EFFECT OF LOG HEAT TREATMENT ON RELEASE OF GROWTH STRESSES IN *EUCALYPTUS NITENS*[1]

*Carlos Rozas**

Assistant Professor
Wood Engineering Department
Faculty of Engineering
University of Bío-Bío
Concepción, Chile
E-mail: erozas@ubiobio.cl

Marcia Vásquez

Assistant Professor
Department of Environmental Forest Management
Faculty of Forest Science
University of Talca
Talca, Chile
E-mail: mvazquez@utalca.cl

Patricia T. Vega

Post-doctoral Scholar
E-mail: patricia.vega@oregonstate.edu

Arijit Sinha†

Associate Professor
Department of Wood Science and Engineering
Oregon State University
Corvallis, OR 97331
E-mail: Arijit.sinha@oregonstate.edu

Claudio Montero

Wood Industries Engineer, M.Sc. Researcher
University of Bío-Bío
Concepción, Chile
E-mail: cmontero@ubiobio.cl

(Received March 2021)

Abstract. The use of *Eucalyptus nitens* has diversified the Chilean lumber industry in unprecedented ways. However, growth-induced strains cause splitting and warping. The objective of this investigation was to determine the effect of the heat treatment applied to logs of *Eucalyptus nitens* on the reduction of growth stresses and improvement of quality in sawn wood. Logs were extracted at different heights of the tree for 15-yr and 20-yr-old tress. The sawmill process was allowed to obtain radial, mixed, and tangential plane pieces, at two thicknesses (25 and 50 mm). The evaluation of MC and warping was according to Chilean National Standards. The results obtained in this research suggest that by applying the heat treatment to *Eucalyptus nitens* logs, a significant reduction in growth strains can be achieved. Heat treatment also increased the quality of the pieces in terms of bow, crooking, and twisting. Therefore, there are substantial benefits of using heat treatments to reduce defects caused by growth strains and thus increase the quality of the wood and reduce its warp.

Keywords: Growth stresses, *Eucalyptus nitens*, wood quality, warping.

INTRODUCTION

The use of *Eucalyptus* species has diversified the Chilean lumber industry (Severo and Tomaselli 2000). However, its processing is impeded by

* Corresponding author
† SWST members

Wood and Fiber Science, 53(3), 2021, pp. 178-193
https://doi.org/10.22382/wfs-2021-18

growth stress-induced strains, which causes splitting at the time of logging and warping during milling (Nicholson 1973; Ferrand 1983; Yang and Waugh 2001; Raymond et al 2004; Yang 2005; Biechele et al 2009; Carvalho et al 2010; Rezende et al 2010). The splitting and warping cause significant economic losses and reduce sawmill yield (Severo and Tomaselli 2000; de Fégely 2004; Malan 1979; Junior and Garcia 2003; Amer et al 2017).

Several techniques have been developed to reduce growth strains in both sawlogs and lumber (Chafe 1979; da Rocha and Tomaselli 2002; Washusen et al 2009), which combined with improvements in milling and drying technologies have enabled yield improvements. Although there are noteworthy advances, growth strains still remain the main limitation for the use of Eucalyptus wood. The growth strains exert longitudinal traction on the fibers close to the bark, which gradually decreases to approximately 2/3rd of the log radius, shifting to compression of the fibers toward the pith (Jacobs 1965; da Rocha and Tomaselli 2002). These forces cause splitting in logs and warping in lumber (Malan 1979; Ferrand 1983; Severo and Tomaselli 2000.

Reducing growth stresses by applying heat and moisture to logs or lumber has been well studied (Lutz 1974; Chafe 1979; Weik et al 1984; Kubler 1987; Okuyama et al 1987; Severo and Tomaselli 2000). These studies have achieved satisfactory success in reducing growth strains and associated defects, and consequently have enhanced wood quality and yield. Thermal treatments increase lignin plasticization through the application of heat and humidity, which produces a gradual release of growth stresses and thus reduces splitting (Lenth and Haslett 2003).

Skolmen (1967) applied a 24-h heat treatment on *Eucalyptus saligna* logs with diameters between 15 and 20 cm and reduced growth stresses by 50%. Lutz (1967) applied a treatment with water at 93°C for 48 h, totally eliminating growth stresses. In addition, Lutz (1978) applied a treatment at 65°C for 48 h, which decreased the stresses by 67%. Other studies such as Tejada et al (1997), Severo and Tomaselli (2000), and succesfuly reduced growth stresses in Eucalyptus with various vaporization regimens.

The reduction of growth stresses through thermal treatments minimizes the presence of warping in lumber (Severo and Tomaselli 2000), the defects associated with sawing and drying of wood (Calonego and Severo 2004), and reduces cracks in the sawn lumber (Calonego and Severo 2005). However, Severo and Tomaselli (2000) stress that the pieces near the pith have the greatest number of defects; therefore, it is difficult to totally eliminate growth strains close to this area.

To apply an effective thermal treatment to the logs, the thermal properties of the wood must be understood (Calonego and Severo 2004). Among the relevant properties to define the heating time are specific heat, conductivity, and thermal diffusivity (Forest Products Laboratory 2010). Other factors such as species, log diameter, MC, initial and final temperature, as well as the geometry of the heating chamber, and the medium used are important (Steinhagen et al 1980; Calonego and Severo 2004). For Lutz (1978), in hardwood species there is a relationship between wood density and heating temperature, recommending that species with a density of 0.45 g/cm^3, 0.50 g/cm^3, 0.55 g/cm^3, and 0.60 g/cm^3 apply a heat treatment with a heating temperature of 48°C, 60°C, 70°C, and 85°C, respectively.

There is a lack of complete characterization of the effect of heat treatment on growth stresses in *Eucalyptus nitens* logs. Additionally, improvement in the yield and quality of lumber from logs has not been quantified. The objective of this study was to determine the effect of the heat treatment, applied in logs of *Eucalyptus nitens,* on the reduction of growth stress and the improvement of quality in sawn wood.

MATERIALS AND METHODS

Origin of the Selected Trees

Eucalyptus nitens trees were provided by the company Agrícola y Forestal Natalhue Ltda., located in the province of Valdivia, in the Huenuye Norte farm, sector Lanco-Panguipulli (39°29′78″ South and 78°41′34″ West), Chile. According to the Köppen classification, the climate is a Cfsb type, which is an oceanic climate of short summer drought and Mediterranean influence. Annual precipitation is 2351 (mm/year), presenting high RH and low temperatures throughout much of the year (Dirección Meteorológica de Chile 2001). The region consisted of a plantation with an initial density of 1666 trees/ha, which was thinned at 6 yr (700 trees/ha), at 8 yr (400 trees/ha), and at 10 yr (200 trees/ha). Additionally, three prunings were carried out at 2.5 yr (2.5 m in height), at 3.5 yr (between 5 and 6 m in height), and at 5 yr (9 m in height).

Selection of Trees and Obtaining Logs

Seven trees of *Eucalyptus nitens* of 15 yr and five trees of 20 yr were used (Table 1), to which the diameter at breast height was measured with a precision caliper of 0.001 m. Then each tree was cut, and the total height was measured. From each 15-yr-old tree, two logs, 4 m in length were obtained totalling to 14 logs. Table 1 presents the summary of log selection and subsequent experimental design. First log was extracted from height between 0.3– and 4.3 m and the second one from 4.3– and 8.3 m. For 20-yr-old tress, three, 4-m long logs were extracted from heights between 0.3– and 4.3 m, 4.3– and 8.3 m, and 8.3– and 12.3 m, from each tree, totaling to 15 logs (Table 1). In total, 29 logs were used – 14 from 15-yr-old trees and 15 from 20-yr-old trees. Each of the 29 logs was cut into half to obtain two 2.0-m logs, allowing one to be used for heat treatment (T) and the other to be used as a control (C).

The heat treatment was performed in a 1700-L mash tank with an automatic temperature control heating system that consisted of six electric resistances of 1.5 kW each. The applied heating regimen started from 40°C and was constantly increased till 70°C. The program ended once the center of the logs reached a temperature of 45°C. The temperature was monitored using three "T" type thermocouples inserted at three different depths (3 cm from the surface, midway to the center of the log, and the center of the log). Each thermocouple was sealed with heat- and water-resistant silicone. The data obtained from the thermocouple were continuously logged and stored in a data logger.

Measurement of Physical Properties

To determine the physical properties, a 0.3-m thick disk was removed at both ends of each 4.0-m log. The disk was used to determine the MC and density, as recommended by the Chilean Standard NCh 176/1 Of.86 (Instituto Nacional de Normalización 1984) and NCh 176/2 Of.86 (Instituto Nacional de Normalización 1988), respectively.

Sawing Process

For milling, a band sawmill was used with a 40-HP, 3-phase motor, 1-m flywheel diameter, a saw blade

Table 1. Material description and experimental design of the study.

Test matrix

Age of tree	No. of trees	Log 1 height range and quantity		Log 2 height range and quantity		Log 3 height range and quantity	
15	7	0.3-4.3 m	7	4.3-8.3 m	7	NA	
20	5		5		5	8.3-12.3 m	5

Experimental design

Tree age	Treatment	No. of logs	Total pieces	Pieces tangential plane	Pieces radial plane	Pieces mixed plane
15 yr	T	13	61	10	32	19
	C	15	69	10	31	28
20 yr	T	13	74	16	34	24
	C	15	95	11	45	39

T, Logs with heat treatment; C, Control logs.

length of 7200 mm, and a maximum cutting height of 60 cm. The applied sawmill program allowed us to obtain 25- and 50-mm thick pieces, prioritizing radial plane pieces, since these exhibited better behavior during mechanical transformation and drying.

Measurement of Growth Stresses in the Logs

The growth strain, as a direct measure of growth stress, for each log was measured indirectly using a 0.01-mm precision caliper. The distance between the first cut and the log was measured as the band sawmill cut approximately 2/3rd of the length of the log, equal to 1.34 m.

Measurement of the Quality of the Sawmill Process

To assess the quality of the milling process, the thickness variation was measured every 0.50 m along each piece. For this purpose, a 0.1-mm precision digital caliper was used, avoiding measuring over knots or other defects present in the piece. The first measurement was made in the exit direction of the band sawmill. This was done with the purpose of identifying eventual problems during milling.

Measurement of Warping in Lumber

The measurement of warping was focused on bow, twist, and crook. The Chilean standard NCh 993 from 72 was used as a reference. A specially adapted measuring table, a digital caliper with 0.01-mm precision and a metric ruler with precision 0.001 m were used.

Obtaining the Final Quality in Each Piece

The final quality of each piece was obtained based on the Chilean standard NCh 993 of 72. For this, Eq 1 was used, which scored 1.00 points for warping of quality A, 0.75 points for quality B, 0.50 points for quality C, and 0.25 points for quality D. Finally, the sum of the scores of each warp quality determined the total quality for each piece.

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} Y_{ij} \ (1) \qquad (1)$$

where Q: Final quality of the piece (%). Y_{ij}: warping value measured in piece i, assessing warp j (bowing, twisting and crooking) $\forall_i$: 1, n and $\forall_j$: 1 = bow, 2 = crook, 3 = twist).

Design of Experiments

The conditions of the experiment are summarized in Table 1, which details the number of logs tested with heat treatment (T) and the control logs (C) grouped by tree age, as well as the number of pieces obtained after sawing.

Statistical Analysis of the Results

A descriptive analysis was carried out on each analyzed variable, obtaining the measures of central tendency, dispersion, as well as the maximum and minimum values and confidence intervals. An analysis of variance (ANOVA) with a significance level of 5% (p-value: 0.05) was applied, and the comparison between means was done with a Tukey test (p-value: 0.05). The assumptions of independence (Durbin–Watson test), correlation (Pearson test), and normality (Kolmogorov-Smirnov test) were verified. All statistical analysis was performed with Minitab 16® software and supplemented with word processing software.

RESULTS AND DISCUSSIONS

Characteristics and Properties of the Trees Used

All the basic attributes measured from the samples are reported in Table 2. The basic density in the 15 yr decreased with height. While for 20-yr-old trees the basic density decreased with the height of the tree initially but then an increase was observed. This trend was noticed in the same species by other authors (Purnell 1988; Lausberg et al 1995). Furthermore, it was observed that the MC decreased with the height of the tree regardless of the age.

Log Heating Time

The effect of tree properties on the heating time showed a positive and strong significant

Table 2. Descriptive statistics of physical and dendrometric properties of the selected trees of *Eucalyptus nitens* (standard deviation in parentheses).

			15 yr			20 yr			
Properties	Statistics	Unit	0.3 m	4.3 m	8.3 m	1.3 m	5.3 m	9.3 m	13.3 m
Basic density	Mean (SD)	kg/m^3	478 (10)	442 (19)	440 (10)	465 (16)	441 (15)	455 (7)	475 (20)
MC	Mean (SD)	%	125 (9)	142 (12)	135 (9)	136 (7)	134 (6)	124 (3)	118 (4)
Log diameter	Mean (SD)	cm	53.4 (6.0)	39.9 (3.6)	36.7 (2.5)	55.3 (5.2)	48.7 (4.1)	45.8 (4.8)	44.3 (3.8)
Diameter at breast height	Mean (SD)	cm	49.6 (3.3)			55.5 (5.2)			
Total tree height	Mean (SD)	m	37.0 (1.4)			40.3 (0.7)			

relationship with the diameter of the log ($p < 0.001$), had a moderate relationship with the age of the tree ($p = 0.002$), and with the basic density ($p = 0.035$). In contrast, the height of the log had a negative relationship and was not significant ($p = 0.592$). It was further observed that only the diameter ($p < 0.001$) and the height of the log ($p = 0.026$) significantly affected the warm-up time of the logs (Table 3). This observed significance is consistent with previous studies (Lutz 1967; Walser 1974). This can be explained by the anisotropy of wood, which influences the heating time while also determining the longitudinal and radial heating rate of the log. The ANOVA showed that the effect of the height of the log was less than the effect of the diameter. Correlation analysis did not detect a significant relationship between the diameter and the heating time, which is counter intuitive. Essentially, density of the wood determines the heating time of the logs, since the thermal diffusivity during heating is inverse to the density of the wood.

Log Growth Strain

The growth strains were indirectly assessed by measuring the opening between the log and the saw during the first cut (Table 4). Log growth strain in heat-treated (T) samples were less than that of control specimen. Results showed a 37.4% reduction in growth strains in heat treated (T) logs and corroborated by ANOVA and the Tukey test ($p < 0.001$).

Similar trends were reported by Severo and Tomaselli (2000), who by vaporizing *Eucalyptus dunnii* logs for 20 h were able to reduce growth strains by 54%. Calonego and Severo (2005) reduced growth stresses by 32.4%, while Severo and Tomaselli (2000) reduced these tensions in vaporized logs of *Eucalyptus dunnii* by 49%. Similar growth strain reduction trends were observed by Skolmen (1967) on *Eucalyptus saligna*. The release of growth strains by applying heat treatments in either water or steam is due to the combined action of heat and humidity, which produces a plasticization of lignin causing a gradual reduction of internal stresses in the log (Chafe 1979).

Initial MC in Lumber

The initial MC in lumber (Table 5) showed no significant differences between parts obtained from heat-treated logs (T) and control logs (C). However, there were significant differences with the age of the tree, as pieces obtained from 20-yr-old trees had a significantly ($p < 0.01$) lower MC when compared with the pieces obtained from

Table 3. Analysis of correlation and analysis of variance (ANOVA) for the heating time of the logs of *Eucalyptus nitens*.

		Log diameter	Tree age	Log height	Basic density
Heating time of the logs (hours)	Pearson correlation	0.838	0.552	−0.104	0.393
	p-value	<0.001*	0.002*	0.592	0.035*
	F	22.31	0.04	5.64	2.84
	p-value	<0.001**	0.842	0.026**	0.105

* Significant correlation at significance level of 5%; ** Significant at a significance level of 5%, with *F*-test.

Table 4. Descriptive statistics, ANOVA, and Tukey's test for growth stresses measured in heat-treated logs (T) and control logs (C).

Logs	*N*	Mean**	SD	SE	CV	Min	Max	CI at 95%
T	29	11.06[a]	2.35	0.44	21.3	6.71	16.25	10.23-11.88
C	29	15.20[a]	2.09	0.39	13.7	11.50	20.65	14.43-16.09
ANOVA					$F = 51.71$			
					p-value < 0.001*			

T, Heat treatment logs; C, control logs; i, number of observations; Mean, average value of the sample (mm); SD, standard deviation (mm); SE, standard error (mm); CV, coefficient of variation (%); Min, minimum value (mm); Max, maximum value (mm); IC, confidence interval at 95% (mm).

[a] Significant difference at a 5% significance level, with Tukey test.

* Significant at 5% with *F*-test; ** Different letters denote significant differences at a 5% significance level, with Tukey test.

15-yr-old trees. The results showed significant differences between the initial MC measured in the lumber pieces from heat-treated and control logs, with lower MC in the pieces from the heat-treated logs. These results were noticed by Mellado (1993), who detected a reduction of about 3% in MC in lumber from logs vaporized at 90°C for 18 h and 36 h. Similarly, Severo and Tomaselli (2000) reported a 5.5% decrease in MC in lumber from *Eucalyptus dunnii* subjected to vaporization.

Total Sawing Variation and Coefficient of Variation

The results showed that both the Total Sawing Variation (ST) (Fig 1[a]) and the coefficient of variation in thickness (CVE) (Fig 1[b]) were of smaller magnitude in the pieces from heat-treated (T) logs, which was verified in three types of cut and trees of both ages. In general, the pieces obtained from heat-treated logs had a lower total sawing variation (ST) than the control logs. Specifically, a smaller ST was detected in radial plane pieces of 25 mm thickness. However, an interaction was observed between the thickness of the pieces and the age of the tree. In addition, ST did not exceed 2 mm, as its range was between 0.41 and 1.73 mm in heat-treated logs, while ST ranged between 0.88 and 2.85 mm in control logs.

The pieces obtained from treated logs had a coefficient of variation in thickness (CVE) between 1.4% and 6.1%, which was lower than the CVE values of control logs, which were between 1.6% and 10.5%. Additionally, the CVE was smaller in 25-mm thick parts, while the CVE showed no significant differences with the type of cut. The main causes of thickness variation during the milling process are the vibration between the log and the cutting element. Other studies (Loehnertz et al 1996; Zavala 2003) relate this mainly to the properties of the wood, its level of abrasiveness, and the diameter of the log. So proper selection of the cutting element also determines the level of the CVE and in turn

Table 5. Initial MC per tree age and log treatment.

Age	Logs	*N*	Mean**	SD	SE	CV	Min	Max	CI at 95%
15 yr	T	61	126.3[a]	0.13	0.02	10.9	99.0	157.8	121.7-130.9
	C	70	126.1[a]	0.17	0.02	13.5	90.3	162.4	121.8-130.3
20 yr	T	75	105.5[a]	0.18	0.02	16.6	71.8	155.7	101.4-109.6
	C	95	107.9[a]	0.21	0.02	19.8	71.5	162.2	104.3-111.6
	ANOVA					$F = 28.45$			
						p-value < 0.001*			

T, Heat treatment logs; C, control logs; *N*, number of observations; Mean, average value of the sample (mm); SD, standard deviation (mm); SE, standard error (mm); CV, coefficient of variation (%); Min, minimum value (mm); Max, maximum value (mm); IC, confidence interval at 95% (mm).

* Significant at 5% with *F*-test; ** Different letters denote significant differences at a 5% significance level, with Tukey test.

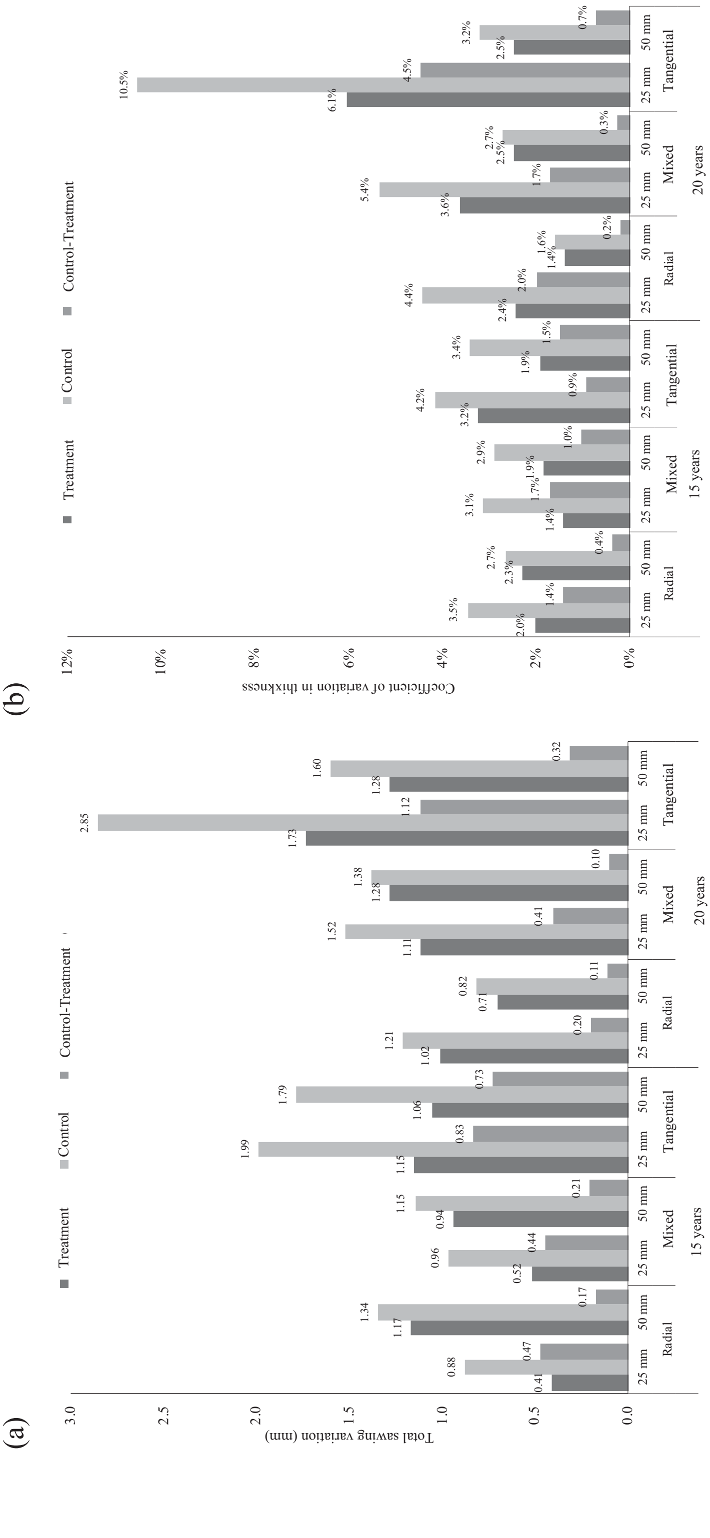

Figure 1. (a) Total sawing variation (ST) and (b) coefficient of variation in thickness (CVE) of pieces grouped by treatment, thickness, cut orientation, and tree age.

Table 6. Percentage of pieces without presence of warping.

	Logs with treatment			Control logs		
Type of warping	Radial	Mixed	Tangential	Radial	Mixed	Tangential
Bow	13.6%	11.4%	0.0%	3.9%	0.0%	0.0%
Crook	0.0%	6.8%	20.0%	0.0%	1.5%	4.8%
Twist	3.0%	6.8%	8.0%	3.0%	0.0%	0.0%

performance of the milling process (Rasmussen et al 2004).

Presence of Warp in Sawn Wood

In the radial plane, all pieces presented, 13.6% did not have bowing, and only 3% had no twist after heat treament (Table 6). In the tangential plane, the heat treatment did not eliminate the bowing, but 20% of the pieces did not have crooking and about 8% did not show twisting. In general, heat treatment was effective in reducing the percentage of warped pieces. There was a higher percentage of pieces with qualities A and B for bowing. The same was observed for crooking and twisting, as the percentage of pieces with quality D decreased with heat treatment, while there was an increase in the percentage of pieces with A and B qualities (see Table 7).

The percentage of pieces without warping was higher for pieces from heat-treated logs. Several studies showed that the crooking is smaller in tangential pieces and larger in radial pieces (da Rocha and Tomaselli 2002), which was also verified in this research. Heat treatment decreased the crooking especially in radial pieces, so these results represent important implications for the improvement of the quality of *Eucalyptus nitens* wood. The quality of green lumber was increased by applying heat treatment to logs, obtaining a higher proportion of pieces of A and B qualities when analyzing the three types of warping.

Table 7. Quality of green lumber with and without heat treatment of the logs.

	Logs with treatment			Control logs		
Grade	Bow	Crook	Twist	Bow	Crook	Twist
A	10.4%	5.9%	5.2%	1.8%	1.2%	0.0%
B	66.7%	25.9%	15.6%	56.4%	14.6%	9.1%
C	17.8%	37.0%	41.5%	27.2%	30.3%	37.6%
D	5.2%	31.1%	37.4%	14.6%	53.9%	53.5%
Total	100%	100%	100%	100%	100%	100%

Quality of the Bowing in Sawn Wood

The heat treatment increased the percentage pieces in radial plane and mixed planes with B quality and decreased the C quality pieces in 25-mm thick pieces (Fig 2). For 50-mm thick pieces, there was an increase in A quality and a decrease in the percentage of D quality pieces. Heat treatment allowed a significant increase in the percentage of A quality in tangential-plane pieces of 25-mm thickness from of 15-yr-old trees. This treatment also increased the percentage of quality B for tangential plane pieces of 25-mm thickness obtained from 20-yr-old trees. Flat-swan pieces of thickness of 50 mm showed an increase of C quality pieces and a decrease in the percentage of quality D pieces from logs 15- and 20 yr old. In general, it was observed that radial and mixed plane pieces showed a predominance of B quality in bowed pieces, and that C and D quality prevailed in the tangential plane.

The ANOVA (Table 8) did not detect a significant effect of the heat treatment of the logs on the bowing. However, a reduction was observed for both 15- and 20-yr-old trees and for 25- and 50-mm thickness, which became more evident in the pieces obtained from 20-yr-old trees.

In general, tangential plane pieces with bowing had a predominance of grades C and D, while radial plane pieces were mostly graded A and B. Regarding the heat treatment of logs, these had a larger percentage of grade A radial plane pieces, being the cut orientation, which showed the best results in terms of quality, although tangential plane pieces did not present grade A or B. The complexity of recovering pieces with bowing in tangential plane lumber is due to its severity in *Eucalyptus* and intensifies according to the cutting plan used, for this reason, it is important to use a cutting plan that prioritizes radial plane pieces and using strategies such as applying compensating cuts, which are useful when sawing wood with large growth strains.

Statistical analysis did not reveal significant differences for the bowing of lumber obtained from

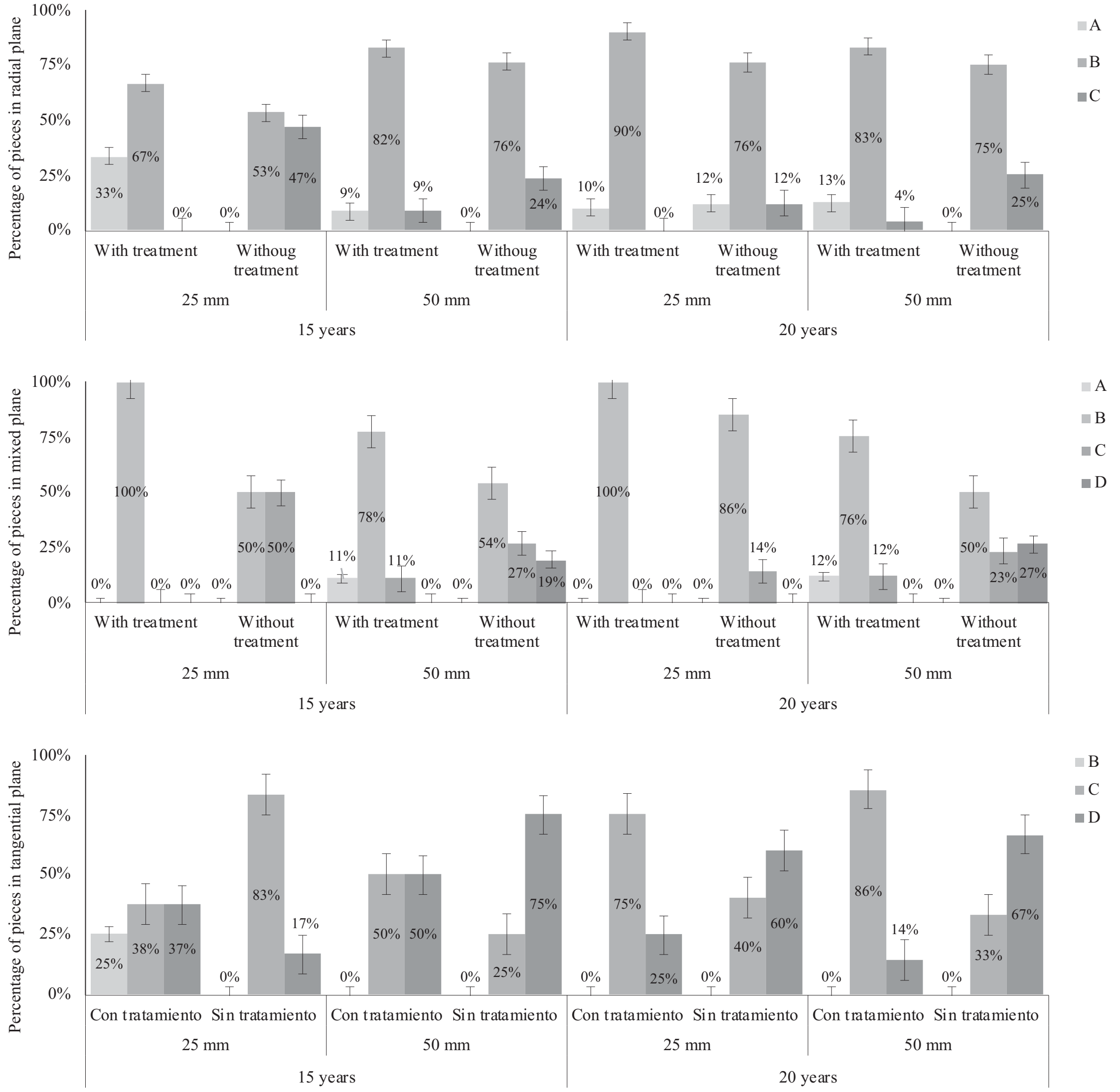

Figure 2. Quality of sawn wood with bowing grouped by heat treatment, thickness, and tree age.

treated logs and control logs, so it was not possible to conclude with certainty the effect of heat treatment on bowing. Despite this, there was a reduction of this type of warping with heat treatment, which was 4.35% and 2.52% for 25-mm thick and age of the tree of 15 and 20 yr, respectively, while the thickness of 50 mm had a reduction of 12.19% and 9.52% for the age of the tree of 15 and 20 yr, respectively. The difficulty of reducing the bowing is, according to Calonego and Severo (2005), complex as it is achieved by applying heat treatments in logs. Therefore, we recommend supplementing it with specific sawmill strategies in combination with appropriate kiln drying programs for each species, which would finally allow to correct and reduce this type of warping.

Quality of Crooking in Sawn Wood

The heat treatment increased the percentage of radial plane pieces of grades B and C while decreasing the percentage of grade D pieces in both 25-mm

Table 8. Descriptive analysis, ANOVA, and Tukey test for bowing.

Thickness	Age	Logs	N	Mean**	SD	%R	SE	CV	Min	Max	IC at 95%
25 mm	15 yr	Treated	18	4.14[a]	1.36	4.35	0.32	33.0	2.30	6.72	3.54-4.75
		Control	23	4.32[a]	1.19		0.25	27.6	2.76	7.24	3.79-4.86
		ANOV[a]	F: 0.200								
			Valor-p: 0.655								
	20 yr	Treated	19	3.61[a]	1.03	12.19	0.24	28.6	1.86	5.00	3.04-4.18
		Control	39	4.05[a]	1.34		0.22	33.1	2.19	6.34	3.65-4.54
		ANOV[a]	F: 2.340								
			Valor-p: 0.132								
50 mm	15 yr	Treated	42	3.97[a]	1.31	2.52	0.20	32.9	1.24	7.11	3.53-4.41
		Control	45	4.07[a]	1.54		0.23	37.8	1.60	6.65	3.64-4.49
		ANOV[a]	F: 0.110								
			Valor-p: 0.743								
	20 yr	Treated	56	3.57[a]	1.24	9.52	0.17	34.8	1.38	5.76	3.19-3.94
		Control	53	3.91[a]	1.55		0.21	39.7	0.92	8.71	3.53-4.29
		ANOV[a]	F: 0.166								
			Valor-p: 0.201								

T, Heat treatment logs; C, control logs; *N*, number of observations; Mean, average value of the sample (mm); SD, standard deviation (mm); *%R*, percentage of reduction of bowing due to heat treatment (%); SE, standard error (mm); CV, coefficient of variation (%); Min, minimum value (mm); Max, maximum value (mm); IC, confidence interval at 95% (mm).

* Significant at 5% with *F*-test; ** Different letters denote significant differences at a 5% significance level, with Tukey test.

and 50-mm thickness (see Fig 3). Mixed plane pieces with heat treatment showed an increase of the percentage of grade A pieces in both thicknesses and both 15- and 20-yr-old trees, with the exception of 25 mm parts obtained from 15-yr-old trees, where there was an increase in grade C and a decrease in grade D. Finally, tangential plane pieces showed that the heat treatment increased grade B pieces and, in some cases, increased grade A pieces while decreasing the percentage of pieces with grades C and D qualities.

A significant reduction in crooking was observed with heat treatment (Table 9) in both thickness of pieces and across bot ages of tree. In addition, there was a reduction of 48.53% and 43.47% in 25-mm thick pieces from 15- and 20-yr-old trees, respectively. The corresponding reduction in 50 mm pieces was 24.15% and 31.01% for 15- and 20-yr-old trees, respectively.

The heat treatment of logs allowed to obtain a significant improvement in the quality of pieces with crooking in all the conditions studied. Specifically, grades C and D dominated the pieces obtained from the control logs, while the treated logs had a higher percentage of grade B pieces. Also, heat treatment reduced grade D pieces and increased grades C and B in radial plane and mixed plane parts. Tangential plane pieces showed a noticeable decrease in grades C and D, whereas they showed an increasing percentage of grades A and B pieces. In general, an increase in grade B and a reduction in the percentage of grade D pieces were observed with heat treatment. Calonego and Severo (2004) significantly reduce crooking by vaporizing the logs, which is consistent with the results of this research. It is evident that the use of logs with treatment allows to increase the quality and to reduce the magnitude of the crooking. However, it is important to emphasize that crooking is a complex warp to reduce, both in the sawmill and during kiln drying.

The heat treatment allowed to obtain a significant reduction of warping (Table 10) in the pieces of 25-mm thick and 15 yr age of tree (*p*-value = 0.001). In addition, there was a reduction rate of 58.32% and 6.07% in 25-mm thick pieces and from 15- and 20-yr-old trees, whereas, for the thickness of 50 mm, these values were 12.47% and 5.66% for 15- and 20-yr-old trees, respectively.

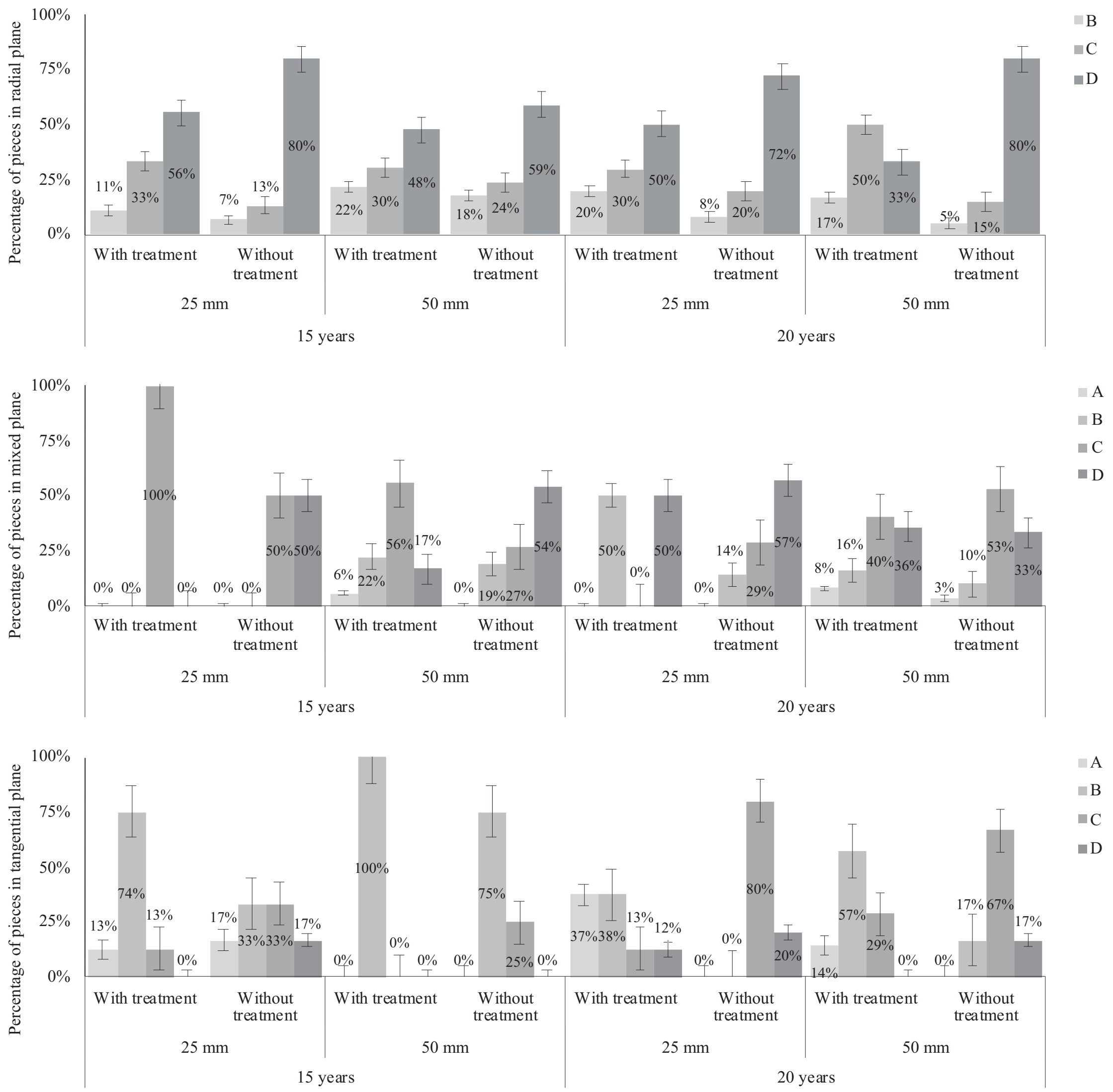

Figure 3. Quality of sawn wood with crooking grouped by heat treatment, thickness, and tree age.

Pieces with twisting showed the best results for the 25-mm thick parts, presenting a larger percentage of pieces of grades A and B when compared with those of thickness of 50 mm. Overall the heat treatment increased the quality of the pieces, increasing grades A and B, and decreasing the percentage of grade C and D pieces, for both thicknesses, tree age, and cut orientation (Fig 4). A significant reduction of twisting in 25-mm-thick and 15-yr tree-age pieces (p-value = 0.001), which corresponded to a 58.32% reduction was observed. Although there were no significant differences for the other conditions studied, there was a reduction in the nominal value of the twisting by around 5.66% and 12.47%, when heat treatment was applied.

The final quality (Table 5 and Fig 5) of the sawn wood pieces showed that the heat treatment of logs was effective in increasing the quality by reducing warping for both thicknesses, tree age,

Table 9. Descriptive analysis, ANOVA, and Tukey test for crooking.

Thickness	Age	Logs	N	Mean**	SD	%R	SE	CV	Min	Max	IC at 95%
25 mm	15 yr	Treated	18	3.75[a]	1.74	48.53	0.41	46.4	1.75	6.77	2.58-4.91
		Control	23	5.57[a]	2.88		0.60	51.7	1.50	10.02	4.53-6.60
		ANOV[a]	F: 5.59								
			Valor-p: 0.023*								
	20 yr	Treated	19	3.52[a]	2.07	43.47	0.47	58.8	1.20	7.67	2.44-4.59
		Control	39	5.05[a]	2.45		0.39	48.6	0.90	9.71	4.40-5.73
		ANOV[a]	F: 5.49								
			Valor-p: 0.023*								
50 mm	15 yr	Treated	41	3.81[a]	1.60	24.15	0.25	42.1	1.14	7.43	3.20-4.42
		Control	47	4.73[a]	2.23		0.33	47.1	1.39	11.29	4.16-5.30
		ANOV[a]	F: 4.89								
			Valor-p: 0.030*								
	20 yr	Treated	50	3.45[a]	1.31	31.01	0.19	39.3	1.54	7.00	2.89-3.80
		Control	55	4.52[a]	1.86		0.25	41.3	0.72	8.46	4.08-4.95
		ANOV[a]	F: 13.61								
			Valor-p: $<$ 0.001*								

T, Heat treatment logs; C, control logs; *N*, number of observations; Mean, average value of the sample (mm); SD, standard deviation (mm); %*R*, percentage of reduction of bowing due to heat treatment (%); SE, standard error (mm); CV, coefficient of variation (%); Min, minimum value (mm); Max, maximum value (mm); IC, confidence interval at 95% (mm).

* Significant at 5% with *F*-test; ** Different letters denote significant differences at a 5% significance level, with Tukey test.

Table 10. Descriptive analysis, ANOVA, and Tukey test for twisting.

Thickness	Age	Logs	*N*	Mean**	SD	%*R*	SE	CV	Min	Max	IC at 95%
25 mm	15 yr	Treated	18	5.83[a]	2.71	58.32	0.64	46.4	1.15	9.53	4.38-7.29
		Control	22	9.23[a]	3.29		0.70	35.7	3.34	16.44	7.91-10.54
		ANOV[a]	F: 12.31								
			Valor-p: 0.001*								
	20 yr	Treated	16	5.27[a]	2.70	6.07	0.62	51.3	1.00	9.24	3.84-6.07
		Control	39	5.59[a]	3.29		0.53	58.9	1.99	12.90	4.59-6.59
		ANOV[a]	F: 0.14								
			Valor-p: 0.714								
50 mm	15 yr	Treated	42	8.10[a]	3.97	12,47	0.61	49.1	2.01	16.85	6.92-9.27
		Control	47	9.11[a]	3.71		0.54	40.7	2.03	18.58	8.00-10.22
		ANOV[a]	F: 1.55								
			Valor-p: 0.217								
	20 yr	Treated	52	6.54[a]	3.26	5.66	0.45	49.8	1.82	12.73	5.65-7.43
		Control	56	6.91[a]	3.25		0.43	47.1	1.05	13.81	6.05-7.77
		ANOV[a]	F: 0.34								
			Valor-p: 0.559								

T, Heat treatment logs; C, control logs; *N*, number of observations; Mean, average value of the sample (mm); SD, standard deviation (mm); %*R*, percentage of reduction of bowing due to heat treatment (%); SE, standard error (mm); CV, coefficient of variation (%); Min, minimum value (mm); Max, maximum value (mm); IC, confidence interval at 95% (mm).

* Significant at 5% with *F*-test; ** Different letters denote significant differences at a 5% significance level, with Tukey test.

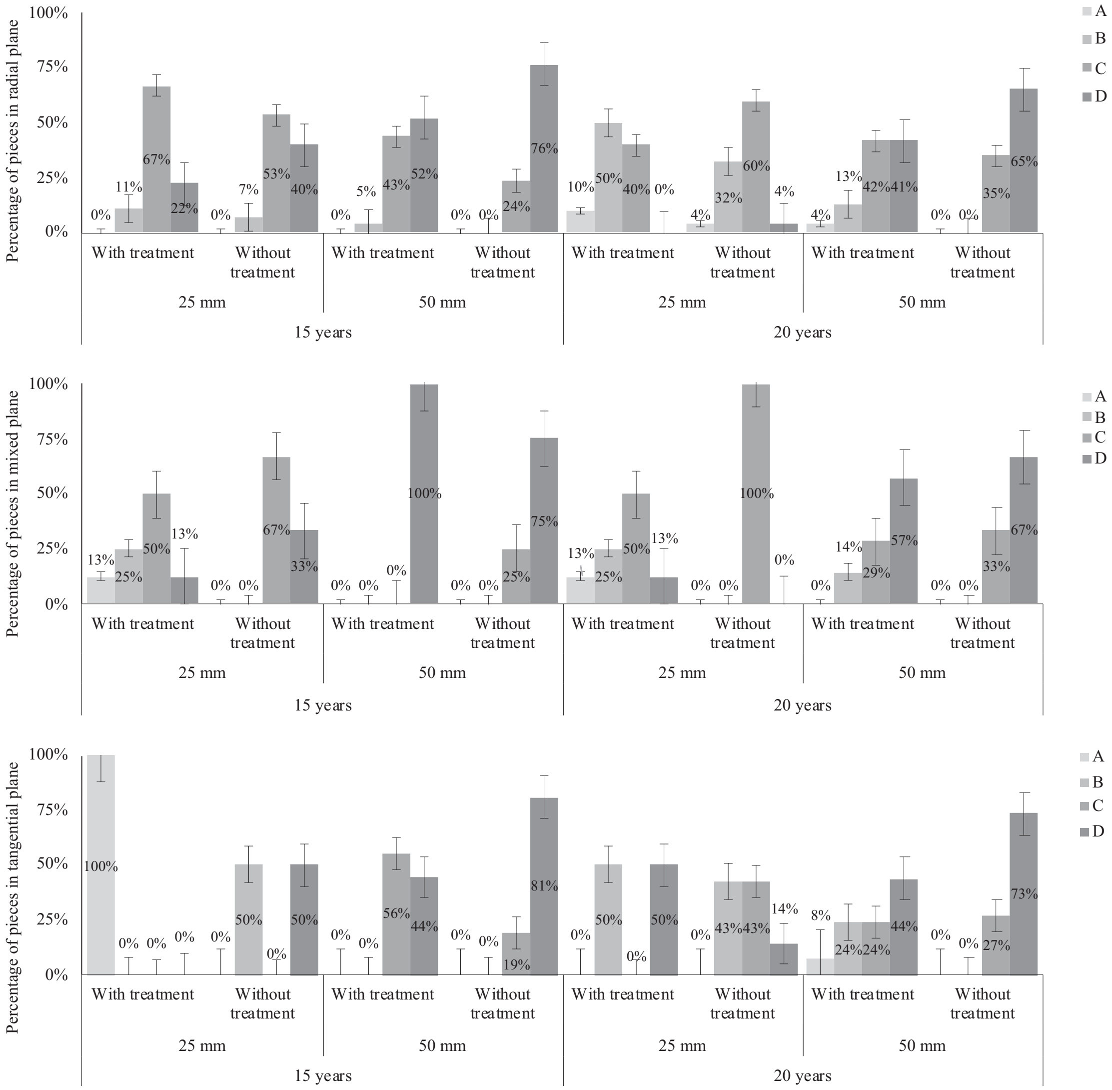

Figure 4. Quality of sawn wood with twisting grouped by heat treatment, thickness, and tree age.

and cut orientation. In addition, it was confirmed that pieces from heat-treated logs increased their final quality by a percentage between 5% and 11% for tangential plane pieces, between 2% and 18% for mixed plane pieces, and between 2% and 13% for tangential plane pieces. Although the largest increase in final quality corresponded to the 25-mm thick pieces, no differences were observed between the two tree ages. These results corroborate studies (Rezende et al 2010; Severo and Tomaselli 2000; Rozas et al 2005) that emphasize the benefits of using heat treatments to reduce defects caused by growth strains and thus increase the quality of the wood and reduce its warp.

CONCLUSIONS

The results obtained in this research suggest that by applying the heat treatment to *Eucalyptus nitens* logs, a significant reduction in growth strains can

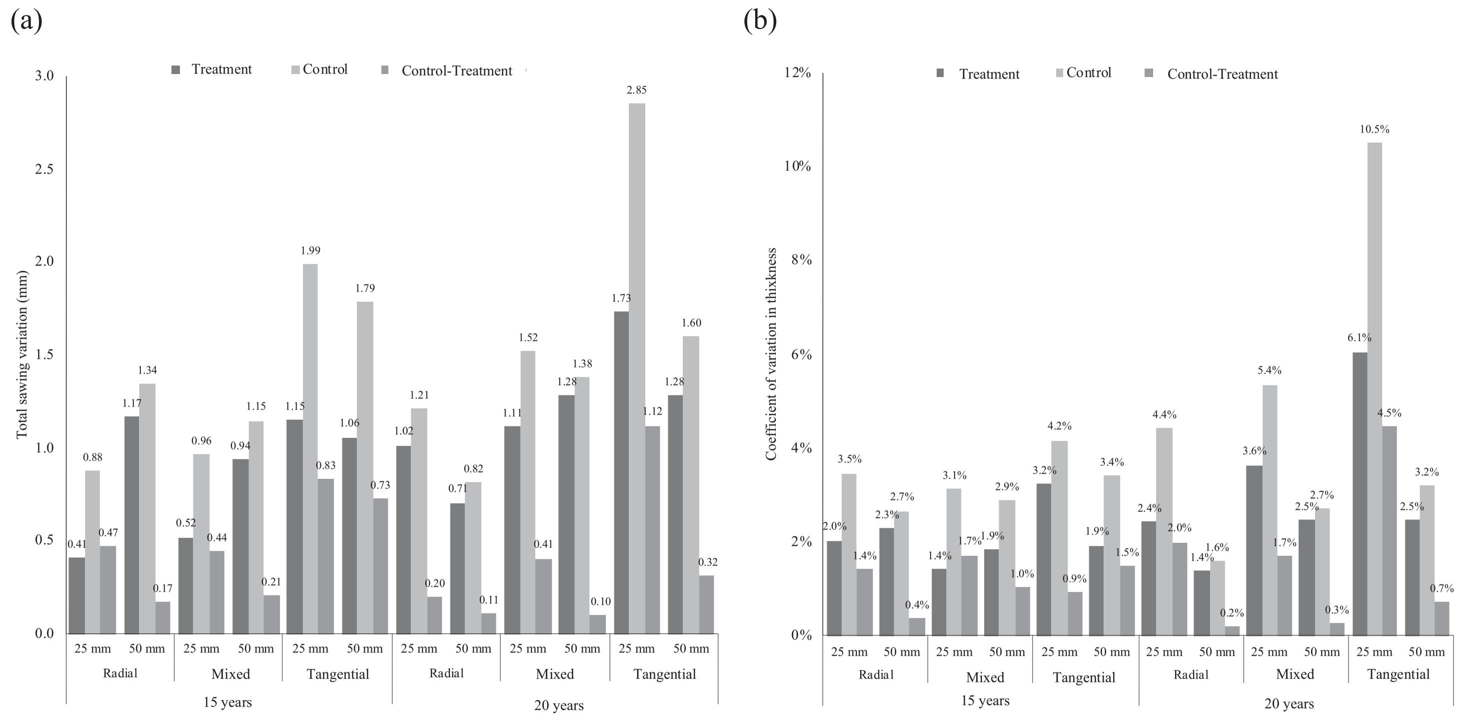

Figure 5. Final quality in sawn wood grouped by treatment, thickness, cut orientation, and tree age.

be achieved. Heat treatment also increased the quality of the pieces in terms of bow, crooking, and twisting. Therefore, within the parameters studied, there are substantial benefits of using heat treatments to reduce defects caused by growth strains and thus increase the quality of the wood and reduce its warp.

REFERENCES

Amer M, Kabouchi B, Rahouti M, Famiri A, Fidah A (2017) Determination of growth stresses indicator, moisture profiles and basic density of clonal eucalyptus wood. J Ind Acad Wood Sci 14:91-98.

Biechele T, Nutto L, Becker G (2009) Growth strain in *Eucalyptus nitens* at different stages of development. Silva Fenn 43(4):669-679.

Calonego FW, Severo ETD (2004) Efeito da vaporização de toras na secagem da madeira de *Eucalyptus grandis*. Floresta Ambient 11:7-13.

Carvalho AM, Gonçalves M, Amparado K de F, Latorraca JV de F (2010) Height and diameter correlations with growth tensions in trees of *Corymbia citriodora* and *Eucalyptus urophylla*. Rev Arvore 34:323-331.

Chafe SC (1979) Growth stress in trees. Aust For Res 9:203-223.

Chafe SC (1985) Variation in longitudinal growth stress with height in trees of *Eucalyptus nitens* Maiden. Aust For Res 15:51-55.

da Rocha M, Tomaselli I (2002) Efeito do modelo de desdobro na qualidade da madeira serrada de *Eucalyptus grandis* e *Eucalyptus dunnii*. Cerne 8:70-83.

de Fégely R (2004) Sawing regrowth and plantation hardwoods with particular reference to growth stresses part A literature review. Forest & Wood Products Research & Development Corporation, Australia.

Dirección Meteorológica de Chile (2001) Climatología regional. Dirección Meteorológica de Chile, Santiago de Chile.

Ferrand JC (1983) Growth stresses and silvicuture of eucalyptus. Aust For Res 13:75-81.

Forest Products Laboratory (2010) Wood handbook: Wood as an engineering material. USDA, Madison, WI.

Instituto Nacional de Normalización (1984) NCh176/1:1984. Madera - Parte 1: Determinación del contenido de humedad. Instituto Nacional de Normalización, Santiago de Chile.

Instituto Nacional de Normalización (1988) NCh 176/2. Of86 Madera-Parte 2: Determinacion de la densidad. Instituto Nacional de Normalización, Santiago de Chile.

Jacobs MR (1965) Stresses and strains in tree trunks as they grow in length and width. Leaflet, For. and Timb. For Timber Bur Camberra Aust 1-15.

Junior LS, Garcia JN (2003) Rendimento em madeira serrada de *Eucalyptus urophylla*. Sci For 63:32-43.

Kubler H (1987) Growth stresses in trees and related wood properties. In: For Prod Abstr. pp 61-119.

Lausberg MJF, Gilchrist KF, Skipwith JH (1995) Wood properties of *Eucalyptus nitens* grown in New Zealand. N Z J Sci 25:147-163.

Lenth C, Haslett A (2003) Moisture uptake patterns in pressure steaming of Radiata Pine. Holz Als Roh- Werkst 61: 444-448. doi: 10.1007/s00107-003-0419-0.

Loehnertz SP, Cooz IV, Guerrero J (1996) Hardwood sawing technology in five tropical countries. Forest Prod J 46:51-56.

Lutz JF (1967) Research at Forest Products Laboratory reveals that heating southern pine bolts improves veneer quality. Plywood Panel 7:20-28.

Lutz JF (1974) Techniques for peeling, slicing and drying veneer. USDA Forest Service, Forest Products Laboratory, Madison, WI.

Lutz JF (1978) Wood veneer: Log selection, cutting, and drying. Department of Agriculture, Forest Service, Washington, D.C.

Malan FS (1979) The control of end splitting in sawlogs: A short literature review. South Afr For J 109:14-18. doi: 10.1080/00382167.1979.9630151.

Nicholson JE (1973) Effect of storage on growth stress in mountain ash logs and trees. Aust For 36(Mar):114-124.

Okuyama T, Kanagawa Y, Hattori Y (1987) Reduction of residual stresses in logs by direct heating method. J Jpn Wood Res Soc 33:837-843.

Purnell RC (1988) Variation in wood properties of *Eucalyptus nitens* in a provenance trial on the eastern Transvaal highveld in South Africa. South Afr For J 144(1): 10-22.

Rasmussen HK, Kozak RA, Maness TC (2004) analysis of machine-caused lumber shape defects in British Columbia sawmills. Forest Prod J 54:47-56.

Raymond CA, Kube PD, Pinkard L, Savage L, Bradley AD (2004) Evaluation of non-destructive methods of measuring growth stress in *Eucalyptus globulus*: Relationships between strain, wood properties and stress. For Ecol Mgmt 190:187-200. doi: 10.1016/j.foreco.2003.10.011.

Rezende RN, Lima JT, Silva JRMD, et al. (2010) Air drying of logs from an *Eucalyptus urophylla* clone for carbonization use; air drying of logs from an *Eucalyptus urophylla* clone for carbonization use. Cerne 16:565-572.

Rozas EC (1993) Contribuição ao desenvolvimento tecnológico para a utilização de madeira serrada de Eucalyptus grandis (Hill ex Maiden) na geração de produtos com maior valor agregado. Curitiba, Brazil.

Rozas C, Sánchez R, Pinedo P (2005) Secado de *Eucalyptus nitens* y globulus y su aprovechamiento en blocks, pisos y muebles. Maderas Cienc Tecnol 7:109-120.

Severo ETD, Tomaselli I (2000) Efeito da vaporização no alívio das tensões de crescimento em toras de duas procedências de *Eucalyptus dunnii*. Sci Agrar 1:29-32.

Skolmen RG (1967) Heating logs: To relieve growth stresses. Forest Prod J 17:41-42.

Steinhagen HP, Meyers GE, Kubler H (1980) Heating time charts for frozen and nonfrozen veneer logs. Forest Prod J 30:27-37.

Tejada A, Okuyama T, Yamamoto H, Yoshida M (1997) Reduction of growth stress in logs by direct heat treatment: Assessment of a commercial-scale operation. Forest Prod J 47:86-93.

Walser DC (1974) Steam-injection knife improves veneer quality [Pseudotsuga menziesii, Picea glauca albertiana, Thuja plicata]. Forest Prod J 24:70-79.

Washusen R, Harwood C, Morrow A, Northway R, Valencia JC, Volker P, Wood M, Farrell R (2009) Pruned plantation-grown *Eucalyptus nitens*: Effect of thinning and conventional processing practices on sawn board quality and recovery. N Z J Sci 39: 39-55.

Weik BR, Wengert EM, Schroeder J, Brisbin R (1984) Practical drying techniques for yellow-poplar S-D-R flitches. Forest Prod J 34:39-44.

Yang JL (2005) The impact of log-end splits and spring on sawn recovery of 32-year-old plantation *Eucalyptus globulus* Labill. Holz Roh- Werkst 63:442-448. doi: 10.1007/s00107-005-0035-2.

Yang J-L, Waugh G (2001) Growth stress, its measurement and effects. Aust For 64:127-135. doi: 10.1080/00049158.2001.10676176.

Zavala D (2003) Efecto del sistema de aserrío tradicional en las características de la madera de encinos. Madera Bosques 9:29-39. doi: 10.21829/myb.2003.921284.