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RESEARCH PAPER

Reduction of growth stresses in logs of *Hieronyma alchorneoides* Allemão from fast-growth plantations using steaming and heating: effects on the quality of lumber

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Abstract

• ***Key message*** **Growth stresses are usually present in the fast-growing trees of forest plantations and can be evaluated along stem diameter. Growth stresses are relaxed after tree felling and during sawing and drying, and are manifested in the lumber quality. Different methods have been employed to reduce the effect of growth stresses, such as steaming and heating treatments. Excellent growth and yield in forest plantations of *Hyeronima alchorneoides* were observed, but they showed difficulties in the primary sawing process and a high incidence of wood warping during the drying process. Steam and heat treatments on the log were used to study their effects on *H. alchorneoides* sawlog and to evaluate lumber quality**.

• ***Context*** Growth stresses in *Hieronyma alchorneoides* Allemão trees growing under fast-growth conditions show high and negative effects on the lumber quality (increased warps and splits or checks). Therefore, steaming and heating treatments have been applied to reduce these effects on the lumber.

• ***Aims*** The main objective of the present work was to evaluate the effects of steaming and heating treatments on sawlogs of *Hieronyma alchorneoides* from the fast-growth plantations to reduce the longitudinal surface growth stress.

• ***Methods*** Twenty-six trees ready for felling in the third thinning were sampled and commercial logs measuring 2.5 m long were extracted from them at different heights. These logs were used to investigate the effect of steaming and heating treatments and the growth stresses were measured before and after treatment. Crooking due to sawing, colour and wards, splits and checks were measured.

• ***Results*** The results showed that the internal temperature of the logs was approximately 85 °C after the heating treatment, and it was nearly 90 °C after the steaming treatment. It resulted in a reduction of 1500 με (micro-deformations) before the treatment to 1000 με after the treatment. Therefore, crooking due to sawing decreased significantly in logs or semi-logs. The parameters such as colour, luminosity (L*), redness (a*) and lightness (b*) decreased in heartwood while L* increased and a* and b* decreased in sapwood, which led to the decrease in quality of the lumber, the magnitude and incidence of the defects in treated logs.

• ***Conclusion*** As compared to untreated logs, the best performance was obtained with steaming treatment, followed by the heating treatment. The difference found between steaming and heating can be attributed to the temperature in the internal part of the log, which was more than 90 °C in steaming treatment; meanwhile, in the heating treatment, the internal temperature of the log was slightly lower (80–85 °C). Therefore, glass transition can be more easily reached by steaming treatment than by the heating treatment.

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Contributions of the co-authors MOYA contributed with designing the experiment, sampling of tree, measuring of growth stress, running the data analysis and coordinating the research project.
TENORIO contributed with designing the experiment, writing the paper and running the data analysis.

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1 Introduction

Tree growth stresses have been widely studied as regards their causes (Archer 1987) and management applied to the trees (Kubler 1988). These stress effects on wood processing have also been studied (Dinwoodie 1966; Yang and Waugh 2001; Gril et al. 2017). However, growth stresses formed within the tree stems are assessed using different quantitative methods (e.g. cross-cutting or heating), which permit quantifying only one component of the growth stresses named the residual growth stresses. They are related to residual growth stresses and are permanently associated with the wood of the living trees while they are growing (Gril et al. 2017). In contrast, growth stresses are the result of the combined action of two mechanisms: cell wall maturation and the increase of dead-weight (Barnett and Jeronimidis 2003). During maturation of the secondary cell wall, the fibres tend to deform in the axial and transversal directions, although these dimensional changes are limited by the already formed xylem (Archer 1987). The restraint induces mechanical stress at the outermost surface of the secondary xylem, which is located beneath the layer of the differentiating xylem. During each growth increment, in the older xylem, a counteractive stress distribution takes place, which is superimposed on the pre-existing stress (Gril et al. 2017). As the tree weight increase, it is supported by the older xylem; therefore, it needs to distribute the additional stress to equilibrate the effect of gravity. The growth stresses are distributed in the mature rings, which are measured on the outer surface of the trunk, and residual growth stresses are called 'longitudinal surface growth residual stresses' (LRGS) (Nicholson 1971; Yang et al. 2005).

Growth stresses are present in most species (Archer 1987), predominantly in the fast-growing trees of forest plantations and can be evaluated along stem diameter (Kojima et al. 2009). These stresses in *Eucalyptus* have been studied widely (Nicholson 1973), especially its effects on industrial processes and quality of the wood (Yang 2005; Valencia et al. 2011; Gril et al. 2017). They start to liberate once the log is cut from the tree, and if not sawn immediately; LRGS begin to manifest in the form of cracks at the ends of the logs (Alméras and Clair 2016). When the log is sawn, LRGS become evident in the form of warps (crooking, bowing and twisting), splits and checks in the boards (Entwistle et al. 2016). The magnitude of these defects are species-specific, which may result in considerable economic losses for foresters and sawmills (Gril et al. 2017).

Studies related to growth stresses in regions having tropical climate are limited, except for some species of the genus *Eucalyptus* (Cassens and Serrano 2004). Recently, a few studies have been carried out on growth stresses in some species, including *S. macrophylla* (Gilbero et al. 2019), *T. grandis* (Wahyudi et al. 2001; Millán Granados and Serrano 2004; Solorzano et al. 2012), *Bombacopsis quinata* (Millán Granados and Serrano 2004), *Hevea brasilensis* (Pelozzi et al. 2014; Rodrigues et al. 2018), *A. mangium* (Wahyudi et al. 1999) and some species in French Guiana (Clair et al. 2006; Ruelle et al. 2007).

Different methods are implemented during wood processing to reduce the effect of LRGS that helps to increase the quality of the wood (Archer 1987; Kubler 1988; Yang and Waugh 2001; Ratnasinga et al. 2013; Gril et al. 2017). The application of specific sawing patterns (Johansson and Ormarsson 2009; Ratnasinga et al. 2013) and methods that include prolonged storage in the open air and underwater sprays, burying and soaking in water (Nogi et al. 2003). These methods lead to the relaxation of LRGS at high temperatures, which is induced by boiling, steaming and smoking (Tejada et al. 1997; Nogi et al. 2003; Severo et al. 2010; Pelozzi et al. 2014; Rodrigues et al. 2018). High temperature and steaming soften the physical structure of the material, due to which the wood reaches the glass transition temperature (Lenth and Kamke 2001; Pelozzi et al. 2014). When the wood reaches this temperature, the hydrothermal recovery appears, and the polymers, especially lignin, are softened. Therefore, rearrangement of the molecular and microstructure of material takes place that consequently results in the relaxation of internal stresses and thus leads to the enhancement of residual stress (Nogi et al., 2003; Gril et al. 2017; Rodrigues et al. 2018).

Nowadays, several tropical species are gaining relevance in commercial reforestation projects in Costa Rica due to increased knowledge on their genetics, propagation and plantation management (Murillo 2018). For example, a fast-growing species, *Hyeronima alchorneoides* Allemão (pilón, common name in Spanish in Costa Rica), having rotation periods of less than 25 years, shows remarkable growth and yield in forest plantations (Delgado et al. 2003; Redondo-Brenes and Montagnini 2006). However, recent research regarding wood quality of this species (Moya and Muñoz 2010; Moya et al. 2011, 2019; Tenorio et al. 2016a, b) exhibited two significant problems, i.e. (i) difficulties in the primary sawing process and (ii) high incidence of wood warping during the drying process.

These problems are owing to high LRGS in logs extracted from plantation trees, which represent an increased incidence of warps, checks and splits. Additionally, the drying process accentuates the warps in tension wood and high juvenile wood content with high longitudinal shrinkage (Zobel and Sprague 1998), producing very low-quality lumber (Moya et al. 2013, 2019; Tenorio et al. 2016b).

Few studies on *H. alchorneoides* and other tropical species are investigated for the reduction of growth stresses by using 24 h of heat or steam treatments to the logs, and to understand how these treatments influence the longitudinal growth stress before the sawing process on wood colour and the quality of wood concerning warps, checks and splits. Therefore, the present work aims to study the longitudinal surface growth residual stresses (LRGS) in sawlogs of *H. alchorneoides* from a fast-growing plantation under heat and steam treatments for 24 h at 115 °C and to evaluate the effects of those treatments on the quality of the lumber (incidence of warps, checks and splits) and reduction of the growth stresses after log sawing. The present study will help to improve the lumber recovery of logs from the commercial plantations in tropical regions for better profitability. Moreover, this species has high specific gravity, which is found in few plantation grown species. In addition, the wood of *H. alchorneoides* can be satisfactorily used for structures.

2 Material and methods

2.1 Plantation localization and characteristics

A fast-growth plantation of *Hieronyma alchorneoides* that belongs to the company Cinco Ceibas Rainforest Reserve and Adventure Park, located in Pongola-Heredia Costa Rica (10°34′24”N and 84°08′25”W) was sampled. The site is characterized by a moist tropical climate with average annual precipitation of 4135 mm and a dry season between March and April with a mean annual temperature of 24.7 °C. At the time of sampling, the plantation was 12 years old, was being thinned for the third time, and its density was 450 N/ha. The plantation was established by seedlings cultivated in a jiffy forestry pellet with an initial planting density of 3 m × 3 m (1100 N/ha). Based on previous studies (Moya et al. 2013, 2019; Tenorio et al. 2016b) on sawlog from plantation-grown trees, problems occur in wood quality; thus, it was considered that 12 year-old plantations show a high level of growth stresses.

2.2 Tree sampling

Twenty-six trees, with average diameters of 19 cm, from the plantation were sampled for the different log treatments (Table 1). The sampled trees were chosen from the trees marked for felling in the third thinning. Therefore, these were not the best individuals. However, those individual trees having less trunk deformation, from which at least three commercial logs of 2.5 m long could be extracted, were selected. The diameter at breast height (DBH) was determined at 1.3 m, and the north-south position was marked on each selected tree. Commercial logs measuring 2.5 m long (2–3 per tree), a cross-section 3-cm-thick from the base of the tree and the other end of each commercial log were extracted. The following heights were established for the study: (i) 0.0–2.5 m, (ii) 2.5–5.0 m, (iii) 5.0–7.5 m and (iv) 7.5–10.0 m. All the logs were marked on the north and south sides.

2.3 Longitudinal residual stress measurement in standing trees

Before felling the tree, the LRGS present on the surface of logs or cambial zone on the north and south positions of standing trees were determined (Moya and Tenorio 2021). These were called LRGS in standing trees ($LRGS_{stand\text{-}tree}$). These $LRGS_{stand\text{-}tree}$ were taken according to the methodology proposed by Nicholson (Nicholson 1971). This method consists of removal of the bark, as shown in Fig. 1a; inserting two Phillip screws with gauge separation; determining the gauge separation (called initial length) with the help of an extensometer (Hugenberger tensotast) (Fig. 1b). Subsequently, two cuts were made at 6 mm from the point where the screws were placed, and 2 min later, this distance between the points was measured again (Fig. 1b); this was the final length. This measurement was done because the fibres of the surface area of the tree or log were under tension; therefore, the screw heads tended to get closer after the knife cuts were made. The difference or dimensional change of the final length relative to the initial length was expressed in micro-deformation units (με) (Eq. 1), which represents the LRGS, which is calculated as follows:

Longitudinal surface growth residual stresses (LRGS) in με = (initial distance – final distance) * 20 (1)

Table 1 Dasometric conditions of *Hieronyma alchorneoides* sampled trees used for $heating_{treatment}$ and $steaming_{treatment}$ of sawlogs

Treatment of sawlogs	Diameter at breast height (cm)	Height of first branch (m)	Total height (m)	Sampled trees
$Heating_{treatment}$	19.2 (33.9)	12.1 (28.0)	21.2 (17.0)	8
$Steaming_{treatment}$	19.7 (38.2)	9.1 (31.4)	17.9 (20.3)	10
Untreated	20.2 (34.3)	10.9 (25.4)	19.9 (19.9)	8
Average	19.7 (36.2)	10.4 (30.8)	19.3 (19.8)	–

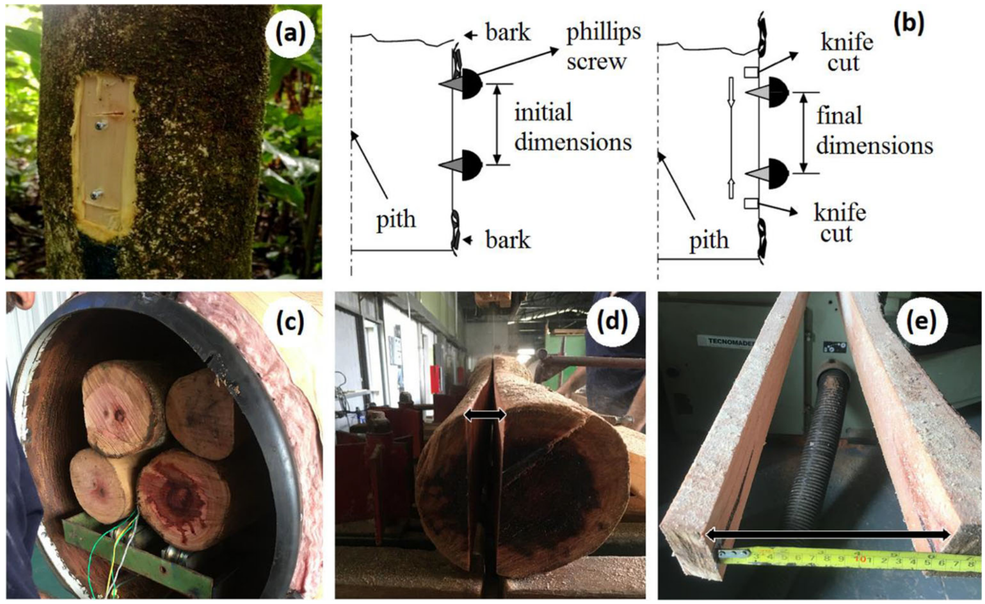

Fig. 1 Longitudinal surface growth residual stresses (LRGS) on the surface of logs or cambial zone measured in a standing tree (**a**), representation diagram of centre deflection measuring of micro-strain by knife cut (**b**), logs located in a steam or heat chamber (**c**), sawlog crooking (**d**) and semi-log crooking (**e**) due to sawing

2.4 Treatments to reduce the longitudinal residual stress

Two treatments were used to reduce the LRGS and to increase the lumber quality: (1) heating$_{treatment}$, where the logs were heated for 24 h at 115 °C and (2) steaming$_{treatment}$, where the logs were steamed for 24 h at 70 Pa. Untreated samples (without heating or steaming) were used as a control for comparison purpose. During heating$_{treatment}$ and steaming$_{treatment}$, the logs were placed inside a horizontal tank with measurements of 60 cm diameter, 3 m long and 4–6 log capacity (Fig. 1c). In the lower part of the tank, three 1000 watts cartridge heaters were placed for the heating$_{treatment}$. In contrast, for the steaming$_{treatment}$, two sprayer lines were set at 180 degrees from each other to allow steam supply at 8 kg/cm^3, 4 l/min and a temperature of 115 °C.

2.5 Moisture content, temperature and longitudinal residual stress determination

Moisture content (MC), LRGS and temperature variation inside the log were determined for each log in the different treatments. The MC was determined in the cross-sections obtained at different tree heights. The cross-sections were cut into six radial portions, and three of these were selected to measure the MC, according to ASTM D-4442-07 standard (ASTM 2016). The LRGS was determined in all the logs before (LRGS$_{before\text{-}treatment}$) and after (LRGS$_{after\text{-}treatment}$) heating$_{treatment}$ and steaming$_{treatment}$ and in the untreated logs. The measurements were again performed in the north and south sides, at half the length. The procedure followed to determine the LRGS was the same as described above for standing trees (Nicholson 1971). To determine the logs internal temperature; the temperature variations were obtained by introducing a probe into three of the 4–6 logs placed inside the tank. The probe was inserted in the central area of the log, up to half the diameter, and it was monitored every 5 min and the probes were connected to a TESTO datalogger, model 177-T175, to record the data.

2.6 Crooking due to sawing determination

The logs were sawn using a typical pattern for producing lumber in Costa Rica (Serrano and Moya 2011). Semi-logs were obtained and then sawn into 2.5 cm boards. Sawing was done using a band saw, and a single-cut re-sawing saw. The cutting pattern is shown in Fig. 2, where cuts 1 and 2 were performed with the band saw, while the block cuts (cuts 3 and 4) were made with the help of a re-sawing saw. The crooking$_{due\text{-}to\text{-}sawing}$ were measured at the time of making the cuts in the logs and semi-logs (Fig. 1d-e). A board was selected from ten panels from each treatment (heating$_{treatment}$, steaming$_{treatment}$ and untreated) to determine the MC after the treatment. A cross-section was extracted at 27 cm from the end of the board from each chosen board to select the MC by using standard ASTM D-4442-07 (ASTM 2016).

2.7 Lumber quality and colour evaluation

Lumber quality parameters such as warps (twists, crooks, bows and cups), checks and splits were measured from each board as per the methods described by Tenorio et al. (2012). For warp measurement, each piece was positioned on a flat table to examine the extent of each warp type. If the amount of warp appeared so small that a meaningful determination seemed implausible, a judgement of ‘no presence’ was assigned. When the

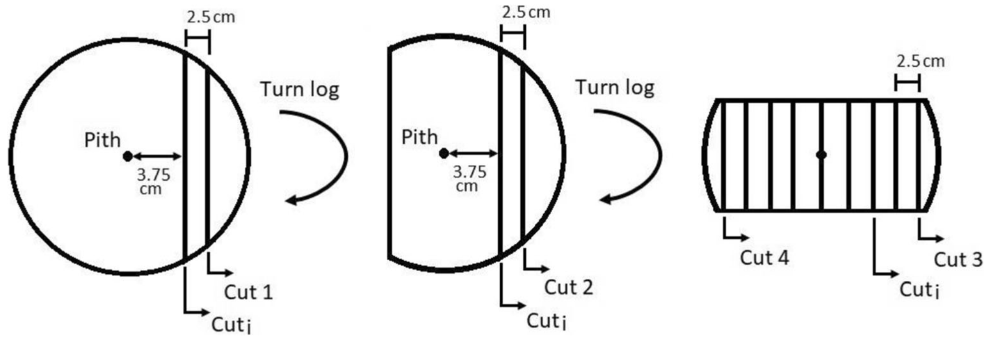

Fig. 2 Sawing pattern utilized in untreated and heating$_{treatment}$ and steaming$_{treatment}$ for *Hieronyma alchorneoides* logs from the fast-growth plantation

measurement was judged to be required, it was made via the insertion of a calibrated inclined plane wedge. With the wedge inserted to the point of mild refusal, the measurement was read at the calibrated vertical face of the wedge (Tenorio et al. 2012). The splits represented the separation of fibre caused by the tearing apart of the wood parallel to the wood rays and their lengths were measured from the transversal face. Checks (represent end-grain surface and extending along with the size of a board) were measured along its transversal face. The colour was determined for all the boards obtained from the logs in each treatment. Where the boards had sapwood and heartwood, colour was determined in both types of tissue. A miniScan XE Plus spectrophotometer (HunterLab Inc., New York, USA) was utilized to obtain the values of the CIE L*a*b* standardized chromatological system.

2.8 Statistical analysis

One-way ANOVA was used to LRGS in standing trees, LRGS before treatment, LRGS after treatment, crooking due to sawing, wood colour parameters (L*, a* and b*) and lumber quality (warp, crook and split) parameters. The Tukey test was used to test the mean difference at a $p < 0.01$ level of significance and the SAS 8.1 statistics program for Windows (SAS Institute Inc., Cary, N.C., USA) was used to carry out the analyses.

3 Results

3.1 Temperature variation

Effect of temperature variation on reducing the LRGS for improving the lumber quality is provided in Table 2, which presents the mean values of temperature and time of the different treatments applied to the logs. Lumber under heating$_{treatment}$ shows a stabilization time, total time and maximum interior temperature that is lower than lumber under steaming$_{treatment}$ (Table 2). This temperature variation is reflected in the different log diameters (Fig. 3).

As shown in Fig. 3, the inner temperature of the logs' increase as the treatment time increases. As expected, at the beginning of the heating$_{treatment}$, the inner temperature was found highest in the smaller log (14.3 cm diameter), followed by the 16.1 cm diameter log and logs with larger diameters (17.8 cm and 20.6 cm). After 8 h of treatment, the increase in temperature goes hand in hand among all the logs of different diameters investigated here (Fig. 3a). Similar behaviour was observed with the steaming$_{treatment}$, in which the log with a smaller diameter presented higher temperature for the same period compared to larger diameters (Fig. 3b).

Similarly, more significant differences were observed between the temperatures in logs of the steaming$_{treatment}$ and the heating$_{treatment}$. The logs under heating$_{treatment}$ reached the stabilization time in close to 14 h (Fig. 3a), while for logs under steaming$_{treatment}$ the time needed for stabilization was 18 h (Fig. 3b).

3.2 Longitudinal residual stress variation

As expected, LRGS$_{stand\text{-}tree}$ were greater than LRGS$_{before\text{-}treatment}$, which in turn were greater than LRGS$_{after\text{-}treatment}$ for all heights (Fig. 4a). The values of LRGS increased as the height at which the log was extracted (Fig. 4). The average value of LRGS was 1550.46 με at 0.0–2.5 m (Fig. 4a), 1847.42 με at 2.5–5.0 m (Fig. 4b), 2065.83 με at 5.0–7.5 m (Fig. 4c) and 2658.66 με at 7.5–10.0 m height (Fig. 4d).

Table 2 Temperature variation in heating$_{treatment}$ and steaming$_{treatment}$ for *Hieronyma alchorneoides* logs from the fast-growth plantation

Parameters	Heating$_{treatment}$	Steaming$_{treatment}$	Average for two treatments
Stabilization time (hours)	20:16:09	20:52:37	20:39:27
Maximum temperature (°C)	85.96	89.62	88.30
Total time (hours)	23:52:18	24:20:00	24:10:16

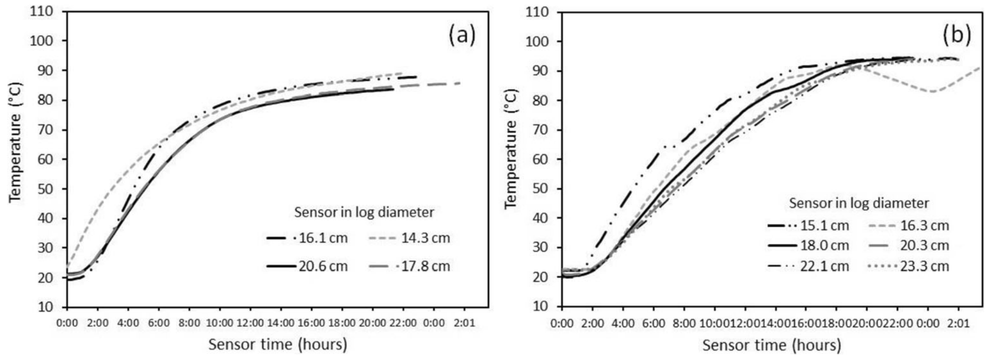

Fig. 3 Temperature variation inside the logs of *Hieronyma alchorneoides* in relation to time for heating$_{\text{treatment}}$ (**a**) and steaming$_{\text{treatment}}$ (**b**)

With regard to the effect of the treatment on the LRGS of logs before sawing at different heights, the ANOVA test showed that the log treatment was not statistically significant in LRGS$_{\text{stand-tree}}$ and LRGS$_{\text{before-treatment}}$ (Table 3). Therefore, statistical differences in LRGS at those times of the process were not observed (Fig. 4a). However, the log treatment before sawing presented statistically significant effects in LRGS$_{\text{after-treatment}}$ at all heights (Table 3); therefore, differences between the treatments evaluated were observed, and logs under the heating$_{\text{treatment}}$ showed the highest values (Fig. 4). Another result was those values of LRGS increased with the increasing height of the log.

3.3 Crooking due to sawing variation

Table 4 shows the average values of crooking$_{\text{due-to-sawing}}$ obtained in logs and semi-logs according to height and treatment. In the three treatments for logs and semi-logs, the value of crooking$_{\text{due-to-sawing}}$ side 1 was greater than in crooking$_{\text{due-to-sawing}}$ side 2. However, a tendency to increase or diminish the value of crooking$_{\text{due-to-sawing}}$ in the log or semi-logs with increasing tree height was not observed.

The effect of the log treatment before sawing was statistically significant in the different crooking$_{\text{due-to-sawing}}$ at most of the heights, except for heights of 2.5–5.0 m for side 1 in logs and semi-logs and heights of 2.5–5.0 m in semi-logs side 2 (Table 3). Comparison of the averages showed that crooking$_{\text{due-to-sawing}}$ in logs and semi-logs on side 1 and side 2 at all heights, the steaming$_{\text{treatment}}$ presented the lowest values relative to heating$_{\text{treatment}}$ and untreated, except for crooking$_{\text{due-to-sawing}}$ in logs on side 1 and in semi-logs side 1 at heights of 5.0–7.5 m and in semi-log side 2 at heights of 2.5–5.0 m, where no statistical differences were observed between

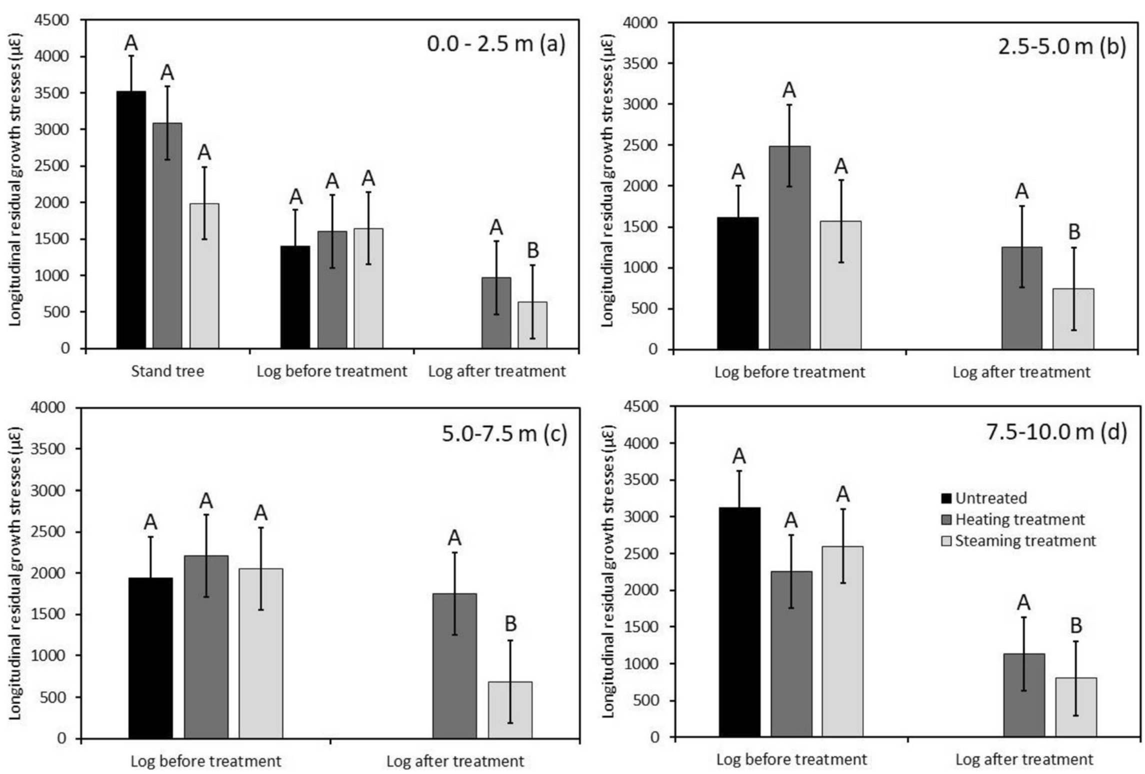

Fig. 4 Longitudinal growth stress per the height of *Hieronyma alchorneoides* wood from the fast-growth plantation

Table 3 F-value of ANOVA for different parameters measured in logs, semi-logs and lumber of *Hieronyma alchorneoides* for different tree heights

Parameter		Height (m)			
		0.0–2.5	2.5–5.0	5.0–7.5	7.5–10.0
$LRGS_{stand\text{-}tree}$		3.18^{NS}	–	–	–
$LRGS_{before\text{-}treatment}$		0.44^{NS}	2.42^{NS}	0.10^{NS}	1.27^{NS}
$LRGS_{after\text{-}treatment}$		4.44*	5.51*	5.47*	4.33*
$Crooking_{due\text{-}to\text{-}sawing}$ in log side 1		33.31**	8.06**	1.95^{NS}	22.62**
$Crooking_{due\text{-}to\text{-}sawing}$ in log side 2		8.50**	5.99**	4.33*	4.35*
$Crooking_{due\text{-}to\text{-}sawing}$ in semi-log side 1		7.73**	14.06**	0.63^{NS}	57.46**
$Crooking_{due\text{-}to\text{-}sawing}$ in semi-log side 2		31.21**	0.24^{NS}	6.16**	7.23**
Sapwood colour	L*	33.86**	20.16**	1.59^{NS}	6.77**
	a*	50.38**	39.96**	4.49*	1.83^{NS}
	b*	20.44**	4.87*	2.26^{NS}	0.28^{NS}
Heartwood colour	L*	38.78**	39.32**	11.33**	1.63^{NS}
	a*	16.83**	16.52**	1.37^{NS}	12.34**
	b*	29.90**	39.20**	16.43**	7.44*
Bow		2.04*	2.67*	1.88*	2.88*
Crook		1.12^{NS}	0.48^{NS}	12.00**	9.42**
Twist		0.62^{NS}	21.01*	0.31^{NS}	35.66**
Check		3.94*	3.79*	3.60*	3.37*
Split		3.88*	1.10^{NS}	2.46^{NS}	0.02^{NS}

** statistically significant at 99% ($P < 0.01$) and *statistically significant at 95% ($P < 0.05$)

treatments (Table 4). No statistical differences were observed between the untreated and the logs under $heating_{treatment}$ about $crooking_{due\text{-}to\text{-}sawing}$ in logs and semi-logs on side 1 and side 2 at most of the heights (Table 4). At heights of 0.0–2.5 m, $crooking_{due\text{-}to\text{-}sawing}$ in logs side 1, at heights of 7.5–10.0 m in logs side 1 and in semi-logs on both sides (i.e., on 1 and 2), the untreated logs presented the highest values, followed by the logs under $heating_{treatment}$ and lastly by the logs under $steaming_{treatment}$ with the lowest values (Table 4).

3.4 Colour evaluation

Colour parameters (L*, a* and b*) for sapwood and heartwood differed. Heartwood presented values of L*, a* and b*

Table 4 $Crooking_{due\text{-}to\text{-}sawing}$ measured in logs and semi-logs under different treatments per tree height of *Hieronyma alchorneoides* wood from the fast-growth plantation

Tree height (m)	Treatment	$Crooking_{due\text{-}to\text{-}sawing}$ in logs (mm)		$Crooking_{due\text{-}to\text{-}sawing}$ in semi-logs (mm=	
		side 1	side 2	side 1	side 2
0.0–2.5	Untreated	72.0^{A} (23.1)	42.2^{A} (40.1)	52.6^{A} (59.4)	39.2^{A} (25.0)
	$Heating_{treatment}$	41.4^{B} (25.2)	33.1^{A} (32.0)	38.8^{A} (57.5)	32.2^{A} (26.8)
	$Steaming_{treatment}$	26.9^{C} (61.2)	19.9^{B} (88.4)	21.7^{B} (78.0)	14.0^{B} (71.2)
2.5–5.0	Untreated	52.0^{A} (31.9)	31.0^{A} (46.2)	56.8^{A} (27.4)	24.3^{A} (133.2)
	$Heating_{treatment}$	43.6^{A} (42.8)	28.8^{A} (35.9)	64.2^{A} (62.4)	24.5^{A} (84.2)
	$Steaming_{treatment}$	24.9^{B} (73.0)	16.3^{B} (79.8)	15.3^{B} (94.4)	19.6^{A} (133.2)
5.0–7.5	Untreated	57.6^{A} (30.3)	43.8^{A} (39.7)	57.5^{A} (72.85)	46.3^{A} (70.0)
	$Heating_{treatment}$	49.6^{A} (21.9)	41.3^{A} (25.2)	55.9^{A} (34.88)	26.3^{AB} (36.3)
	$Steaming_{treatment}$	44.0^{A} (37.1)	23.7^{B} (36.3)	40.7^{A} (13.26)	7.7^{B} (79.4)
7.5–10.0	Untreated	57.6^{A} (24.4)	32.3^{A} (14.9)	78.6^{A} (15.16)	46.0^{A} (57.7)
	$Heating_{treatment}$	45.1^{B} (10.5)	36.9^{A} (52.9)	42.1^{B} (24.86)	16.9^{B} (112.3)
	$Steaming_{treatment}$	18.5^{C} (21.9)	13.0^{B} (26.7)	17.0^{C} (33.96)	4.5^{C} (115.5)

The values in parentheses correspond to the coefficients of variation. Different letters between treatments mean that there are statistical differences ($P < 0.05$)

lower than sapwood. As for the effect of treatments before sawing, in heights lower than 5 m all parameters were statistically influenced by the treatment. For the rest of the heights, the effect of the treatment was irregular regarding colour parameters (Table 3).

The differences between the different log treatment, parameters L* and b* in heartwood under $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$ were statistically higher than in untreated wood at all heights. In contrast, no statistical differences were observed in the L* and b* parameters of wood under $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$ (Table 5). As for parameter a* of heartwood, the $\text{steaming}_{\text{treatment}}$ wood presented the statistically highest values for most of the heights, followed by $\text{heating}_{\text{treatment}}$ lumber and lastly by untreated lumber, except for heights of 5.0–7.5 m, where no statistical differences appeared between the lumbers of the three treatments (Table 5).

The sapwood tends to become lighter when exposed to $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$. This was because at most heights parameter L* increased and a* and b* decreased (Table 5). As for parameter L* at heights of 0.0–2.5 m and 2.5–5.0 m, untreated wood presented the statistically lower values; at 5.0–7.5 m, there were no differences between the three treatments and at 7.5–10.0 m, untreated wood gave the statistically lowest value (Table 5). Regarding parameter a*, at most heights, untreated wood had the highest values relative to $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$. At most heights, no differences were observed between $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$ wood, except for heights of 7.5–10.0 m, where no differences between the three treatments were found (Table 5). As for heights of 0.0–2.5 m and 2.5–5.0 m regarding parameter b*, untreated wood showed the statistically highest values, while the other two treatments showed no differences. The remaining heights presented statistical differences in the parameter b* within the three treatments (Table 5).

3.5 Lumber quality evaluation

Lumber obtained from logs under three different treatments presented three different types of warps (bow, crook and twist), checks and splits (Table 6 and Fig. 5), while cup defects were found absent. Bow and crook incidence accounted for over 90%; twist incidence was low, and check and split stood above 30% in the $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$ (Fig. 5). No correlation was observed with height variation for warps, checks or splits.

The influence of the treatment of the logs on the magnitude of the warp was statistically significant in the case of the bow at all heights (Table 3). Therefore, the differences in the means showed that at all heights bow of lumber from untreated logs presented the statistically highest values but no such statistical differences were observed between $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$ (Table 6). On the other hand, the lumber with treatments $\text{heating}_{\text{treatment}}$ or $\text{steaming}_{\text{treatment}}$ showed no influence on the bow with regard to diminishing or increasing the percentage of pieces showing this defect. In contrast, lumber from untreated logs showed a tendency towards diminishing bow incidence.

The effect of log treatments on lumber crook was statistically significant at heights of 5.0–7.5 m and 7.5–10 m (Table 3), which is reflected in the means values obtained in $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$ and they were statistically lower than untreated logs (Table 6). The values at heights under 5.0 m of crook were statistically equivalent between

Table 5 Colour parameters measured in logs of *Hieronyma alchorneoides* from the fast-growth plantation under different treatments and different tree heights

Tree height (m)	Treatment	Colour parameters in the heartwood			Colour parameters in sapwood		
		L*	a*	b*	L*	a*	b*
0.0–2.5	Untreated	23.2^{B} (22.3)	13.6^{C} (39.8)	9.3^{B} (57.9)	52.1^{B} (13.8)	20.3^{A} (20.3)	26.1^{A} (16.5)
	$\text{Heating}_{\text{treatment}}$	39.2^{A} (23.7)	16.7^{B} (23.5)	16.8^{A} (26.1)	63.2^{A} (5.4)	13.1^{B} (17.1)	22.8^{B} (7.1)
	$\text{Steaming}_{\text{treatment}}$	36.8^{A} (18.2)	20.0^{A} (23.8)	17.0^{A} (22.1)	61.1^{A} (8.1)	14.0^{B} (16.5)	21.5^{B} (12.3)
2.5–5.0	Untreated	22.4^{B} (24.8)	13.7^{C} (40.4)	8.9^{C} (54.4)	53.1^{C} (14.8)	19.6^{A} (25.9)	25.2^{A} (24.3)
	$\text{Heating}_{\text{treatment}}$	36.4^{A} (20.9)	17.4^{B} (10.9)	16.3^{B} (22.0)	64.1^{A} (8.8)	11.3^{C} (20.2)	22.1^{B} (6.0)
	$\text{Steaming}_{\text{treatment}}$	37.1^{A} (12.9)	20.0^{A} (13.3)	19.8^{A} (19.9)	58.3^{B} (9.8.7)	15.7^{B} (19.0)	23.0^{AB} (12.9)
5.0–7.5	Untreated	29.8^{B} (32.3)	18.8^{A} (20.8)	12.8^{B} (35.6)	62.2^{A} (10.0)	15.5^{A} (28.7)	25.3^{A} (23.0)
	$\text{Heating}_{\text{treatment}}$	45.0^{A} (8.7)	20.7^{A} (12.0)	22.5^{A} (16.4)	65.0^{A} (5.0)	12.2^{B} (17.2)	22.9^{A} (7.4)
	$\text{Steaming}_{\text{treatment}}$	43.4^{A} (9.5)	20.9^{A} (10.4)	20.5^{A} (12.8)	63.2^{A} (4.4)	13.6^{AB} (15.3)	22.6^{A} (8.2)
7.5–10.0	Untreated	–	–	–	66.3^{A} (4.9)	12.4^{A} (20.8)	23.2^{A} (29.6)
	$\text{Heating}_{\text{treatment}}$	38.9^{A} (30.0)	17.1^{B} (9.2)	15.9^{B} (30.1)	63.7^{AB} (6.0)	12.3^{A} (29.2)	22.5^{A} (9.5)
	$\text{Steaming}_{\text{treatment}}$	47.9^{A} (3.6)	22.1^{A} (14.3)	34.3^{A} (51.7)	60.1^{B} (4.7)	14.8^{A} (12.0)	21.7^{A} (9.8)

The values in parentheses correspond to the coefficients of variation. Different letters between treatments mean there are statistical differences ($P < 0.05$)

Table 6 Magnitude and incidence of bow, crook and twist defects in lumber from logs under different treatments and different tree heights of *Hieronyma alchorneoides* from the fast-growth plantation

Tree height (m)	Log treatment	Board total	Bow		Crook		Twist	
			Value (mm)	Incidence (%)	Value (mm)	Incidence (%)	Value (mm)	Incidence (%)
0.0–2.5	Untreated	25	14.5^{A} (46.1)	88.0	7.9^{A} (67.8)	96.0	1.7^{A} (59.6)	8.0
	$\text{Heating}_{\text{treatment}}$	36	11.8^{B} (53.9)	72.2	6.5^{A} (35.2)	97.2	2.0^{A} (50.2)	11.1
	$\text{Steaming}_{\text{treatment}}$	69	11.4^{B} (53.8)	79.7	7.2^{A} (47.2)	92.8	2.9^{A} (10.0)	1.5
2.5–5.0	Untreated	24	14.7^{A} (39.4)	75.0	6.6^{A} (41.0)	91.7	2.7^{A} (10.0)	4.2
	$\text{Heating}_{\text{treatment}}$	29	10.4^{B} (82.4)	86.2	6.2^{A} (48.3)	86.2	0.9^{B} (101.9)	13.8
	$\text{Steaming}_{\text{treatment}}$	36	10.3^{B} (48.0)	66.7	7.1^{A} (60.7)	88.9	0.0 (0.0) ^{B}	0.0
5.0–7.5	Untreated	24	16.2^{A} (52.7)	100.0	10.9^{A} (37.7)	100.0	1.9^{A} (53.7)	16.7
	$\text{Heating}_{\text{treatment}}$	16	11.1^{B} (65.1)	81.3	5.2^{B} (44.1)	100.0	1.7^{A} (60.4)	12.5
	$\text{Steaming}_{\text{treatment}}$	13	13.0^{B} (46.8)	61.5	7.7^{B} (55.0)	92.3	0.0 (0.0) ^{A}	0.0
7.5–10.0	Untreated	11	22.9^{A} (51.6)	90.9	6.6^{A} (45.3)	90.9	5.5^{A} (31.4)	18.2
	$\text{Heating}_{\text{treatment}}$	13	14.4^{B} (56.4)	84.6	3.8^{B} (42.2)	69.2	1.5^{B} (68.6)	30.8
	$\text{Steaming}_{\text{treatment}}$	7	13.6^{B} (45.8)	100.0	3.6^{B} (34.0)	100.0	3.3^{B} (10)	28.6

The values in parentheses correspond to the coefficients of variation. Different letters between treatments means that there are statistical differences ($P <$ 0.05)

$\text{heating}_{\text{treatment}}$, $\text{steaming}_{\text{treatment}}$ and untreated logs. If compared with untreated logs, a crook defect was diminished in logs under $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$ (Table 6).

Similarly, at heights of 2.5–5.0 m and 7.5–10.0 m (Table 3), twisting effects due to log treatments were observed, but no such statistical differences were observed at heights of 0.0–2.5 m and 5.0–7.5 m among the three treatments (Table 6). At heights of 2.5–5.0 m and 7.5–10.0 m, lumber from untreated logs presented the highest twisting values, while lumber from $\text{heating}_{\text{treatment}}$ and $\text{steaming}_{\text{treatment}}$

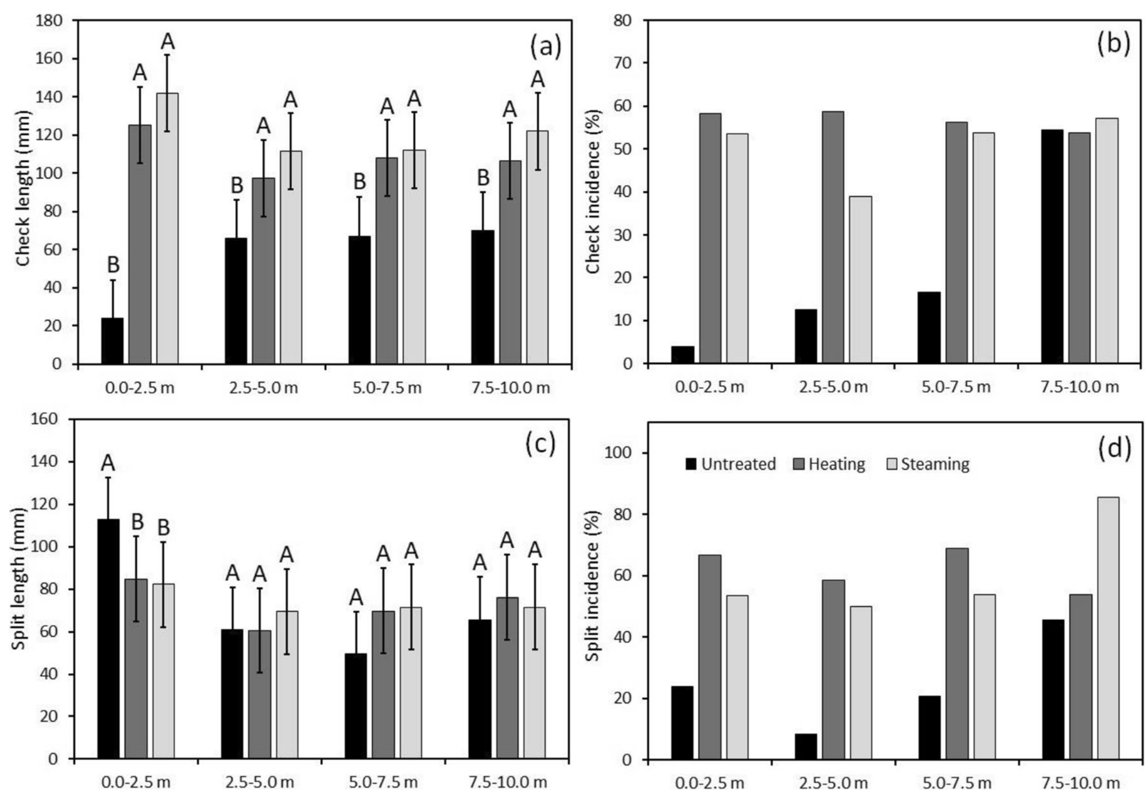

Fig. 5 Length and incidence of check and split defects per height in *Hieronyma alchorneoides* wood from the fast-growth plantation

log showed no differences in the values (Table 6). As compared to the other treatments, the percentage of twist incidence in lumber from steaming$_{treatment}$ showed a reduction in its occurrence (Table 6).

4 Discussion

The reduction between LRGS$_{stand\text{-}tree}$ and LRGS$_{before\text{-}treatment}$ (Fig. 4a) was attributed to the relaxation of growth stress after the tree was felled, resulting in strain recovery, or released strain (Gril and Thibaut 1994; Gril et al. 2017). The viscoelastic properties of wood permit a delayed recovery; therefore, residual stress is lower than residual stress in standing trees, as was shown in the present study of *H. alchornoidesf*.

Steam or heat application contributes to the release of LRGS in logs (Severo et al. 2010; Pelozzi et al. 2014). The variation in temperature by treatment of steaming or heating generally follows the model proposed by Steinhagen et al. (Steinhagen et al. 1987). This model proposes that the optimum steaming time relates to the log diameter, the thermal diffusivity constant and the Fourier number, which indicates the temperature that the log should reach (Calonego and Severo 2006). Temperature variation in the logs of different diameters of *Hieronyma alchorneoides* in both the heating$_{treatment}$ and the steaming$_{treatment}$ shows the behaviour of Steinhagen et al.'s model (Fig. 3a, b), in which the temperature increases in the first hours and then tends to stabilize. However, the temperature variation depends on the diameter of the log (Fig. 3a, b).

Appropriate heating or steaming times soften the structure of the wood (Lenth and Kamke 2001; Pelozzi et al. 2014; Rodrigues et al. 2018) and overall the LRGS (Tejada et al. 1997; Nogi et al. 2003; Severo et al. 2010; Pelozzi et al. 2014; Rodrigues et al. 2018), as was evidenced in the present study when the logs of *H. alchorneoides* were steamed or heated, the magnitude of LRGS diminished significantly after these treatments (Fig. 4a).

The decrease of LRGS after steaming or heating (Fig. 4a), the reduction of crooking$_{due\text{-}to\text{-}sawing}$ measured in logs and semi-logs (Table 4) and the diminution of the magnitude of the bow, crook, twist and split length (Table 6, Fig. 5c) are signs that with the steaming and heating treatments the glass transition temperature needed to reduce the LRGS was reached. Reaching the adequate glass transition temperature in the log due to heating$_{treatment}$ or steaming$_{treatment}$ results in softening of the cellulose and the matrix that forms lignin and hemicelluloses (Kelley et al. 1987). Lignin is thermoplastic in the central layer and the layer S2; that is, it softens at the appropriate temperature (Lenth and Kamke 2001; Pelozzi et al. 2014). Therefore, this softening alleviates the internal stresses through the molecular and microstructural reorganization of the wood (Nogi et al. 2003; Gril et al. 2017; Rodrigues et al. 2018). The softening of cellulose and the matrix that forms lignin and hemicelluloses by heating or steaming activates viscoelasticity of wood, which is related with glass transition temperature (Gril et al. 2017). Both effects are reflected in the reduction of the twists at the time of sawing, such as crooking$_{due\text{-}to\text{-}sawing}$ or warping in lumber of *H. alchorneoides* in this study.

In both treatments, the target temperature of the tank was 115 °C, and the best heat transmission was achieved with steaming$_{treatment}$. This is because the temperature in the internal part of the log was over 90 °C (Fig. 3b). In contrast, in the heating$_{treatment}$, the internal temperature of the log was slightly lower, that is, between 80 and 85 °C (Fig. 3a). The different polymers that make up the wood have different glass transition temperatures, 40 °C in hemicelluloses, 50 °C to 100 °C for lignin and higher than 100 °C for cellulose (Furuta et al. 1997). It is well-accepted that the softening temperature of wood varies between 60 °C and 70 °C in green wood. Owing to the softening of hemicelluloses and lignin, the amorphous areas of cellulose undergo reorganization (Kong et al. 2017). Therefore, the temperature range (80–90 °C) reached in the steaming$_{treatment}$ and heating$_{treatment}$ contains the glass transition temperature of *H. alchorneoides*, i.e., the parameters related to LRGS are favoured, LRGS decrease (Fig. 4a), crooking$_{due\text{-}to\text{-}sawing}$ is reduced (Table 4) and the magnitude of bow, crook, twist and split length decrease (Table 6, Fig. 5c).

As performed in the present study, it is also reported by earlier researchers that steaming and heating treatments result in the reduction of LRGS in logs (Tejada et al. 1997; Nogi et al. 2003; Severo et al. 2010; Pelozzi et al. 2014; Rodrigues et al. 2018). However, LRGS diminished significantly due to steaming$_{treatment}$ as compared to heating$_{treatment}$ (Table 3, Fig. 4) at all heights of the lumber studied in the present study. In turn, other parameters, such as crooking$_{due\text{-}to\text{-}sawing}$ in logs and semi-log with steaming$_{treatment}$ also showed their reduction (Table 4). This indicates that *H. alchorneoides*, the steaming$_{treatment}$ is more effective to reduce LRGS in trees from the forest plantations than the heating$_{treatment}$. Nevertheless, the effect of the steaming$_{treatment}$ and heating$_{treatment}$ was not as evident in the magnitude of the warps (Table 6), splits or checks (Fig. 5); although, a slight reduction of the incidence of these quality parameters in steamed lumber was observed (Table 4 and Fig. 5). This difference is attributed to the fact that the steaming$_{treatment}$ creates better conditions for the relaxation of the different wood polymers. These conditions are: (i) the higher temperature achieved with steaming$_{treatment}$ in the internal part of the lumber, which is approximately 5 °C higher than heating$_{treatment}$ (Fig. 3), is probably causing the entire cross section of the log to reach the glass transition temperature of the wood, allowing greater relaxation; (ii) during steaming, the internal saturated conditions of the chamber ease log relaxation with steaming$_{treatment}$ (Kong et al. 2017) and (iii) the heating$_{treatment}$ creates conditions for the loss of moisture through the ends of the logs and higher incidence of splitting and cracking during the sawing process (Nogi et al. 2001, 2003), as happened in the present study (Table 4 and Fig. 5). Finally, steaming reduces the crystalline zones of cellulose; therefore, the amorphous zones increase (Kong et al. 2017), producing better conditions for the relaxation of growth stresses in steaming$_{treatment}$.

Another important aspect to note is there was a change in colour of lumber in the steaming$_{treatment}$ and heating$_{treatment}$ as compared to that of the wood from untreated logs (Table 5). The changes in the colour parameters of sapwood and heartwood are produced by temperature because it affects the chemical composition of the various wood components (Kocaefe et al. 2008; Salca et al. 2016). Colour changes after the treatments are caused by hydrolysis of the hemicelluloses (Salca et al. 2016). Steaming or heating treatments produce an increase in the white and yellow tones of the wood (increase of L* and b*), which is attributed to the degradation or modification of the components produced by reactions such as oxidation, dehydration, decarboxylation and hydrolysis (Kocaefe et al. 2008). Steaming or heating also darken the lignin, which is linked to parameter a* (increase in a*), which in turn is associated with generation of chromophore groups (Salca et al. 2016) that cause colour change at high temperatures (Table 3, Fig. 1). Although the colour changes significantly due to the heating of the wood by steaming or heating, these changes are not severe for chemical components as to produce important degradation of wood that can affect the structural performance of the wood. On the other hand, untreated logs showed no differences in the colour parameters in relation to wood extracted from steaming$_{treatment}$ and heating$_{treatment}$ logs at the different heights evaluated (Table 5). This is probably due to the fact that the differences in temperatures between steaming$_{treatment}$ and heating$_{treatment}$ were not enough to produce changes in the wood components so as to affect colour parameters.

Steaming or heating treatment of *H. alchorneoides* logs led to a reduction of LRGS in logs (Fig. 4), of crooking$_{due\text{-}to\text{-}sawing}$ in logs and semi-logs (Table 4), and of L* colour parameter. There was an increase in a* and b* colour parameters (Table 5) and regular behaviour of warps, splitting and checking of lumber (Table 6 and Fig. 5) at different heights and treatments (steaming$_{treatment}$ and heating$_{treatment}$). These results indicate that both treatments produce positive effects on wood logs from the fast-growth plantation in relation to reduction of LRGS and, consequently, in the quality parameters of wood associated with these stresses in the trees.

5 Conclusion

The treatments of steaming and heating produce the same effect in logs at all heights, lead to reduction of longitudinal residual stress and crooking due to sawing in logs and semi-logs. They also result in reduction of L* colour parameter, increase of a* and b* colour parameters and reduction of warps, splitting and checking of lumber at all heights. Thus, both treatments applied to logs from the fast-growth plantation of *H. alchorneoides* improve the quality of lumber.

The better reduction in longitudinal surface residual stress in *H. alchorneoides* logs of fast-growing plantations occurs when they are steamed for 24 h, achieving a temperature of 90 °C in the internal part of the log. To improve the quality of logs, the parameters evaluated in steaming treatment indicate that this treatment of log reaches the temperature and results in reorganization of soften hemicelluloses, lignin and the amorphous areas of the cellulose, leading to a decrease in longitudinal growth stress. Heating treatment of *H. alchorneoides* logs also have favourable effects in the reduction of longitudinal residual growth stresses and improve the quality parameters of the sawn wood. However, it does not reach the quality values that are achieved when the logs are steamed. The difference found between steaming and heating can be attributed to the temperature in the internal part of the log; that is, it was above 90 °C in the steaming treatment and in the heating treatment, the internal temperature of the log was slightly lower (80–85 °C); therefore, the steaming treatment results in better a glass transition stage than the heating treatment.

Abbreviations $\mu\varepsilon\theta$, micro-deformation units; *Crooking$_{due\text{-}to\text{-}sawing}$*, crooking produced in the log during sawing; *DBH,* diameter at breast height; *Heating$_{treatment}$*, heating treatment applicated in sawlog before sawing; *LRGS,* longitudinal surface growth residual stresses; *LRGS$_{stand\text{-}tree}$*, longitudinal surface growth residual stresses in standing trees; *LRGS$_{before\text{-}treatment}$*, longitudinal surface growth residual stresses measured before log treatment; *LRGS$_{after\text{-}treatment}$*, longitudinal surface growth residual stresses measured after log treatment; *Steaming$_{treatment}$*, steaming treatment applicated in sawlog before sawing

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Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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