class 1, was used for the mechanical tests and to determine hardness, except for the impact test, where an Amsler universal testing machine was used. The physical tests were conducted using a Sartorius A120S Analytical balance with a range of 0 g -120 g and 0,0001g scale division, a Heraeus UT 6760 air circulation oven with a range of 0 ºC - 300 ºC and 1 ºC scale division capable of maintaining a temperature of 103 ºC ± 2 ºC, and a Mitutoyo Digimatic digital caliper with a range of 0 mm - 300 mm and 0,01mm scale division. All the equipment was calibrated and the uncertainties met the general technical competence requirements for testing laboratories outlined in the standard UNE-EN ISO/IEC 17025 (AENOR, 2005) and the testing standards applied (for example AENOR, 1978).

The statistical analysis was conducted firstly using all individual (test pieces) data, and secondly grouping all data on a matrix. When working with grouped data, analyses were conducted on the mean. Two groupings were defined: 1-m intervals from the base of the stem and 10-ring intervals from the pith (Fig. 3). For the groupings, the statistical analyses were conducted when there were a minimum of six grouping data for each sector studied.

Multiple regression analysis were applied to study variation in stem properties, and polynomial regression analysis were used to determine variation throughout the longitudinal and radial directions, both with all the data and with the means

Table 1. Tests conducted, standard applied and size and number of test pieces.

Test / Ensayo	*Symbol/ Simbología*	*Standard/ Normativa*	*Test piece size/ Dimensiones probetas (mm)*	*No. test pieces/ Número de probetas*
Density / Densidad	r	UNE 56531:77[1]	20x20x40	230
Volumetric shrinkage/ Contracción volumétrica	VS	UNE 56533:77[1]	20x20x40	230
Hardness/ Dureza	H	UNE 56534:77[1]	20x20x300	365
Static bending and modulus of elasticity longitudinal/ Módulo de ruptura a flexión y módulo de elasticidad	MOR / MOE	UNE 56537:79[1]	20x20x300	355
Impact/ Impacto	K	UNE 56536:77[1]	20x20x300	334
Máximun Compressive strength parallel to the grain / Máxima Compresión paralela a la fibra	MCS	UNE 56535:77[1]	20x20x60	304

[1]See references (AENOR, 1977a-e, 1979). /Ver referencias (AENOR, 1977a-e, 1979).

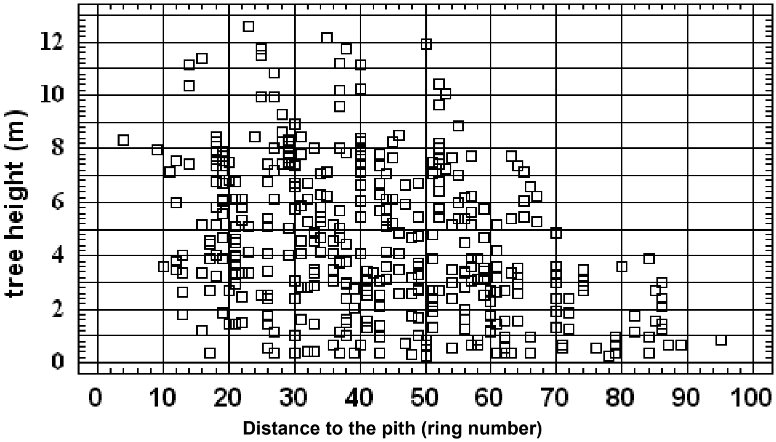

Figure 3. Graphical representation of the data grouped to analyze longitudinal and radial variation of different properties in different tree location from the average value of each group. These data belong to the hardness testing.

of the groups created. In both cases, models with a confidence level higher than 90% ($p < 0,1$) were taken into account. The statistical study was conducted with Statgraphics Centurion XVI-I.

RESULTS

Table 2 shows the results of the multiple regression analysis, in which the dependent variable is the property analysed and

Table 2. Models, coefficient of determination (R^2) and significance level (p) of physical-mechanical properties throughout the longitudinal direction (y, height from the base) and radial direction (x, distance to the pith in no. of rings)

Property	*Model*	*p*	*R^2*
ρ	ρ=0,454+0,003x-0,04y-0,00034x^2+0,000034xy+0,000158y^2	0,0000	0,2028
VS	VS= 0,0930,002x+0,005y-0,000025 x^2-0,000047xy-0,000304y^2	0,0000	0,2469
H	H=1,004+0,041x+0,034y-0,00038x^2 -0,002xy-0,001y^2	0,0000	0,1525
MOR	MOR=60,695+0,886x+0,889y-0,009x^2-0,023xy-0,029y^2	0,0000	0,0791
MOE	MOE= 6710,946+85,183x+199,582y-0,869x^2-2,825xy-11,848y^2	0,0000	0,1002
K	K= 32,3317+0,4922x+1,6632y-0,0061x^2-0,0156xy-0,1291y^2	0,0022	0,0388
MCS	$f_{c,0}$=34,733+0,415x+1,569y-0,004x^2 -0,019xy-0,092y^2	0,0001	0,0826

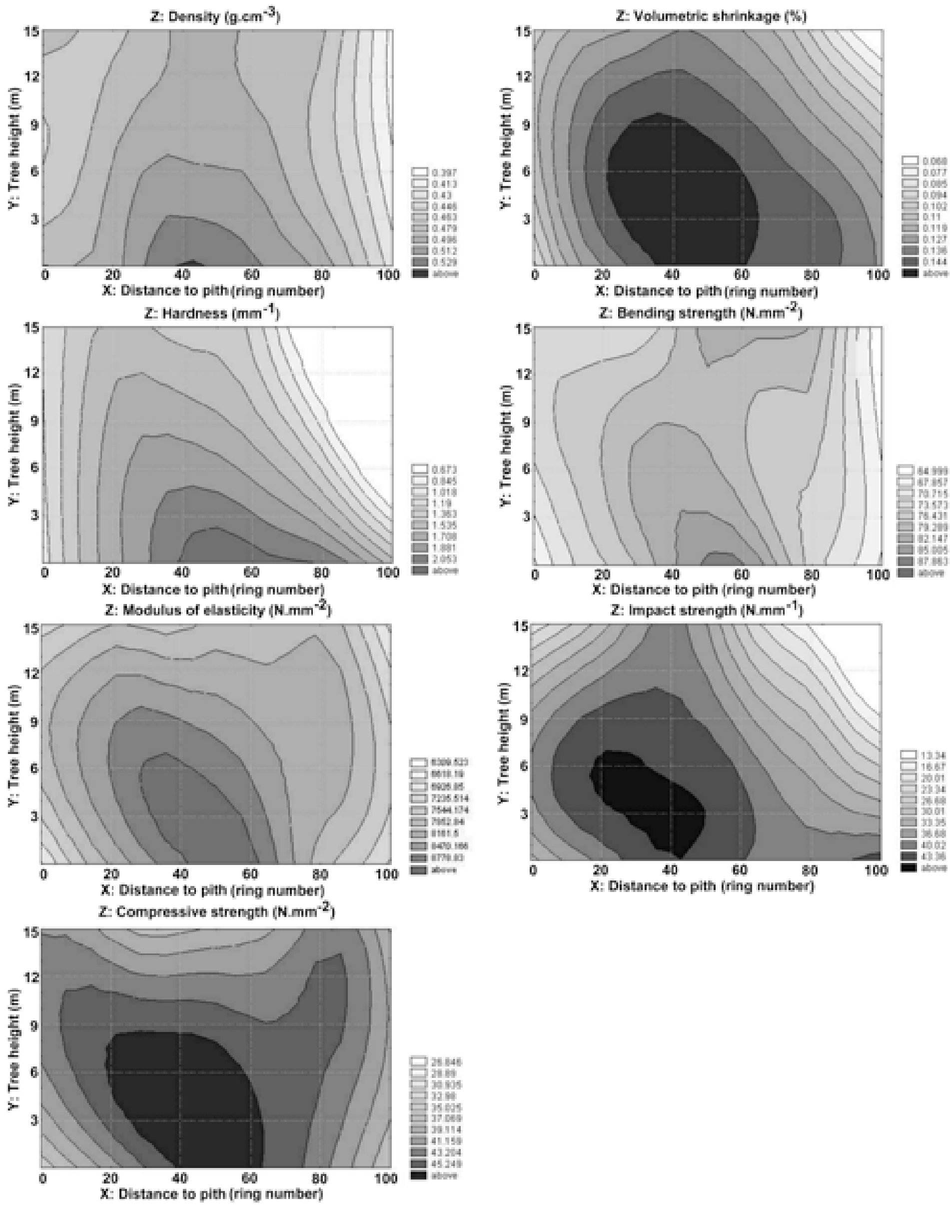

Figure 4. Graphical representation of the multiple regression analyses between physical-mechanical properties and test piece location in relation to longitudinal and radial directions.

the independent variables are the locations in the longitudinal and radial directions of the test pieces. It was seen that the location of the test pieces inside the stem explains less than 25% of the variability in the data obtained for the properties studied. The maximum values were obtained in the first metres of the stem and the central growth rings (Fig. 4).

The results obtained from the simple regression between the properties studied and the location of the test piece throughout the longitudinal and radial directions are shown in tables 3 and 4, respectively. Variability in the physical-mechanical properties throughout the two directions showed high dispersion which produced a similar trend curve for all the properties (figs. 5 and 6), (although the model accounted for less than 25% of the variability in the data in the best fit obtained), and a high mean absolute error (tables 3 and 4). In the longitudinal direction, the wood properties of *A. alba* decreased as height increased, although the relation was not significant in all cases and the model explained less than 7% of the variability in the data (Table 3). In the radial direction, variation of the properties was fitted to a second-degree polynomial curve with a maximum in the central area. For all the properties studied, a significant relation was found between property and location in the radial direction, although the model explained less than 25% of the variability in the data (Table 4).

Tables 5 and 6 show the information from the simple regression obtained to assess variation of the properties for the data grouped in 10-ring intervals from the pith (Table 5) and in 1 m intervals from the base of the stem (Table 6). A drawing of the trend curve is also shown, although only in cases in which a significant relation ($p < 0,1$) existed between the property and the longitudinal or radial direction.

Table 3. Models, coefficient of determination (R^2), significance level (p) and mean absolute error (E) of physical-mechanical properties throughout the longitudinal direction of the tree stem (y).

Property/ Propiedad	Model/ Modelo	p	R^2	E
ρ	ρ= 0,5003-0,00300y	0,000	0,047	0,031
VS	VS= 0,1433-0,0008y	0,083	0,013	0,014
H	H = 1,8641-0,0317y	0,000	0,060	0,314
MOR	MOR = 79,5429-0,1842y,	0,376	0,002	8,429
MOE	MOE = 8301,34+113,675y-11,098y^2	0,0959	0,013	681,789
K	K = 42,3613-0,18842y	0,3707	0,002	8,662
MCS	MCS = 45,9647 – 0,1972y	0,067	0,011	4,034

Table 4, Models, coefficient of determination (R^2), significance level (p) and mean absolute error (E) of physical-mechanical properties throughout the radial direction of the tree stem (x).

Property/ Propiedad	*Model/ Modelo*	*p*	R^2	*E*
ρ	ρ = 0,4395 + 0,0026x-0,0000279x^2	0,000	0,145	0,030
VS	VS = 0,1126 + 0,0016x - 0,000018x^2	0,000	0,220	0,013
H	H = 1,3035 + 0,01967x - 0,0001944x^2	0,000	0,047	0,314
MOR	MOR = 65,3692 +0,6866x -0,00740x^2	0,000	0,070	8,184
MOE	MOE = 7541,180 + 53,773 -0,6169x^2	0,000	0,078	653,09
K	K = 38,6013 +0,2224x -0,00305x^2	0,014	0,025	8,541
MCS	MCS = 41,0933 +0,2393x -0,0027948x^2	0,000	0,057	3,918

DISCUSSION

The statistical models obtained to determine variability in the physical-mechanical properties of the wood of *A. alba* from Mount Montinier in the two directions of the tree stem had low explained variance (tables 2, 3 and 4), with a lower coefficient of determination in the longitudinal direction. Studies of trees from forests in France by Mazet and Nepveu (1991), who compared wood property variation in *A. Alba* with that of *P. abies* and *Pinus sylvestris* L., showed similar results, with the fir wood models showing the lowest coefficient of determination.

However, Sinković (1995), in his study of variation in basic density and volumetric shrinkage throughout the radial direction in trees from a fir forest in Croatia, obtained a third-degree polynomial trend curve with a coefficient of determination of R^2 = 0,62 and 0,70, respectively.

Wood property variation throughout the longitudinal direction

The properties of density, volumetric shrinkage, hardness and maximum compressive strength parallel to the grain showed significant variation in the longitudinal direction, with a downward trend from the base to the crown (Fig. 5), but with explained variance of less than 7% (Table 3), indicating no differences in quality over the entire longitudinal direction.

Variation in density followed the trend described by Panshin and de Zeeuw (1980) for conifers and Wilcox and Pong (1971) for *Picea mariana* Britton, Sterns & Poggenb., *Abies balsamea* Mill., *Abies concolor* Lindl. & Gord. and *Tsuga canadensis* Carrière. The downward trend in volumetric shrinkage throughout the stem was analogous to that obtained by Yao (1969) for *Pinus taeda* (Table 3). This pattern may be attributable to maximum tracheid length occurring at the base of the

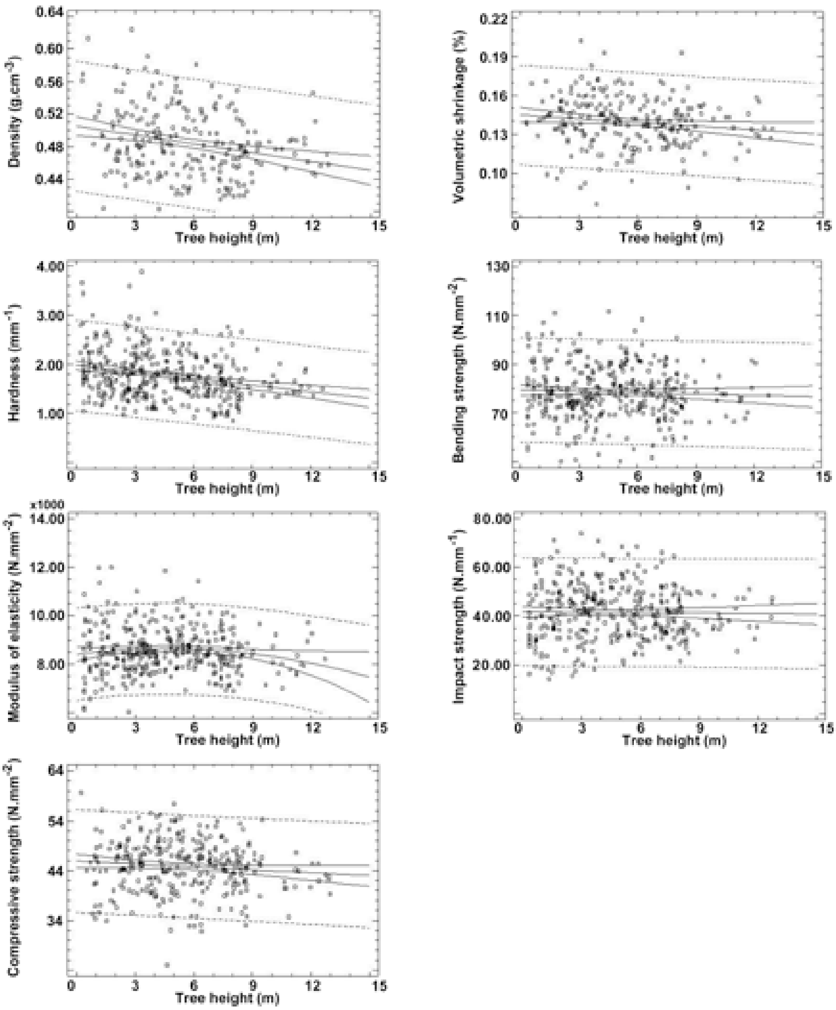

Figure 5. Graphical representation of the simple regression analyses between physical-mechanical properties and test piece location in relation to longitudinal direction of the tree stem.

Table 5. Trend curve*, coefficient of determination (R^2) and significance level (p) of the regression models for physical-mechanical properties throughout the longitudinal direction for the data grouped in intervals of 10 growth rings from the pith to the bark

		Growth rings / Anillos de crecimiento						
		0-10	*10-20*	*20-30*	*30-40*	*40-50*	*50-60*	*60-70*
ρ	Trend curve/Curva de tendencia		‿		/		/	
	No. data groups/nº de grupos de datos	10	12	12	12	10	10	9
	p	0,126	0,047	0,765	0,052	0,391	0,012	0,316
	R^2	0,446	0,494	0,058	0,327	0,093	0,566	0,143
VS	Trend curve/Curva de tendencia		/					
	No. data groups/nº de grupos de datos	10	12	12	12	10	10	9
	p	0,203	0,010	0,171	0,345	0,820	0,407	0,299
	R^2	0,173	0,498	0,324	0,211	0,055	0,087	0,332
H	Trend curve/Curva de tendencia				\	\	\	\
	No. data groups/nº de grupos de datos		12	12	12	11	12	10
	p		0,204	0,632	0,001	0,000	0,013	0,026
	R^2		0,156	0,029	0,684	0,842	0,479	0,529
MOR	Trend curve/Curva de tendencia						\	
	No. data groups/nº de grupos de datos		12	12	12	11	12	10
	p		0,627	0,425	0,733	0,110	0,023	0,245
	R^2		0,025	0,065	0,012	0,288	0,456	0,187
MOE	Trend curve/Curva de tendencia					\		
	No. data groups/nº de grupos de datos		12	12	12	11	12	10
	p		0,884	0,259	0,195	0,002	0,299	0,629
	R^2		0,002	0,125	0,160	0,710	0,119	0,035
K	Trend curve/Curva de tendencia		⌒					
	No. data groups/nº de grupos de datos	7	12	11	12	11	12	9
	p	0,419	0,002	0,713	0,665	0,282	0,821	0,166
	R^2	0,353	0,739	0,081	0,087	0,127	0,006	0,255
MCS	Trend curve/Curva de tendencia		/	⌒	\	\		
	No. data groups/nº de grupos de datos	10	11	12	11	12	12	8
	p	0,895	0,067	0,024	0,028	0,013	0,761	0,106
	R^2	0,002	0,326	0,566	0,433	0,475	0,010	0,376

\	Downward sloping linear trend curve /Curva de tendencia lineal decreciente
/	Upward sloping linear trend curve / Curva de tendencia lineal creciente
⌒	Upward sloping second-degree polynomial trend curve / Curva de tendencia polinomial de segundo grado creciente
‿	Downward sloping second-degree polynomial trend curve / Curva de tendencia polinomial de segundo grado decreciente

trunk (Sanio, 1872; Nicholls and Dadswell, 1962; Panshin and De Zeeuw, 1980; Zobel and Van Buijtenen, 1989) and tracheid size being directly proportional to decrease in microfibril angle (Megraw, 1985, Bendtsen and Senft, 1986). A decreasing relation exists between microfibril angle and tangential shrinkage (Harris and Meylan, 1965) and between microfibril angle and radial shrinkage (Ivkovic *et al.*, 2009; Yamashita *et al.*, 2009).

Variation in maximum compressive strength parallel to the grain throughout the longitudinal direction was fitted to a line with a very gentle slope (Fig. 5). This finding may be attributable to variation of this property throughout the stem being greatly influenced by the presence of juvenile wood, as observed by Machado and Cruz (2005) in a study of *P. pinaster*. In fact, an upward trend was obtained in the first growth rings (Table 5).

Variation in MOR, impact strength and MOE throughout the longitudinal direction did not fit any of the models due to high dispersion of the data (Fig. 5) (Table 3). It can therefore be concluded that no definite pattern exists of these three properties along the entire tree stem. Tsehaye *et al.* (1995) obtained the same result for MOE in *P. radiata*.

Wood property variation throughout the longitudinal direction differed depending on whether the test pieces were from the area of juvenile or mature wood (Table 5). Wood properties at a distance of 0-10 rings from the pith did not show a significant relation to the height variable (Table 5). This result supports the idea that juvenile wood is homogeneous in its behaviour irrespective of height (Larson *et al.*, 2001), which was also noted by Machado and Cruz (2005) in *P. pinaster*. Therefore, in order to understand the changes in wood properties throughout the longitudinal direction, juvenile and mature wood need to be studied individually (Zobel and van Buijtenen, 1989).

Wood property variation throughout the radial direction

Variation in physical and mechanical properties throughout the radial direction can be fitted to a second-degree polynomial trend curve (Fig. 6) with an upward phase from the pith to rings 40-50, followed by a downward phase with a gentler slope to rings 70-75 and a more rapid drop after this point. The trend observed was similar for all heights in the tree (Fig. 4). A noteworthy feature is that the wood closest to the bark had thicker rings and was of lower quality, which is characteristic of over-mature wood. This pattern in variation throughout the radial direction was described by Jayne (1958) for density in *Pinus resinosa* Aiton. It can be explained by relating the variation of the property studied to the juvenile wood percentage stabilisation of the microfibril angle in the region of rings 30-35 (Gorisek and Torrelli, 1999) and the presence of sapwood or heartwood. Deresse *et al.* (2003) observed a significant relation between microfibril angle and MOE and between microfibril angle and MOR in *P. resinosa*, and in the genus *Abies*, Passialis and Kiriazakos (2004) found an increase of 35% in the mean MOE between juvenile and mature wood and a 5% increase in this property between mature sapwood and heartwood.

Variation in wood density in the radial direction did not correspond to the upward trend described for conifers by Panshin and de Zeeuw (1980) or the third level polynomial curve to which *A. alba* from trees growing in Croatia (Sinkovic, 1995) was fitted. Variation in impact strength throughout the radial direction (Fig. 6) is similar to the type of polynomial trend curve described for the other properties, but with no minimum in the vicinity of the pith.

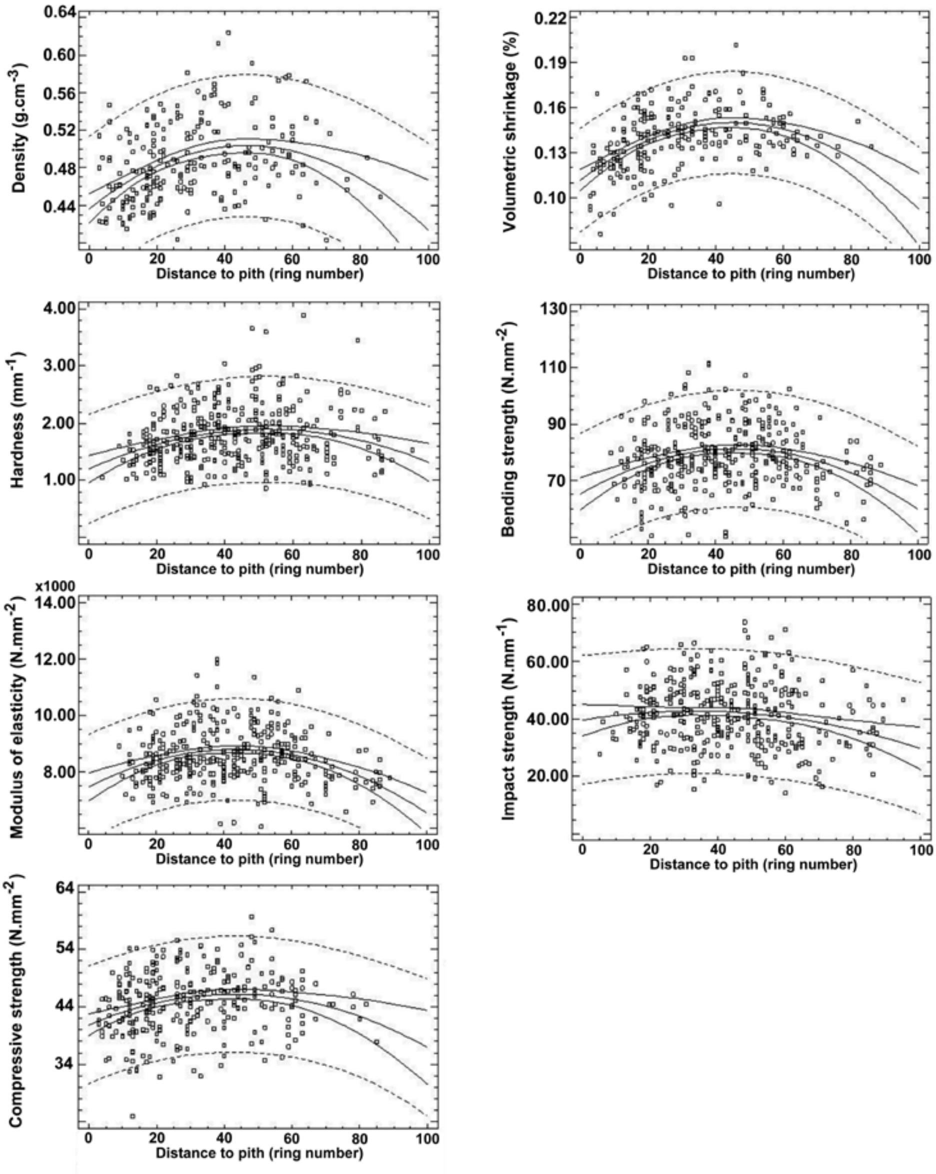

Figure 6. Graphical representation of the simple regression analyses between physical-mechanical properties and test piece location in relation to radial direction of the tree stem.

Table 6. Trend curve*, coefficient of determination (R^2) and significance level (p) of the regression models of physical-mechanical properties throughout the radial direction for the data grouped in 1 m intervals from the base of the tree stem

		Height (m) from the base of the stem /Altura (m) desde la base del fuste								
		0-1	*1-2*	*2-3*	*3-4*	*4-5*	*5-6*	*6-7*	*7-8*	*8-9*
ρ	Trend curve/Curva de tendencia			⌒					⌒	
	No. data groups/nº de grupos de datos		8	7	8	7	7	8	8	9
	p		0,558	0,016	0,157	0,142	0,128	0,372	0,050	0,651
	R^2		0,208	0,813	0,523	0,542	0,642	0,327	0,699	0,193
VS	Trend curve/Curva de tendencia			⌒	⌒	⌒				⌒
	No. data groups/nº de grupos de datos		8	7	8	7	7	8	8	9
	p		0,058	0,025	0,054	0,001	0,152	0,388	0,372	0,059
	R^2		0,680	0,841	0,523	0,949	0,611	0,316	0,327	0,193
H	Trend curve/Curva de tendencia		⌒	⌒	⌒	⌒				
	No. data groups/nº de grupos de datos		8	8	8	7	6	6	6	7
	p	0,126	0,013	0,029	0,019	0,015	0,285	0,228	0,378	0,151
	R^2	0,563	0,822	0,758	0,795	0,878	0,567	0,626	0,386	0,612
MOR	Trend curve/Curva de tendencia				⌒	⌒	⌒			
	No. data groups/nº de grupos de datos	8	8	8	8	7	6	6	7	7
	p	0,133	0,343	0,369	0,054	0,053	0,033	0,904	0,893	0,308
	R^2	0,554	0,348	0,329	0,690	0,770	0,896	0,065	0,052	0,445
MOE	Trend curve/Curva de tendencia	⌒		⌒		⌒				
	No. data groups/nº de grupos de datos	8	8	8	8	7	6	6	7	7
	p	0,039	0,132	0,023	0,127	0,064	0,145	0,618	0,375	0,718
	R^2	0,727	0,555	0,778	0,563	0,748	0,724	0,068	0,159	0,028
K	Trend curve/Curva de tendencia	⌒		⌒			⌒			
	No. data groups/nº de grupos de datos	9	9	8	9	8	8	6	7	7
	p	0,026	0,284	0,043	0,114	0,539	0,038	0,262	0,579	0,255
	R^2	0,705	0,343	0,715	0,516	0,219	0,893	0,591	0,239	0,249
MCS	Trend curve/Curva de tendencia		⌒	⌒	⌒	⌒				
	No. data groups/nº de grupos de datos	7	7	9	9	7	8	6	8	7
	p	0,963	0,073	0,008	0,010	0,059	0,581	0,115	0,699	0,245
	R^2	0,019	0,731	0,803	0,782	0,756	0,238	0,662	0,134	0.506

⌒ Upward sloping second-degree polynomial trend curve / Curva de tendencia polinomial de segundo grado creciente

This circumstance supports the observation made by Barnett and Bonham (2004) that juvenile wood has good resistance to impact because of the relation between microfibril angle and wood flexibility.

As expected because of the very slight variations shown in the physical-mechanical properties in the longitudinal direction of the stem (mean and standard deviation similar throughout the longitudinal direction), no differences were observed in wood property variation from the pith to the bark on analysing different heights in the tree (Table 6). A difference was seen only in the growth ring number (in the radial direction), which showed the maximum value in the trend curve. The maximum value was closer to the pith the higher the analysis was made in the tree, which supports the theory that the maximum value in the trend curve is affected by the transition from juvenile to mature wood (Fig. 4).

Further studies on other populations of *A. alba* in the Spanish Pyrenees will show whether it is possible to extrapolate the trends found in this study to other provenances.

CONCLUSIONS

The low explained variance in the physical-mechanical properties leads to the conclusion that no model exists for the wood of *A. alba* from the Spanish Pyrenees capable of providing a statistical explanation for variation in the behaviour of the wood throughout the tree stem, which means that it is only possible to refer to trends.

Properties that show significant variation throughout the longitudinal direction (density, volumetric shrinkage, hardness and maximum compressive strength) follow a downward trend from the base to the crown, with a gentle slope. The decrease in tracheid length throughout the longitudinal direction may influence this behaviour, although it cannot be stated that a difference in wood quality occurs throughout this direction.

A different pattern was observed throughout the longitudinal direction between test pieces of juvenile and mature wood.

Variation in the physical and mechanical properties throughout the radial direction can be fitted to a second-degree polynomial trend curve with an upward phase from the pith to rings 40-50, followed by a downward phase with a gentler slope to rings 70-75 and a more rapid drop after this point. This behaviour can be explained by relating the variation in density to juvenile wood percentage, microfibril angle and presence of sapwood or heartwood. It was also observed that wood closest to the bark had thicker rings and was of lower quality, which is characteristic of over-mature wood.

Authors encourage carrying further studies on other populations of *A. alba*, as it will allow confirming these trends in other locations, increasing the knowledge about this wood and its technological properties.

ACKNOWLEDGMENTS

The authors are grateful to the Aragon Regional Government Forest Administration and to the Empresa de Transformación Agraria, S.A. (TRAGSA) for assistance in collecting the study samples. We acknowledge Dr. Joaquín Solana, from the Technical University of Madrid, for reviewing the statistical study.

This study is part of the AGL2007-65960 project of the Spanish National Plan for Scientific Research, Development and Technological Innovation, funded by the Spanish Ministry of Education and Science and the European Regional Development Fund (ERDF).

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Manuscrito recibido el 23 de abril de 2012.
Aceptado el 13 de marzo de 2013.

Este documento se debe citar como:
González-Rodrigo, B., L.G. Esteban, P. de Palacios, F. García-Fernández y A. Guindeo. 2013. Variation throughout the tree stem in the physical-mechanical properties of the wood of *Abies alba* Mill. from the Spanish Pyrenees. Madera y Bosques 19(2)87-107.