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Influence of blue stain on density and dimensional stability of *Pinus radiata* timber from northern Galicia (Spain)

Abstract: The presence of blue-stain fungi considerably decreases the value of *Pinus radiata* timber, which is commercially important in Galicia (NW Spain). For this study, seven young pine trees growing in four different plantations were felled, and 20 discs were sampled from different heights in the stems. Parts of the discs were discoloured as a result of fungal infection. The discs were cut into small specimens. Defect-free specimens (controls) were selected for determining density and dimensional stability both in the volume and in the axial direction. Physical properties of fully blue-stained specimens and the controls were compared for each disc based on one-factor analysis of variance. As the factor was blue-stain, the other sources of variation were suppressed, such as tree source, height in the stem, ring width, cambial age and presence of heartwood or sapwood. Most of the physical properties analysed on some sample discs differed significantly between discoloured and unstained wood. The variables most affected by blue stain were basic density and volumetric shrinkage: blue-stained wood was 1.1% lighter and volumetric shrinkage was 5% higher in blue-stained wood than in the controls.

Keywords: axial shrinkage, basic density, blue-stain fungi, hygroscopicity, oven-dry density, *Pinus radiata*, properties depending on stem height, radiata pine, shrinkage, specific gravity, volumetric shrinkage

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Introduction

Spain is fourth in the world in terms of hectares of land covered by radiata pine (*Pinus radiata* D. Don). The small dimension timber is mostly used as raw material in particleboard and fibreboard manufacturing. The abundance of sapwood and juvenile wood in small logs reduces wood quality (Fernández-Golfin Seco 1996; Jayawickrama 2001; Riesco and Díaz 2007). Blue-stain fungi (usually from genera *Aureobasidium*, *Ceratocystis*, *Ceratostomella*, *Endoconidiophora*, *Graphium*, *Lasiodiplodia*, *Leptographium*, *Ophiostoma* and *Sphaeropsis*) commonly appear in sapwood 5–7 days after felling (Forest Products Laboratory 2010). The fungi give the wood a grey-bluish colour and reduce its economic value (Kollmann 1959; Torres Juan 1964). The decline in value is higher in wood used for decorative purposes than for structural applications (AENOR 2008; AENOR 2011). Recent works aiming at biological control of sapstain fungi (Gradinger et al. 2009; Hong et al. 2014) or combating fungi colonisation by quat- and amino-silicones (Ghosh et al. 2012) showed the importance of the research in this field.

Blue staining can be avoided if the moisture content (MC) in sawn planks is quickly reduced by kiln drying or by slower drying combined with treatment with preservatives.

Physical properties in wood affected by blue stain are not substantially modified, with the exception of stability in the axial direction (Rey Prieto and Riesco Muñoz 2012), and hygroscopicity and permeability if the fungal attack is intense and affects mature wood (Kollmann 1959; Torres Juan 1964; Rodríguez and Arriaga 1988; McFarling and Byrne 2003; Byrne et al. 2005; Vignote and Martínez 2006). Byrne et al. (2005) reported the lack of references on the influence of blue stain on the properties of solid wood and it is also emphasised that most studies reported that blue stain does not affect wood from temperate areas.

The aim of the study was to determine the effect of blue stain on density and dimensional stability (shrinkage properties) of solid wood from young radiata pine trees.

Materials and methods

Wood was obtained from seven young and apparently healthy *Pinus radiata* D. Don trees felled in four plots located in northern Galicia. The characteristics of the sampled pines are listed in Table 1. They were in the first third of the usual rotation for the species; i.e., 30–35 years according to Fernández-Golfín Seco (1996). The number of sampled trees met the requirements of European Standard EN 384:2010 and Spanish Standard UNE 56528:1978 (AENOR 1978a) for testing small defect-free wood specimens. Cross-section discs (slabs) of 10 cm thickness were cut from each felled tree beginning at the base and then every metre to 6 m up the stem. The discs were maintained under laboratory conditions until approximately half of the cross surface of the discs was discoloured by blue-stain fungi. The discs were then cut to obtain the maximum number of small prismatic specimens with target dimensions $2 \times 2 \times 4$ cm³ in the R, T and L direction, respectively (AENOR 1978a). The breakdown of the discs, made when the degree of blue stain was sufficient to yield a similar number of stained and unstained specimens in each disc, did not take into account the MC of wood at the time. As a result, tested specimens exhibited MCs varying around the standard value of 12% (AENOR 1978a), although further analyses revealed that the variation was negligible.

The specimens with both ends completely stained (W_{stained}) or completely free of stain ($W_{\text{not st.}}$), were selected for tests. The intensity of stain was not considered but its spreading in the heads. Specimen cross sections were only examined because the stain is less visible on the sides of the samples (Kollmann 1959). The criterion of visually checking the spread of blue stain on the specimen heads was adopted because of its easy application under practical conditions in the mill.

No trace of bark or pith was included to avoid the periphery or the centre of the disc. Thus the possible influence of compression wood (usually located near the pith) was eliminated. The comparison of physical properties between W_{stained} and $W_{\text{not st.}}$ was made separately for each disc to avoid the significant inter-tree and along-tree variation as sources of variation (Kollmann 1959; Zobel and Van Buijtenen 1989; Kininmonth and Whitehouse 1991; Riesco and Díaz 2007). Heartwood as a possible source of variation was discarded because heartwood formation begins after 12–15 years (Fernández-Golfín Seco 1996) and the age of the sampled trees was 13 years on average.

On average 37 specimens per tree were selected and tested according to the Spanish Standards UNE 56531:1977 (AENOR 1977a), UNE 56532:1977 (AENOR 1977b), UNE 56533:1977 (AENOR 1977c), UNE 56528:1978 (AENOR 1978a) and the International Standards ISO 3131:1975, EN 13183-1:2002 and EN 408:2011. The mass of each

specimen was measured to the nearest 0.01 g and the three main dimensions were obtained between centres of opposite faces, to the nearest 0.01 mm. The volume was obtained by considering each specimen as a prismatic piece and multiplying the three main dimensions. The discs were cut when they were fairly dry to avoid fibrous surfaces in case of wet sawing, which leads to irregular faces and errors. The physical properties (listed in Table 2) were measured after cutting the discs. The basic density was calculated as the weight of the specimen in the oven-dry state divided by the volume at saturation MC. The hygroscopicity was calculated as the variation in air-dry density corresponding to a variation of 1% MC.

An analysis of the variance considering the presence/absence of blue stain as a factor was performed to determine possible differences between means of physical properties at $\alpha=0.05$ or 0.01. The differences were averaged for the twenty discs, and expressed in absolute value and as a percentage of the mean for the whole sample. All statistical analyses were performed by Microsoft Excel 2003 (Microsoft Corporation, Redmond, WA, USA) and SPSS Statistics (version 20) software (IBM, Armonk, NY, USA).

Results and discussion

Basic descriptive statistics

Specimens in which both ends were completely stained (W_{stained}) or completely free of stain ($W_{\text{not st.}}$) (without taking into account the intensity or colour of the stain) were tested. The rate of spread of the stain was variable and very high in most cases. Therefore, in some discs the number of $W_{\text{not st.}}$ was not sufficient for statistically reliable comparisons with W_{stained} , and these discs were excluded from the analyses. As a result, the number of valid discs per tree was not always sufficient to enable sampling every metre to a height of six metres in the stem (Table 1).

Mean annual growth ring width was similar to that reported in other studies (Fernández-Golfín Seco 1996) (Table 2). The sampled wood was light, moderately stable and had an intermediate hygroscopicity, according to the standard UNE 56540:1978 (AENOR 1978b). The fibre saturation point

Table 1 Characteristics of sampled trees.

Geographical origin	Tree #	Age of tree (year)	BH ^a diam. (cm)	Total height (m)	No. of discs per tree	No. of specimens per disc ^b
Feás	1	9	10.2	10.1	5	10
	2	12	10.6	9.9	1	8
Xanceda	3	12	13.8	13.3	3	8
	4	13	15.6	14.3	1	18
	5	13	14.7	12.5	5	15
Quindimil	6	14	13.5	12.4	4	11
Palas de Rey	7	19	16.4	11.4	1	43

^aBH: breast height; ^bThe mean number of specimens per disc represents the number evaluated for each property for both stained and unstained material.

Table 2 Basic descriptive statistics of the physical properties of wood from *P. radiata* ($n=260$ specimens). CV=coefficient of variation.

Variable	Abbr.	Mean	CV (%)	Min.	Max.
All specimens					
Ring width (mm)	<i>a</i>	5.9	35	1.8	11.2
Air-dry density (kg m ⁻³)	ρ_{12}	460	12	340	639
Oven-dry density (kg m ⁻³)	ρ_0	425	12	315	591
Basic density (kg m ⁻³)	d_b	379	11	289	535
Volumetric shrinkage (%)	C_v	12.0	19	6.3	18.3
Volum. shrinkage coef. (%)	<i>v</i>	0.36	26	0.16	0.71
Hygroscopicity (kg m ⁻³)	<i>hi</i>	2.9	17	1.5	4.4
FSP _{vol} (%) ^a	psf_v	35	24	15	62
FSP _{axial} (%)	psf_l	32	58	10	99
Axial shrinkage (%)	C_l	0.6	82	0.0	2.2
Axial shrinkage coef. (%)	<i>l</i>	0.02	102	0.00	0.10
Stained wood					
Ring width (mm)	<i>a</i>	5.5	41	1.8	11.2
Air-dry density (kg m ⁻³)	ρ_{12}	456	13	340	585
Oven-dry density (kg m ⁻³)	ρ_0	424	13	315	546
Basic density (kg m ⁻³)	d_b	376	12	289	495
Volumetric shrinkage (%)	C_v	12.5	16	8.3	17.1
Volum. shrinkage coef. (%)	<i>v</i>	0.37	20	0.19	0.62
Hygroscopicity (kg m ⁻³)	<i>hi</i>	2.9	15	1.7	3.7
FSP _{vol} (%) ^a	psf_v	35	19	18	53
FSP _{axial} (%)	psf_l	32	58	10	89
Axial shrinkage (%)	C_l	0.7	84	0.0	2.2
Axial shrinkage coef. (%)	<i>l</i>	0.02	97	0.00	0.10
Non stained wood					
Ring width (mm)	<i>a</i>	6.1	31	2.4	10.8
Air-dry density (kg m ⁻³)	ρ_{12}	462	12	353	639
Oven-dry density (kg m ⁻³)	ρ_0	425	12	323	591
Basic density (kg m ⁻³)	d_b	380	11	294	535
Volumetric shrinkage (%)	C_v	11.7	20	6.3	18.3
Volum. shrinkage coef. (%)	<i>v</i>	0.36	28	0.16	0.71
Hygroscopicity (kg m ⁻³)	<i>hi</i>	2.9	19	1.5	4.4
FSP _{vol} (%) ^a	psf_v	35	26	15	62
FSP _{axial} (%)	psf_l	32	58	10	99
Axial shrinkage (%)	C_l	0.6	80	0.0	2.2
Axial shrinkage coef. (%)	<i>l</i>	0.02	104	0.00	0.10

^aFSP: Fibre saturation point

(FSP) was intermediate according to the interpretation of Gutiérrez and Plaza (1967). The dimensional stability of wood was as expected because of its low density based upon the constants proposed by Koehler (1931). These results correspond to a sample of trees where sapwood was the main constituent because of the young age of the trees.

There was a high degree of variation in the properties related to dimensional stability of wood in the grain direction, namely L (axial) shrinkage, L shrinkage coefficient, and FSP_{axial}. This is also to be expected in young trees that include a large proportion of juvenile wood, in which axial stability is very variable (Zobel and Van Buijtenen 1989; Riesco and Díaz 2007; Forest Products Laboratory 2010).

Influence of blue stain on physical properties

Data from each disc for each physical property were subjected to an Analysis of Variance (ANOVA) with presence/absence of blue stain as a factor. There were no significant differences in mean ring width (Table 3) and therefore significant differences for other variables were not attributable to an indirect effect of ring width variation.

In general, blue-stain fungi had minimal influence on physical properties of wood (Table 2). Only nine of the 20 sampled discs yielded significant differences between W_{stained} and $W_{\text{not st.}}$ for the physical variables analysed (Table 3). Although the number of specimens was not the same in all the discs (Table 1), the sample size had no significant effect on results.

Density appeared to vary significantly in only five of the 20 sampled discs. The differences tended to be small and not biologically significant. W_{stained} was somewhat lighter than $W_{\text{not st.}}$: mean differences of 50 kg m⁻³ (air-dry density), 18 kg m⁻³ (oven-dry density) and 28 kg m⁻³ (basic density) were significant. Similar results were reported by Chapman and Scheffer (1940) with wood of south yellow pines of United States, Aufsess (1981) for *Abies alba* Mill., Schirp et al. (2000) for *P. radiata* or Rey Prieto and Riesco Muñoz (2012) with *Pinus sylvestris* L. Air-dry and basic density were 1.1% lower in W_{stained} (Figure 1), while oven-dry density was 0.5% lower in W_{stained} (Table 4). The variation was similar to that cited by Schirp et al. (2000), in wood of *P. radiata* inoculated with fungi of genus *Ophiostoma*.

Hygroscopicity was only significantly different in two discs (Table 3) and the difference was 3.4% of the mean of the sample (Table 4). These results contradict reports on the influence of blue stain on this variable. Volumetric shrinkage was significantly different in more discs than any other wood property (Table 3). The volumetric shrinkage was 5% higher in W_{stained} (Figure 1 and Table 4). Despite the slight influence of blue stain on volume stability, axial shrinkage was 16.7% lower in W_{stained} , although the differences were only significant in one disc.

The nine discs exhibited significant differences in their physical properties in terms of blue stain as a parameter (Table 3). The differences are visible at the different heights in the stem and at the five trees that differ in size, age and stand. The discs from less than 2 m above ground exhibited more significant differences in basic density between W_{stained} and $W_{\text{not st.}}$. Physical properties in subsamples (W_{stained} and $W_{\text{not st.}}$) differed significantly in the youngest and tallest trees with the greatest slenderness. As slenderness disappears with age (on the small sample analysed), these differences were expected to diminish with the tree age.

Table 3 Mean values of unstained and stained specimens with P-values (top, centre and bottom of each cell, respectively) obtained in the analysis of the variance for each physical property of wood of *P. radiata* in presence or absence of blue stain as a factor. ns=not significant. For abbreviations see Table 2. Only results for discs exhibiting significant differences (P-value <0.050) for at least one of the variables are presented.

Variable	Number of tree in Table 1 (#) and height of the disc in the stem (m)								
	#1, 0 m	#1, 4 m	#3, 4 m	#4, 0 m	#5, 1 m	#5, 2 m	#6, 0 m	#6, 1 m	#6, 6 m
<i>a</i>	ns	ns	ns	ns	ns	ns	ns	ns	ns
ρ_{12}	ns	ns	ns	589	ns	ns	500	481	ns
				542			453	427	
				0.013			0.015	0.010	
ρ_0	424	339	ns	547	ns	ns	464	449	ns
	447	360		508			421	397	
	0.026	0.014		0.024			0.022	0.008	
d_b	379	ns	ns	493	ns	ns	411	396	ns
	400			445			370	352	
	0.022			0.007			0.010	0.010	
C_v	ns	6.8	8.8	11.0	10.8	10.5	ns	ns	11.9
		9.4	10.5	14.1	13.7	12.8			8.6
		0.040	0.015	0.000	0.000	0.044			0.022
<i>v</i>	ns	ns	ns	0.36	0.26	0.23	ns	ns	0.38
				0.42	0.37	0.32			0.30
				0.032	0.003	0.022			0.021
<i>hi</i>	ns	ns	ns	3.79	ns	ns	3.3	ns	ns
				3.13			2.9		
				0.003			0.019		
psf_v	ns	ns	27	ns	ns	ns	ns	ns	ns
			33						
			0.004						
psf_i	ns	ns	ns	ns	ns	ns	ns	ns	ns
C_i	ns	0.44	ns	ns	ns	ns	ns	ns	ns
		0.13							
		0.008							
<i>l</i>	ns	0.02	ns	ns	ns	ns	ns	ns	0.02
		0.00							0.04
		0.018							0.019

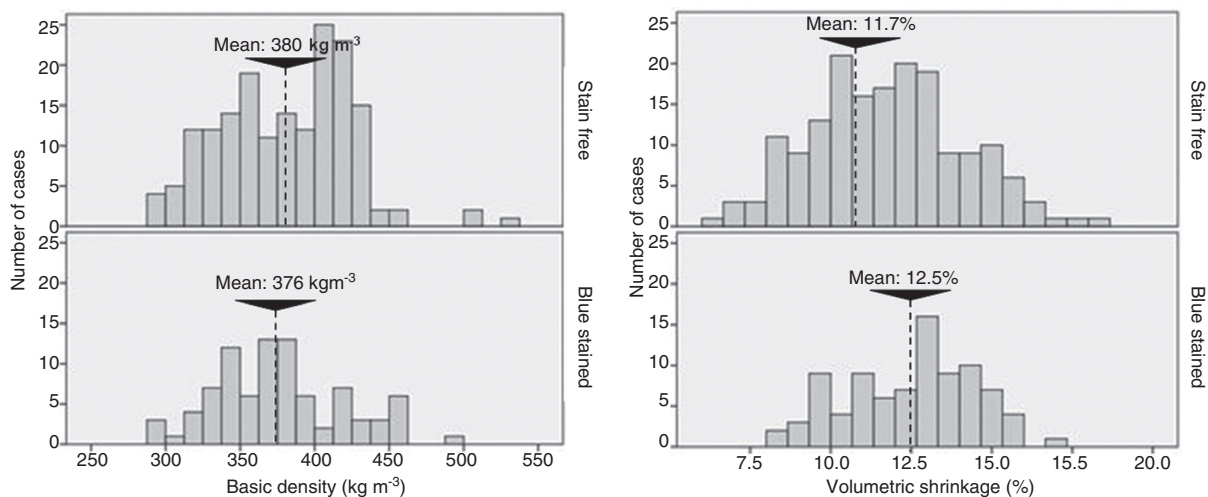


Figure 1 Effect of blue stain on the variations in basic density and volumetric shrinkage in the whole sample of wood of *P. radiata* (20 discs).

Table 4 Differences in physical properties of blue-stained wood of *P. radiata* with reference to stain-free wood for the whole sample; $n=20$ discs; 13 specimens per disc on average.

Variable	Mean decrease in stained wood	
	Absolute	(%)
Ring width (mm)	0.3	5.1
Air-dry density (kg m^{-3})	5	1.1
Oven-dry density (kg m^{-3})	2	0.5
Basic density (kg m^{-3})	4	1.1
Vol. shrinkage (%)	-0.6	-5.0
Vol. shrinkage coef. (%)	-0.02	-5.6
Hygroscopicity (kg m^{-3})	0.1	3.4
FSP _{vol} (%)	0	0.0
FSP _{axial} (%)	-4	-12.5
Axial shrinkage (%)	0.1	16.7
Axial shrinkage coef. (%)	0.00	0.0

Conclusions

The results confirm the generally accepted view that blue-stain fungi have minimal effects on physical properties of wood. This was also the case for young radiata pines. Blue-stain mostly influenced density and volume stability. Blue-stained wood (W_{stained}) was slightly lighter than in $W_{\text{not st.}}$, while volumetric shrinkage was higher in W_{stained} . The differences in physical properties due to blue stain were only significant in some trees and in some parts of the stems, i.e., mainly in basal logs of the youngest trees with the greatest slenderness. Very few discs exhibited significant differences in variables related to axial shrinkage due to blue stain. Further studies should focus on adult trees to verify the lowering tendency of blue stain attack with age as indicated in the present study.

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