PREDICTION OF END SPLITTING IN LOGS OF *EUCALYPTUS NITENS* (H. DEANE & MAIDEN) MAIDEN THROUGH REGRESSION MODELS USING LONGITUDINAL RESIDUAL STRAIN, AND PHYSICAL AND DENDROMETRIC PROPERTIES

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Abstract. The objective of this research was to develop regression models, with the purpose of estimating the growth stresses and end splitting, in 13-yr-old *Eucalyptus nitens* trees located in the province of Valdivia, Chile. A total of 40 trees were sampled. Their longitudinal residual strain (LRS) was measured using the

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CIRAD-Forêt method and compared with the Council of Scientific and Industrial Research (CSIR) index and with a new index proposed in this investigation, called the log splitting index. Physical and dendrometric properties of each selected tree were measured to identify possible correlations between these variables. These predictors were analyzed statistically, allowing the development of regression models, which showed a coefficient of determination (r^2) of 0.783 and 0.770 to predict the LRS and CSIR indexes, respectively. Finally, a relatively robust regression model was developed to predict end splitting in logs using LRS and physical and dendrometric parameters.

Keywords: Longitudinal residual strain, end splitting, CSIR index, IRT index, multiple regression models, growth stresses.

INTRODUCTION

Eucalyptus nitens (H. Deane & Maiden) Maiden have been instrumental in diversification of the Chilean lumber industry because of their high level of adaptation to diverse types of climate and soil (de Assis 1999; de Souza et al 2003), high growth rate, and the ability to produce pruned logs with a high percentage of knot-free wood. The latter is particularly important as it makes *E. nitens* favorable for veneer and lumber industries (Flynn 2003; Díaz et al 2012; França et al 2017), giving it a competitive advantage in providing diverse lumber products. The competitive edge is enhanced due to the existing restrictions on the use of native hardwoods from temperate and tropical forests (Dunn et al 2014). However, *E. nitens* has physical–mechanical limitations that reduce its industrial performance due to the technological restrictions related to the *Eucalyptus* genus and fast-growing hardwoods (Díaz et al 2012; Braz et al 2014; Amer et al 2017; da Silva et al 2017). The presence of severe end splitting of the logs exacerbates the limitation for the widespread use of *E. nitens*. Splitting is produced by growth stresses and causes considerable losses during primary and secondary processing, reducing both quality and industrial performance (de Souza et al 2003; de Fégely 2004).

Growth stress is caused by internal forces inherent to the tree that maintain the stem balance in response to environmental factors (Braz et al 2014, 2017; França et al 2017; da Silva et al 2017). The stress manifestation can be described from an anatomical point of view as the processes of differentiation and maturation of the wood cells (Ferrand 1982; de Fégely 2004; Lima et al 2004). These processes exert stress on the three planes of wood, with the greatest effect in the longitudinal section. The longitudinal component of growth stress is determined by measuring the longitudinal residual strain (LRS), which has a direct correlation with forest harvesting (INFOR 2008; Ormeño 2008) and is obtained by the CIRAD-Forêt method (Navarrete et al 2016).

Generally, growth stresses are visible after logging and during the mechanical transformation of the sawlogs because growth tensions are redistributed in the longitudinal and transversal planes, and then released abruptly, causing end splitting and warping (Ferrand 1982; Touza 2001; Matos et al 2003; de Souza et al 2003; Trugilho et al 2006; Vega et al 2016; Amer et al 2017). The propagation of split ends depends on the initial distribution of the growth stresses in the stem before logging. If they are homogeneous, end splitting will spread in the pith-bark direction. If there is an accumulation of forces in a specific region of the stem, the split ends will be irregular in direction and magnitude. Therefore, it is necessary to understand the factors influencing growth stresses and resulting into end splitting of the logs. Several studies have tried to understand the factors affecting end splitting in several *Eucalyptus* species but yielded mixed results (Monteoliva and Hernández 2014; Vega et al 2016). Studies suggest there are several factors that may influence tree growth stresses, such as genetics, growth rate, inclination of the stem, canopy shape, diameter at breast height (DBH), age, and tree height (Vignote et al 1996; de Souza et al 2003; Lima et al 2004; de Lima et al 2007; Vidaurre et al 2015; França et al 2017).

Considering the importance of predicting, before logging, the behavior, and the presence of end-splitting in sawlogs of *Eucalyptus*, it is useful to measure growth stresses. One method of measurement is the longitudinal residual strain (LRS), which can be obtained indirectly using the CIRAD-Forêt method (Valencia 2008; Burgos et al 2009; Delucis et al 2014; Navarrete et al 2016), which usually is used for tree selection (Valencia et al 2011). Both Lima et al (2004) and Trugilho et al (2007) recommended measuring the LRS at the DBH, because it gives a representative value for each tree. With this method, significant correlations have been reported, such as the LRS and DBH, as well as the growth rate and wood density (Nicholson et al 1972; Malan 2008; Braz et al 2017). Analytical models used to predict the LRS based on the standing tree properties concluded that the use of models is an interesting tool for tree selection with a lower end splitting propensity (Braz et al 2014, 2017).

Another indirect method to estimate growth strains is an index developed by the Council of Scientific and Industrial Research (CSIR) in South Africa, which assigns a score based on the end splitting of the sawlogs (Verryn & Turner 2000). This split index indicator sums up the total number of splits and relates them to the diameter of the log (Lima et al 2007; Trevisan 2010; Beltrame et al 2015b). Similarly, Vega et al (2016) assessed the splitting of sawlogs of *E. nitens* with the maximum split length index, which was used satisfactorily in assessing the wood soaking process, showing an easy application and a strong correlation with the other indices.

Predicting growth strains, induced by internal growth stresses, and their properties in *E. nitens* trees helps minimize the use of sawlogs with a high percentage of splitting. The predictive methods need to be nondestructive, with a high degree of accuracy. This would increase the quality of the logs and the volume of products, with a high added value for this species. Therefore, the goal of this study was to determine the relationship of physical and dendrometric properties with the LRS, the CSIR index, and the log-splitting index (LSI). These relationships were studied in 13-yr-old *E. nitens* trees, which allowed the creation of models to predict end-splitting levels.

MATERIALS AND METHODS

Provenance and Selection of Experimental Material

Forty *E. nitens* trees were selected and procured from the Agrícola y Forestal Natalhue company, located on the Huenuye Norte ranch in the Lanco-Panguipulli sector (39°29′78″ South y 78°41′34″ West) in the Valdivia Province of Chile. According to the Köppen classification of climates (Koppen 1884), this area is a Cfsb type, corresponding to an oceanic climate of short summer droughts with a Mediterranean influence (Dirección Meteorológica de Chile 2001). The average annual rainfall is 2351 mm/yr, with high relative humidity (RH) and low temperatures (Dirección Meteorológica de Chile 2001).

The silvicultural system consisted of a plantation with an initial density of 1666 trees/ha, applying thinning at 6 yr (700 trees/ha), 8 yr (400 trees/ha), and 10 yr (200 trees/ha). Three prunings were also performed: the first at 2.5 yr (tree height 2.5 m), the second at 3.5 yr (tree height 5-6 m), and the final one at 5 yr (tree height 9 m).

Obtaining the Longitudinal Residual Strain (LRS)

The LRS was measured with the CIRAD-Forêt growth strain gauge. Each tree was numbered with its north direction indicated. Next, a bark section of 150 mm wide and 150 mm high was extracted at the DBH (1.3 m) at four points (north, south, east, and west). Then, the extensometer was fixed in the free section of the bark, by means of two metal stops 45 mm apart, and located in the direction of the fiber. Drilling with an electric drill with a 20-mm diameter drill bit caused the rupture of wood fibers and produced the release of internal stresses. A digital comparator recorded the fiber displacement measured in millimeters. Data were stored in an external database (see Fig 1[a]).

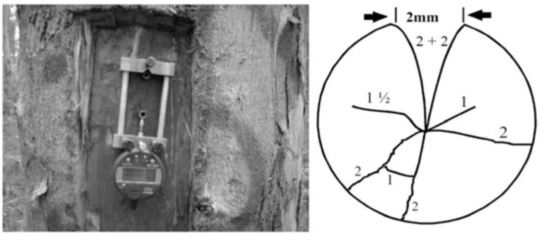

Figure 1. (a) Measurement of LRS in the field using an extensometer; (b) diagram used to score logs using the CSIR index.

Selection and Preparation for Crack Measurement

The number of trees sampled was defined according to the Chilean standard NCh 1208 E of. 1976 (Instituto Nacional de Normalización 1976). The standard suggests a corresponding minimum sample size of 32 trees, which for practical purposes during logging was expanded to 40 trees.

The selected trees were measured at the DBH and then cut with a chainsaw. Subsequently, the total length of each tree was measured with a measuring tape. Afterward, two logs were obtained from each tree—the first from a DBH of 1.3 m up to 5.3 m and the other from a DBH of 5.3-9.3 m, thus totaling 80 logs of 4 m each. These logs were numbered and sealed at both ends with Mobilcer-M liquid (Chile) sealing wax to minimize abrupt loss of moisture. This operation needs to be conducted in less than 1 h. After this, cracks are measured by means of the CSIR index and the Item Response in Trees (IRT) index.

Measurement of Splitting Using the CSIR Index

The measurement of splitting using the CSIR index (Verryn and Turner 2000) consisted of assigning a score to each log according to the length, width, type (radial, diametrical, and tangential), and number of cracks observed (see Fig 1[b]). The score was based on the following criteria: cracks that covered up to 50% of the sawlog radius were assigned one point, cracks that covered up to 2/3 of the radius were assigned 1.5 points, and cracks that covered 100% of the radius were assigned two points. In addition, depending on the width of the crack, a point was added per millimeter.

Measuring Splitting Using the Log Splitting Index

The indicator proposed in this study, named the LSI, considered the cracks that covered 100% of the radius as that is the main limiting factor impeding the use of the sawlog. This type of splitting substantially affects the production of veneers and sawn wood. This index assigns a noticeably lower score to cracks that cover less than 35% of the log radius, since these would not reduce output, especially for veneer production. The scoring detail for each type of splitting is shown in Table 1.

Determining Physical and Dendrometric Properties

The properties calculated were basic density (D_b), green density (D_g), and MC. These physical properties were calculated as described by the NCh 176/1-84 (Instituto Nacional de Normalización 1984) and NCh 176/2-86 (Instituto Nacional de Normalización 1986) standards. The values were determined from 50-mm thick cookies cut at the DBH. The DBH was

Table 1. Score according to the log splitting index (LSI) for each splitting type.

Type of maximum splitting	Score
Crack covers 100% of the log radius	4.00 points
Crack covers between 75% and 100% of the log radius	1.50 points
Crack covers between 50% and 75% of the log radius	0.50 points
Crack covers between 35% and 50% of the log radius	0.25 points
Crack less than 35% of the log radius	0.10 points
Width of crack on the one end	1.00 points/mm

Table 2. Descriptive statistics of physical and dendrometric properties of *Eucalyptus nitens* trees analyzed.

	Statistics[b]							
Properties[a]	N	Mean	SD	SE	CV (%)	Min.	Max.	CI[c]
D_b (kg/m^3)	40	433	27	4.4	6.4	376	500	424-442
D_g (kg/m^3)	40	1078	21	3.5	2.0	1029	1122	1071-1085
MC (%)	40	147	12	1.9	7.9	125	170	143-151
h_t (m)	40	35.3	1.6	0.3	4.5	31.4	39.3	34.8-35.8
DBH (cm)	40	43.5	3.8	0.6	8.8	35.5	51.5	42.3-44.7

DBH, diameter at breast height.

[a] D_b, basic density at DBH; D_g, green density at DBH; MC, MC at DBH; h_t, total height of the tree; DBH, diameter at breast height.

[b] *N*, number of observations; SD, standard deviation; SE, standard error; CV, coefficient of variation; Min., minimum value; Max., maximum value; CI, confidence interval.

[c] 95% confidence level.

calculated with a forestry caliper. The total height of the tree was measured with a 60-m measuring tape. These values are reported in Table 2.

Statistical Analysis

A descriptive exploratory analysis was performed for the LRS, CSIR, and LSI variables, as well as for the physical and dendrometric properties of the trees. An analysis of variance assessed the effect of the studied variables on the LRS, CSIR, and LSI variables. The Kolgomorov–Smirnov test was used to fulfill the normality assumptions. A Tukey's HSD test with a 95% confidence level was used to detect significant differences between groups. A Pearson correlation matrix was used to determine the significance of the relationship between the variables and the predictors. Subsequently, regression models were obtained by the stepwise regression method. All analyses were performed using Minitab 16 software (Minitab 2010, State College, PA).

RESULTS AND DISCUSSION

Longitudinal Residual Strain (LRS) and Split Index

The values for the mean LRS according to cardinal points are shown in Table 3. These values were similar to those obtained by Valdés (2004), who reported a mean LRS of 0.170-0.320 mm; Burgos et al (2009) obtained a mean of 0.147 mm; and Ormeño (2008) reported an LRS mean of 0.126 mm. Meanwhile, Mutizabal (2008) obtained values of 0.020-0.187 mm, and Riquelme (2011) obtained values of 0.073-0.262 mm.

According to orientation, the lowest LRS value corresponded to the east, with a mean of 0.125 mm (±0.033 mm). By contrast, the west

Table 3. Descriptive statistics and ANOVA for the LRS (mm) mean and by orientation (mm).

	Statistics[a]							
Measurements	*N*	Mean	SD	SE	CV (%)	Min.	Max.	CI[b]
LRS north	30	0.132	0.033	0.007	25.2	0.082	0.209	0.119-0.144
LRS south	30	0.141	0.040	0.007	28.1	0.064	0.220	0.126-0.155
LRS east	34	0.125[c]	0.033	0.006	26.4	0.061	0.196	0.114-0.137
LRS west	32	0.153[c]	0.058	0.010	38.1	0.032	0.270	0.132-0.174
LRS mean	34	0.139	0.028	0.005	20.3	0.010	0.215	0.130-0.149
ANOVA	F = 2.66 p-value = 0.051							

ANOVA, analysis of variance.

[a] *N*, number of observations; SD, standard deviation; SE, standard error; CV, coefficient of variation; Min., minimum value; Max., maximum value; CI, confidence interval.

[b] 95% confidence level.

[c] Significantly different, at significance level 5% using an HSD Tukey test.

Table 4. Pearson's correlation for the average LRS, with tree properties.

		Properties[a]				
	Index	D_b	D_g	MC	h_t	DBH
LRS	Pearson's correlation	0.178	0.398[b]	−0.083	0.026	−0.634[b]
	p-value	0.314	0.024	0.610	0.886	0.001

DBH, diameter at breast height.

[a] D_b, basic density at DBH; D_g, green density at DBH; MC, MC at DBH; h_t, total height of the tree; DBH, diameter at breast height.

[b] Significantly different, at significance level 5%.

LRS had the highest mean of 0.153 mm (±0.058 mm). No significant differences were detected between these orientations. These results match those obtained in similar studies (Lima et al 2004; Díaz et al 2012; Beltrame et al 2013; Omonte and Valenzuela 2015). The differences between LRS orientations are due to environmental factors, such as the prevailing wind conditions and competition among trees (Omonte and Valenzuela 2015; Vidaurre et al 2015), whereas Amer et al (2017) attributed it mainly to areas of wood under stress.

Pearson's correlation test (see Table 4) showed a negative significant relationship between the LRS and the DBH (p-value = 0.001), and a positive significant relationship with the D_g (p-value = 0.024). These results reinforce observations by França et al (2017). Regarding physical properties, Hernández et al (2014) and Amer et al (2017) found a positive correlation between the LRS and the D_b, which differs from studies that did not detect a relationship between the LRS and the D_b (Adorno and Garcia 2003; Lima et al 2004; Beltrame et al 2012, 2015a; Braz et al 2017). The literature has varying perspectives on this, which has not allowed an effective determination of any relationship between these physical properties mainly due to high dispersion of values due to inherent characteristics of each tree. Studies by Vignote et al (1996) and França et al (2017) did not detect an effect of the total height of the tree on the LRS.

The CSIR index presented in Table 5 has an average of 4.38 (±1.44) point. These values show (Table 6) a negative correlation with the DBH and a positive correlation with the D_g. To obtain solid products without splitting from *Eucalyptus grandis* logs, Verryn and Turner (2000) recommended a CSIR index of eight points. Dunn et al (2014) evaluated the CSIR in 19-yr-old *E. nitens*, and reported values of 5.5-7.5 points at the time of logging, which are higher than the values obtained in this study. These results show the convenience of using logs of this provenance and the age of harvest to obtain lumber and veneer with low levels of splitting.

The correlation analysis suggested a negative correlation between the CSIR index and the diameter of the log, with this index being lower at the base and greater at the upper end. This observation was in agreement with previously reported results (García and Meneses 2011; Dunn et al 2014). This suggests an effect of the diameter and height of the log on the CSIR.

There are no similar studies that evaluate the effect of physical properties on the CSIR index. This index is usually used as an indicator of log quality, and it is unusual to use as a variable of the milling and peeling processes in the forest industry (Garcia and Meneses 2011). The mean LSI

Table 5. Descriptive Statistics for CSIR and LSI Index.

	Statistics[a]							
Index	N	Mean	SD	SE	CV (%)	Min.	Max.	CI[b]
CSIR	160	4.38	1.44	0.11	32.9	2.00	9.50	4.15-4.60
LSI	160	3.67	2.86	0.23	77.9	0.35	16.00	3.22-4.12

LSI, log splitting index.

[a] N, number of observations; SD, standard deviation; SE, standard error; CV, coefficient of variation; Min., minimum value; Max., maximum value; CI, confidence interval.

[b] 95% confidence level.

Table 6. Pearson's correlation for the average CSIR index.

		Properties[a]				
	Index	D_b	D_g	MC	h_t	DBH
CSIR	Pearson's correlation	0.260	0.661[b]	−0.183	−0.048	−0.492[b]
	p-value	0.106	0.001	0.259	0.783	0.001

CSIR, the Council of Scientific and Industrial Research.

[a] D_b, basic density at DBH; D_g, green density at DBH; MC, MC at DBH; h_t, total height of the tree; DBH, diameter at breast height.

[b] Significantly different, at significance level 5%.

index of the *E. nitens* trees studied was 3.67 (±2.86) points (see Table 5).

The interpretation of these results and their application in the field are reflected in Table 7, which shows the LSI and CSIR values for different types of cracks at the end of the logs. According to Dunn et al (2014), a CSIR of 8.0 points is adequate to obtain veneers, whereas a CSIR of 5.0 points is preferable for lumber (Garcia and Meneses 2011). However, the CSIR does have some limitations, which manifests from how the logs are classified. The CSIR assigns the same value to different crack configurations, as can be observed in cases 1 and 5 (Table 7), where a value of six is assigned, which overestimates the quality of the log (case 5). Consequently, the yield of veneers free of cracks will be lower than expected. The LSI index considers these singularities by assigning a higher score to the presence of cracks, covering more than 75% of the log radius. The results suggest that it is advisable to select logs with cracks less than 75% of the radius (LSI of four points) to minimize splitting in lumber and veneers.

Table 7. Possible cases of cracks in logs measured with the LSI and the CSIR index.

Case	Split	Description	LSI	CSIR
1		2 cracks at R < 7 cm. 1 cracks 7 cm < R ≤ 50% 2 cracks at 50% < R ≤ 75%	2.7	6
2		4 cracks at 50% < R ≤ 75%	4.0	6
3		1 cracks R = 100% 2 cracks at 50% < R ≤ 75% 1 rajadura 7 cm < R ≤ 50%	6.5	6
4		2 cracks at R = 100% 2 cracks at 7 cm < R ≤ 50%	9	6
5		3 cracks at R = 100%	12	6
6		1 crack at R = 100% 2 cracks at 75% < R ≤ 100%	7	5
7		4 cracks at R = 100%	16	8

CSIR, the Council of Scientific and Industrial Research.

Predictive Models the Indices Evaluated

The DBH and D_g were identified as significant predictors of the LRS index ($r^2 = 0.783$, model 1) and the CSIR index nine ($r^2 = 0.770$, model 2), with a significant relationship between both indices ($r^2 = 0.758$, model 3) as reported in Table 8. Furthermore, a significant relationship was detected between the LSI index and the CSIR index ($r^2 = 0.463$, model 4). All the models indicated earlier were statistically significant (p-value < 0.001). Amer et al (2017) developed regression models for the LRS, using the D_b as a predictor, obtaining a coefficient of determination (r^2) between 0.394 and 0.898. Valdés (2004), Mutizabal (2008), and Ormeño (2008) developed a regression model to predict the LRS using the DBH, obtaining a coefficient of determination (r^2) of 0.155 and 0.282 in *E. nitens* of 18 and 11 yr, respectively.

The models suggest an increase in the LRS will cause an increase in the CSIR index, indicating a higher capability of the models to predict splitting of logs by field measurement of the LRS.

CONCLUSIONS

The wood from 13-yr-old *E. nitens* used in this study exhibited a low degree of splitting, hence making it viable for use in lumber and veneer production. It is suggested to select logs with cracks smaller than 75% of the radius.

The LRS in 13-yr-old *E. nitens* showed high variability in the perimeter, with statistically significant differences between the east and west orientations. The LRS and CSIR had negative correlations with the DBH, and positive correlations

Table 8. Parameters of the model $\gamma_i = \beta_0 + \beta_1 \times \mathrm{DBH}_i + \beta_2 \times D_{gi} + \beta_3 \times \mathrm{LRS}_i + \beta_4 \times \mathrm{CSIR}_i + \varepsilon_i$, to determine the mean LRS and CSIR in 13-y-old *Eucalyptus nitens*.

Modelo	γ_i	β_0	β_1	β_2	β_3	β_4	r^2	*F*-value	*p*-value
1	LRS	−0.239	$-5.802\mathrm{E}^{-3}$	$5.86\mathrm{E}^{-4}$	—	—	0.783	50.42	<0.001[a]
2	CSIR	−31.84	−0.2104	0.0425	—	—	0.770	41.80	<0.001[a]
3		−3.04	—	—	52.22	—	0.758	244.4	<0.001[a]
4	LSI	−2.12	—	—	—	1.29	0.463	32.71	<0.001[a]

CSIR, the Council of Scientific and Industrial Research; DBH, diameter at breast height; LRS, longitudinal residual strain (mm); $\mathrm{CSIR}_{\mathrm{LRS}}$, model determined by using the LRS as a predictor; $\mathrm{CSIR}_{\mathrm{p-}}$, model determined by using the properties as a predictor; LSI, log splitting index, proposed in this study (pts); ε, associated error.

[a] Significant at significance level 5%.

with the D_g. There were no significant correlations among the total height, D_b, and MC. In addition, there was no significant correlation between the LSI and the studied properties.

The CSIR index can assign the same score to different splitting configurations, overestimating the quality of the logs, and therefore, the yield of veneer free of cracks is lower than expected. Conversely, the LSI index assigning a higher score if cracks are present, and especially, if cracks range for more than 75% of the log radius, recommend an LSI of four points.

The LSI can be successfully predicted using the CSIR, which is linearly correlated to the LSR. Therefore, predicting splitting of the logs by measuring the LRS on the field is possible. Multiple regression models allowed predicting the average LRS ($R^2 = 0.783$) and the CSIR ($R^2 = 0.770$) using data from the DBH and the D_g with a high degree of confidence. A regression model ($r^2 = 0.737$) was proposed that predicted the CSIR using the LRS measurements in a simple, economically viable way, and using the minimum resources. Although the correlation coefficients are not ideal, they are high to indicate strong relationships after accounting for the inherent variability in wood. Therefore, a relatively robust model was developed to predict end splitting in logs using longitudinal residual strain, and physical and dendrometric parameters.

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