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Mejoramiento de las condiciones de procesamiento primario, secado y usos estructurales de la madera de almendro (*Dipteryx panamensis*) y pilón (*Hieronyma alchorneoides*) de plantaciones forestales de Costa Rica
Código 1401025

(DOCUMENTO I)

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Mejoramiento de las condiciones de procesamiento primario, secado y usos estructurales de la madera de almendro (*Dipteryx panamensis*) y pilón (*Hieronyma alchorneoides*) de plantaciones forestales de Costa Rica

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2. RESUMEN

La madera de almendro (*Dipteryx panamensis*) y pilón (*Hieronyma alchorneoides*) presenta una densidad entre los 0,6 a 0,7 g/cm^3, lo que significa que poseen una alta resistencia mecánica y que podrían ser utilizadas en usos estructurales. Sin embargo, la madera proveniente de plantaciones forestales de estas dos especies se caracteriza porque: (i) durante el aserrío las trozas liberan tensiones de crecimiento dando como resultado madera con torceduras y rajaduras, (ii) durante el proceso de secado la madera es propensa a producir pandeos y reventaduras y (iii) estas dos situaciones han provocado problemas para la comercialización y el establecimiento de un posible mercado para la madera proveniente de plantaciones de estas especies. Por lo tanto, la presente investigación tuvo el objetivo mejorar las condiciones procesamiento primario y de secado, así como establecer los valores de resistencia estructural de vigas de madera aserrada y laminada de almendro y pilón procedentes de plantaciones forestales de Costa Rica. Para el cumplimiento de estos objetivos se estableció una propuesta metodológica de dos sistemas de aserrío, dos sistemas de secado y el desarrollo de dos posibles productos a comercializar de estas especies. Antes de realizar el proceso de aserrío se implementaron dos tratamientos en las trozas: calentado y vaporizado, con el fin de mitigar la manifestación de las tensiones de crecimiento. En el secado se realizó una etapa de vaporizado a mitad del tiempo de secado y en el diseño de productos se fabricaron vigas laminadas de 5 x 10 cm and 5 x 15 cm. Los resultados mostraron que los tratamientos de vapor y calentamiento en trozas reducen los efectos de torceduras en la madera aserrada durante el proceso de aserrío y reaserrio. Así mismo, se encontró que el vaporizado de las trozas tiene un mayor efecto en la calidad de la madera en relación al calentamiento, para las dos especies. Se encontró que la aplicación de una etapa de vaporizado en el secado, aumenta la calidad de la madera aserrada. Finalmente, en la evaluación de la madera para uso estructural como vigas laminadas se determinó que los esfuerzos de diseño variaron de 10 a 26 MPa y que la madera almendro presenta valores ligeramente mayores que la de pilón. Además, se estableció que las vigas laminadas presentan un mejor comportamiento en los parámetros de flexión y por lo tanto los valores de diseño en relación a la madera sólida, dando como resultado que se obtengan valores de separación entre apoyos más amplios cuando son utilizados en entrepisos.

Improvement of the conditions of primary processing, drying and structural uses of almond (*Dipteryx panamensis*) and pilón (*Hieronyma alchorneoides*) wood from forest plantations in Costa Rica

Abstract

Wood from almendro (*Dipteryx panamensis*) and pilón (*Hieronyma alchorneoides*) present a density between 0.6 to 0.7 g / cm^3, then they are classified as high mechanical resistance and that they could be used in structural uses. However, the wood from forest plantations is characterized by: (i) during sawing the logs release growth stresses resulting in warping and cracking lumber, (ii) during the drying process the wood produce twist and cracking defects and (iii) these two situations have caused problems for the commercialization and the establishment of a possible market for wood from plantations of these species. Therefore, the present research aimed to improve the primary processing and drying conditions, as well as to establish the structural strength values of solid and laminated beams from forest plantations wood in Costa Rica. The methodological proposal of two sawing systems, two drying systems and the development of two possible products of these species to be commercialized is established. Before carrying out the sawing process, two treatments were implemented in the logs: heated and steamed, in order to mitigate the manifestation of growth tensions. In drying, a steaming stage was carried out in the middle of the drying time and in the design of products, laminated beams of 5 x 10 cm and 5 x 15 cm were manufactured. The results showed that the steam treatment and heating of logs reduces the warping effects in the lumber during the sawing and re-sawing process. Likewise, it was found that the steaming of the logs has a greater effect on quality than when the logs are heated in the two species tested. In drying, it was found that the application of a steaming stage increases the quality of the sawn wood during drying. Finally, in the evaluation of wood for structural use as laminated beams, it was found that the design stresses varied from 10 to 26 MPa and that almendro wood presents slightly higher values than pilón. In addition, it was established that laminated beams have better behavior in bending parameters and therefore design values in relation to solid wood, resulting in wider separation values between supports when they are used in mezzanines.

3. PALABRAS CLAVE

Plantaciones forestales, madera tropical, maderas de alta densidad, reforestación.

Key words: plantation forest, wood plantation, tropical wood, hardwood, reforestation

4. INTRODUCCIÓN

Maderas duras (densidad sobre 0,6 g/cm^3) como el *Dipteryx panamensis* (almendro) e *Hieronyma alchorneoides* (pilón) se desarrollan en los bosques naturales de Costa Rica y tienen un mercado establecido para su madera. Estas especies son utilizadas en la construcción de casas, específicamente en cerchas, pisos y columnas de soporte de paredes, es decir, en usos donde se demande de una resistencia estructural alta (Moya et al., 2014). Así mismo, son utilizadas en otro tipo de construcciones donde es necesario que los materiales cuenten con buenas propiedades mecánicas o de resistencia, como por ejemplo en puentes, carrocerías para camiones de transporte de carga, entre otros (Moya et al. 2014).

La madera de plantación de almendro y pilón presenta una densidad ligeramente inferior a la madera proveniente del bosque natural (Tenorio et al., 2016), sin embargo, esta disminución no es un problema para que la madera de plantación sea introducida en los mismos nichos de mercado establecidos para la madera del bosque natural (Moya et al., 2013). No obstante, a la madera proveniente de plantaciones forestales se le atribuyen dos problemas principales, los cuales las hacen difíciles de comercializar, y son la baja calidad de la madera aserrada obtenida en el aserrío y la presencia de una alta cantidad de defectos en la madera luego del proceso de secado. (Moya et al., 2015).

En los arboles de plantaciones de rápido crecimiento (Chafe, 1979) la madera próxima a la corteza es sometida a una tensión longitudinal, pero al aproximarse a la médula ocurre una compresión en el sentido transversal, de forma que la madera dentro árbol es sometida a fuerzas contrarias. La combinación de esos dos tipos de fuerzas tiende a causar rajaduras en las trozas al ser cortadas y torceduras en la madera aserrada en el momento del aserrío (Severo y Tomaselli, 2000). Pero, aunque las tensiones se liberan en gran porcentaje durante el proceso de aserrío, un porcentaje queda aún si liberar y por lo general es liberado durante el proceso de secado de la madera (Gril et al., 2017).

Las tensiones de crecimiento presentes en las trozas pueden ser liberadas por medio de algunos tratamientos, entre los que se destacan la aplicación de vapor de agua o el calentamiento de las trozas (Kubler, 1987; Gril et al., 2017). Chafe (1979) y Kubler (1987) explican que las tensiones de crecimiento pueden “relajarse” cuando hay una aplicación de calor, gracias a que el calor aplicado hace que las cadenas de celulosa se plastifiquen dando como resultado la desaparición de las fuerzas presentes en las paredes de las células de las fibras (Kubler, 1987) y por tanto la calidad de la madera aserrada aumenta (Gril et al., 2017).

Se establece que cuando las trozas se calientan a una temperatura de 80-95°C las tensiones de crecimiento se pueden reducir hasta en un 90% (Sujan et al., 2016). Al respecto, Gril et al. (2017) y Rodríguez et al. (2018) aplicaron un modelo de calentamiento de trozas desarrollado por Tejada et al (1997). En este método la fuente de calor es generada por los mismos residuos producidos en los aserraderos y la corriente de aire caliente (entre 80-100°C) pasa perpendicular al eje de las trozas (Tejada et al., 1997).

La aplicación de vapor es otro tratamiento utilizado para la liberación de las tensiones de crecimiento en las trozas y así mejorar la calidad de madera aserrada (Severo et al, 2010). No obstante, este método resulta menos efectivo que cuando se les aplica calor directo a las trozas (Gril et al., 2017). Esto debido a que el vapor de agua tarda más tiempo en plastificar las paredes celulares de las fibras. Por ejemplo, Severo y Tomaselli (2000), implementaron un sistema de vaporizado en trozas de eucalipto en Brasil por un periodo de 24 horas y encontraron que las tensiones se reducen en un 50% en relación con trozas que no han recibido el tratamiento de vapor.

En el secado de la madera, la aplicación de vapor a madera aserrada previo el proceso de secado es también una alternativa ampliamente utilizada para reducir la liberación de las tensiones de crecimiento, lo que se traduce en una disminución de defectos como torceduras o encorvaduras (Severo et al., 2010). Al respecto, Rodríguez et al. (2018) aplicaron vapor de agua a madera aserrada de eucalipto por 24 horas y fue encontrada una reducción de los defectos de secado.

Otra forma muy efectiva de reducir los defectos durante el secado de la madera es colocar tornillos sin fin con platinas que atraviesan de lado a lado la pila de madera y luego, diariamente realizar ajustes con la ayuda de tuercas en los tornillos con el fin de mantener presionadas las tablas para evitar la formación de torceduras en la madera. Este sistema fue aplicado por Berrocal et al. (2017) durante el secado de madera aserrada de teca y fue encontrado que se disminuye la presencia de defectos de secado en aproximadamente un 50%.

Otro aspecto importante de destacar es que, en Costa Rica, a pesar de tener establecido el mercado para la madera de bosque natural de almendro y pilón, la comercialización de la madera proveniente de plantaciones forestales es muy escasa. Entre las causas que se pueden señalar esta la falta de usos para estas especies, debido a los problemas de calidad que se desarrollan durante los procesos de aserrío y secado. Además, en los últimos 10 años el uso de la madera ha decaído en las construcciones civiles (Serrano y Moya, 2012) debido a su desplazamiento por materiales como el acero y el concreto y por la incursión de otros materiales importados, que vienen respaldados por significativos avances tecnológicos, extensa información técnica y un mercadeo muy agresivo (Fournier, 2008).

En la actualidad la madera está teniendo un auge debido a sus ventajas ecológicas. La madera es el material renovable, sostenible, estético y confortable para diversos usos en el mercado de la construcción (Fournier, 2008). Este aspecto ha permitido que la sociedad costarricense vuelva nuevamente sus ojos hacia la madera como material de construcción y por lo tanto se busquen nuevas condiciones que permitan la introducción de la madera proveniente de plantaciones forestales en el mercado. Pero para esto es necesario que en especies como almendro y pilón se trabaje en el desarrollo de procesos tecnológicos en aspectos de transformación, secado y elaboración de productos de valor agregado. De forma que el objetivo de este proyecto de investigación fue mejorar las condiciones procesamiento primario y de secado por medio de la aplicación de calor y vapor a trozas y madera aserrada, y establecer los valores de resistencia estructural de madera aserrada y vigas laminadas de almendro y pilón provenientes de plantaciones forestales de Costa Rica.

5. ARTÍCULOS CIENTÍFICOS:

Artículo 1: Steaming and heating *Dipteryx panamensis* logs from fast-grown plantations: reduction of growth strain and effects on quality

Steaming and Heating *Dipteryx panamensis* Logs from Fast-Grown Plantations: Reduction of Growth Strain and Effects on Quality

Roger Moya
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Abstract

Steaming and heating as pretreatments before log sawing reduce the negative effects of growth strain (GS). The object of this work was to study the reduction of GS in logs of *Dipteryx panamensis* from a fast-growth plantation using steaming and heating treatments and evaluate the effects on the lumber quality. According to the results, the maximum temperature in the center of the log was approximately 90°C after 24 hours for both treatments. GS decreased after heating and steaming. The average value of GS for three treatments was 2,085.61 microdeformation units (με) before the treatment, decreasing to average value to1,692.14 με after the treatments. This reduction in turn produced a reduction of crook due to sawing measured in logs and semilogs and a decrease in the values and incidence of crook, bow, twist, and split. Similarly, color parameters (L*, a*, and b*) were statistically affected by the treatment, except for parameter L* in sapwood. In general, wood darkening was observed. Lastly, both treatments applied to *D. panamensis* logs showed few differences in GS, in crook due to sawing measured in logs and semilogs, and in the values and incidence of crook, bow, twist, and split. Therefore, both treatments achieved GS reduction in *D. panamensis* lumber.

Growth strain (GS) in trees has been widely studied concerning its causes (Archer 1987) and management applied to the trees (Kubler 1988). GS is related to mechanical strain permanently borne by the wood of the living tree while it is growing (Gril et al. 2017). GS is 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 fibers tend to deform in the axial and transversal directions, although these dimensional changes are limited by the already-formed xylem (Archer 1987). Then, the restraint induces a mechanical stress at the outermost surface of the secondary xylem, located beneath the layer of differentiating xylem. It provokes in the older xylem, during each growth increment, a counteractive stress distribution which is superimposed on the preexisting stress (Gril et al. 2017). When GS is measured on the outer surface of the trunk it is called ''longitudinal surface growth strain'' (LGS; Nicholson 1971, Yang et al. 2005).

GS is present in most species (Archer 1987), particularly in fast-growing species in forest plantations, in which GSs are stronger, and which tend to present GS more frequently (Kojima et al. 2009). When the log is sawn, GS becomes evident in the form of warps (crook, bowing, and twisting), splits, and checks in the boards (Entwistle et al. 2016). The magnitude of these defects depends on the species, but it can result in considerable economic losses for foresters and sawmills (Gril et al. 2017).

Different log treatments have been implemented to reduce the effect of GS and thus increase the quality of the lumber (Archer 1987, Kubler 1988, Yang and Waugh 2001, Ratnasinga et al. 2013, Gril et al. 2017). GS relaxation occurs at high temperatures induced by boiling, steaming, and smoking applications on logs (Tejada et al. 1997, Nogi et al. 2003, Severo et al. 2010, Pelozzi et al. 2014, Rodrigues et al. 2018). Direct heat and steaming soften the physical structure of the material as the wood reaches the

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glass transition temperature (Lenth and Kamke 2001, Pelozzi et al. 2014, Li et al. 2020). When the wood reaches this temperature, its polymers are softened, molecular rearrangement and microstructure of the material occurs, and consequently internal strains are released (Nogi et al. 2003, Gril et al. 2017, Rodrigues et al. 2018). The temperature (80°C to 140°C) produces softening of the cellulose and the matrix that forms lignin and hemicelluloses (Salmén 1984, Kelley et al. 1987). During softening, the lignin along and across the fiber direction is shown to be related to the stiffening effect of the cellulose microfibrils preferentially aligned along the fiber (Salmén 1984). Therefore, this softening alleviates the internal strain through the molecular and microstructural reorganization of the wood (Nogi et al. 2003, Gril et al. 2017, Rodrigues et al. 2018, Li et al. 2020).

Moreover, 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). Fast-growing species with rotation periods of less than 25 years, such as *Dipteryx panamensis* (Almendro), show excellent growth and yields in forest plantations (Delgado et al. 2003, Redondo-Brenes and Montagnini 2006, León et al. 2017). *Dipteryx panamensis* wood presents specify gravity of 0.7 to 08; its porosity is diffuse–porous, stored rays and axial parenchyma are vasicentric, confluent, aliform, lozenge–aliform, and winged-aliform (Moya et al. 2019). Recent research regarding wood quality of this species (Moya and Muñoz 2010; Moya et al. 2011, 2019; Tenorio et al. 2016a, 2016b) showed two types of problems: (1) problems in the primary sawing process and (2) high incidence of wood warping during the drying process.

These problems owe to high GS incidence in logs extracted from plantation trees, therefore warps, checks, and splits are frequent in the boards obtained from the sawing process. Added to this, the drying process accentuates the warps, producing very low-quality lumber (Moya et al. 2013, 2019; Tenorio et al. 2016b).

Few studies on tropical species and on forest plantation species (Gilbero et al. 2019) have quantified the reduction of GS obtained by applying heat or steam treatments to the logs, and how these treatments influence the quality of wood in species in forest plantations. Therefore, the present work aims to study the LGS in sawlogs of *D. panamensis* from fast-growing plantations under heat and steam treatments for 24 hours at 115°C; then, evaluate the effects of those treatments on the quality of the lumber (incidence of warps, checks, and splits) and wood color measured by L*a*b* color systems after log sawing.

Materials and Methods

Site and characteristics of the plantation

Sampling took place in a fast-growth plantation of *D. panamensis* that belongs to the company Reforest the Tropics Inc., located in San Juan Norte, Turrialba, Costa Rica. The site presents moist tropical climate with average annual precipitation of 2,854 mm and a dry season between January and May. The mean annual temperature is 22.9°C. At the time of sampling the plantation was 16 years old. The initial planting density of the plantation was 3 m by 3 m (1,100 trees/ha). At the time of sampling the density of the plantation was 550 *n*/ha.

Tree selection and sampling

Sixty-nine trees were sampled with diameters greater than 13 cm, which corresponded to the minimum diameter for a sawmill (Table 1). For each selected tree, the diameter at breast height and total height were determined and the north–south positions were marked at breast height. A commercial log 2.5 m long and a cross-section 3 cm thick at the base of the tree and at the end of the 2.5-m log were extracted. North and south sides were marked in all logs.

Treatments used to reduce the longitudinal growth strain and increase the quality of lumber

Two treatments were used to reduce the LGS and increase lumber quality: (1) heating, in which the logs were heated for 24 hours at 115°C and (2) steaming, in which the logs were steamed for 24 hours at 70 Pa and where the temperature reached 115°C. Untreated samples (without heating or steaming) were used for comparison.

During heating and steaming, the logs were placed inside a horizontal tank measuring 60 cm diameter and 3 m long, with a 4- to 6-log capacity (Fig. 1a). For heating, three 1,000-W cartridge heaters were placed in the lower part of the tank. For steaming, two sprayer lines were placed 180° one from the other, to allow steam supply at 8 kg/cm^3, 4 L/min, and 115°C temperature.

Parameters measured during the heating and steaming treatments

Moisture content (MC), LGS, 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 the base of the tree and at 2.5 m tree height. The cross-sections were cut into six radial slices and three of them were chosen to measure the MC, according to the ASTM D-4442-07 standard (ASTM International 2016). The LGS was determined in all the logs before (LGS_{before} and after (LGS_{after}) the heating and steaming and in the untreated logs. The measurements were again performed on the north and south sides, at half the length. The LGS in each side of the logs was measured according to the methodology proposed by Nicholson (Nicholson 1971). This method involves removing an area of the bark (Fig. 1b), placing two Phillips screws with gauge separation, and determining the gauge separation (called initial length) with the help of an extensometer (Hugenberger tensotast). Then, two cuts were made at 6 mm from the point where the screws were placed and 2 minutes later this distance between the points was measured again; this was the final length. Because the fibers of the surface area of the tree or log were under tension, the screw heads tended to get closer after the knife cuts were made. The difference or

Table 1.—Dasometric conditions of Dipteryx panamensis *trees used in heating and steaming treatments of sawlogs.*

Treatment of sawlogs	Diameter at breast height (cm)	Total height (m)	Sampled trees
Heating	14.77 (13.0–18.0)[a]	15.24 (9.3–18.6)	28
Steaming	15.07 (13.0–20.1)	16.75 (2.6–19.4)	21
Untreated	16.29 (12.8–19.0)	15.61 (14.0–20.5)	20

[a] The values in parenthesis correspond to minimum and maximum values.

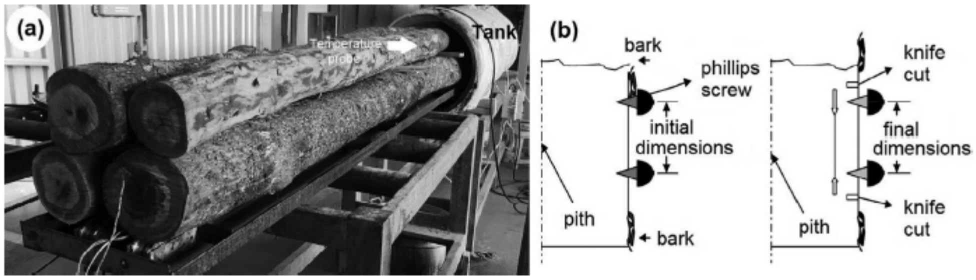

Figure 1.—Horizontal tank for steam and heat application to sawlog (a) and Longitudinal surface growth strain representation of center deflection measuring of microstrain by knife cut (b).

dimensional change of the final length relative to the initial length was expressed in microdeformation units (με; Eq. 1), which represents the LGS (in με).

$$\text{Longitudinal surface growth strain (LGS) in } \mu\varepsilon = (\text{initial distance} - \text{final distance}) * 20 \quad (1)$$

The temperature variation was obtained by introducing a probe into three of the four to six logs placed inside the tank, to determine the log's inside temperature. The probe was inserted to half the diameter and at the central area of the log (Fig. 1a). The temperature was monitored in the center of log with the objective of knowing the variation of temperature and the maximum temperature in the center of the log. The temperature was monitored every 5 minutes and the probes were connected to a Testo datalogger, model 177-T175 (Testo SE & Co. KGaA, Titisee-Neustadt, Germany), to record the data. The data temperature collections were used for determination of temperature and time of stabilization. The scatterplot graph between time and temperature was done and where temperature change was low or approximately 1°C, the stabilization was established.

Sawing pattern and crook due to sawing

The logs were sawn using a typical pattern for producing lumber in Costa Rica (Serrano and Moya 2011). Semilogs were obtained and then sawn into 2.5-cm boards. Sawing was done using a band saw and a single-cut resawing saw. The cutting pattern is shown in Figure 2a, where Cuts 1 and 2 were performed with the band saw, while the block cuts (Cuts 3 and 4) were made with the resawing saw. At the time of making the cuts in the logs and semilogs the crook due to sawing were measured (Fig. 2b and 2c). We tried to take a board from every 10 boards from each treatment (heating, steaming, and untreated) to determine the MC after the treatment. A cross-section was extracted from each chosen board, at 27 cm from the end of the board. MC was determined using standard ASTM D-4442-07 (ASTM International 2016).

Lumber quality and color evaluation

Warp (twist, crook, bow, and cup), check, and split as lumber quality parameters were measured in each board. The methods are detailed in Salas and Moya (2014) and Tenorio et al. (2011). Color was determined for all the boards obtained from the logs in each treatment. Where the boards had sapwood and heartwood, color 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 (Hunter and Harold 1987). The CIE L*a*b* color system estimates the value of three variables: coordinate L* for lightness, representing the position on the black–white axis (L* = 0 for black, L* = 100 for white); coordinate a* for the position on the red–green axis (positive values for red, negative values for green); and coordinate b* for the position on the yellow–blue axis (positive values for yellow, negative values for blue; Hunter and Harold 1995).

Statistical analysis

One-way analysis of variance (ANOVA) was applied to LGS before treatment and LGS after treatment, crook due to sawing, wood color 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 level of significance of $P < 0.01$. The SAS 8.1 statistics program for Windows (SAS Institute Inc., Cary, North Carolina, USA) was used to carry out the analyses.

Results

Temperature variation

Table 2 presents the maximum temperature inside the log and time of the different treatments applied to the logs. Lumber under heating treatment showed a stabilization time and maximum inside temperature lower than lumber under steaming treatment. However, the total time was slightly less than in the steaming (Table 2).

As for variation of the temperature with time inside the logs, differences were observed between heated and steamed logs (Fig. 3). In logs under steaming the diameter influenced internal heating, as logs with smaller diameter presented higher temperatures for the same period than logs with bigger diameters (Fig. 3b). This behavior was not

Table 2.—Temperature variation in heating and steaming for Dipteryx panamensis *logs from a fast-growth plantation.*

Parameters	Heating	Steaming	Average for two treatments
Stabilization time (h)	20.844	23.382	22.500
Maximum temperature reached (°C)	89.00	91.00	90.00
Total time of treatment (h)	26.889	25.278	26.083

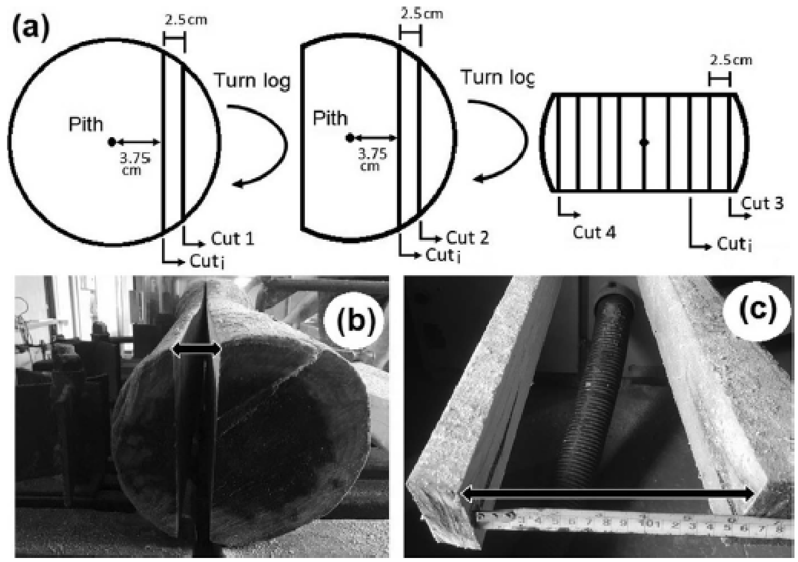

Figure 2.—Sawing pattern utilized in un-treated and heating and steaming for Dipteryx panamensis *logs from a fast-growth plantation (a); crook due to sawing in sawlogs, (b) and crook due to sawing in semi-logs (c).*

observed regarding heating, as small and big diameters presented similar behavior with little internal temperature variation among them (Fig. 3a).

LGS and crook due to sawing

With regard to the effect of the treatment on the LGS of logs before sawing, the ANOVA showed that the log treatment was not statistically significant between in LGS_{before} and LGS_{after} (Table 3); average value of LGS_{before} for three treatments was 2,085.61 με and average value of LGS_{after} was 1,692.14 με for all treatments (Fig. 4a). On the other hand, as expected, the values of LGS were lower in logs after treatment (Fig. 4a).

Regarding the effect of the treatment during log sawing it was statistically significant in the values of crook, meaning that the treatments applied to the logs have an effect relative to untreated logs (Table 3). Figure 4b shows the mean values of crook obtained in logs and in semilogs per treatment. In all cases, untreated logs and semilogs presented the highest values of crook relative to heated and steamed logs. No statistical differences were observed between the logs under heating or steaming treatment (Fig. 4b).

Color evaluation

Color parameters (L*, a*, and b*) for sapwood and heartwood differed. Heartwood presented lower values of L*, higher values of a*, and values of b* similar to those of sapwood (Table 4). As to the effect of the treatment before sawing, most parameters were statistically affected by the treatment, except for parameter L* in sapwood (Table 3). Parameters L* and b* presented values statistically higher for heartwood under heating than untreated and under steaming, while no differences were observed between the latter (Table 4). Parameter a* in wood subjected to heating and steaming treatment showed no statistical differences between them and averages greater than in untreated wood.

There were no differences among treatments regarding parameter L* in sapwood, while parameter a* in untreated wood presented the statistically highest average, followed

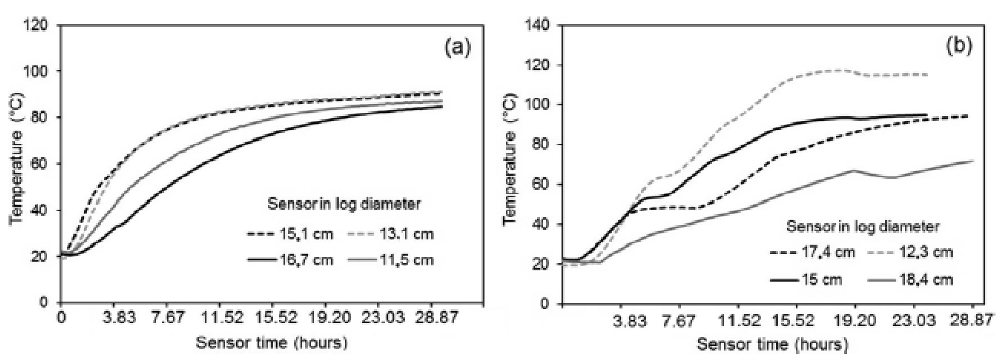

Figure 3.—Temperature variation inside the logs of Dipteryx panamensis *in relation to time for (a) heating and (b) steaming.*

Table 3.—F value of ANOVA for different parameters measured in logs, semilogs and lumber of Dipteryx panamensis.

Parameter	Value[a,b]
LGS before treatment	0.09[a]
LGS after treatment	0.77[a]
Crook in log Side 1	9.85**
Crook in log Side 2	5.76**
Crook in semilog Side 1	11.15**
Crook in semilog Side 2	3.93*
Sapwood color	
L*	1.41[a]
a*	6.50**
b*	8.12**
Heartwood color	
L*	12.62**
a*	8.04**
b*	12.33**
Bow	4.71*
Crook	1.92[a]
Twist	0.92[a]
Check	2.73*
Split	3.00*

[a] Not significant.
[b] * = Statistically significant at 95% ($P < 0.01$); ** = Statistically significant at 95% ($P < 0.05$).

by heat-treated and steam-treated wood. Conversely, parameter b* in untreated wood presented the statistically lowest average, while wood under heating and steaming showed no differences between each other (Table 4).

Lumber quality

Lumber obtained from logs under three different treatments presented three types of warps (bow, crook, and twist), checks, and splits (Table 5; Fig. 5), while cup defects were not present. Incidence of bow defects stood over 85%, crook over 65%; the incidence of twist was around 20% (Table 5) and check and split incidence was over 50% in heating and steaming (Fig. 5b).

The effect of the treatments on the value of the defect was statistically significant only in the case of lumber crook (Table 3), while the differences in the averages showed that the value of bow in untreated lumber were statistically higher, with no statistical differences between heating and steaming (Table 5). As for crook and twist, no statistical differences were observed between the treatments (Table 5).

With respect to the values of checks and splits, the effect of log treatment was statistically significant in both cases (Table 3). The differences in the means indicate that lumber under heating presented statistically lower average crack length, while lumber under steaming showed the highest average crack length and untreated lumber presented no differences relative to the other treatments (Fig. 5a). As for check length, untreated lumber showed the lowest average, while lumbers under heating and steaming presented higher values (Fig. 5a).

Discussion

Steam or heat application contributes to release of LGS in logs (Severo et al. 2010, Pelozzi et al. 2014). Appropriate heating or steaming times soften the structure of the wood (Lenth and Kamke 2001, Pelozzi et al. 2014, Rodrigues et al. 2018) and lessens the LGS altogether (Tejada et al. 1997, Nogi et al. 2003, Severo et al. 2010, Pelozzi et al. 2014, Rodrigues et al. 2018), as was evidenced when the logs of *D. panamensis* were steamed or heated and LGS showed significant reduction after the treatments (Fig. 4a).

The reduction of LGS after steaming or heating (Figure 4a) indicates that the temperature reached in the center of the log during these two treatments, approximately 90°C (Table 2), allows reaching the glass transition temperature, which in many species varies from 80°C to 100°C (Kelley et al. 1987, Kong et al. 2017). The temperature achieved by heating and steaming produce softening of the cellulose and the matrix that forms lignin and hemicelluloses (Salmén 1984, Kelley et al. 1987). Lignin found in the middle lamina and in layer S2 is thermoplastic (Salmén 1984); i.e., it softens at the appropriate temperature (Lenth and Kamke 2001, Pelozzi et al. 2014). Therefore, this softening alleviates the internal strain through the molecular and microstructural reorganization of the wood (Nogi et al. 2003, Gril et al. 2017, Rodrigues et al. 2018).

A source of variation affecting the log's internal temperature and therefore the possibility of reaching the glass transition temperature is log diameter, in particular in logs under steaming (Fig. 3b). In heating, the set target temperature of the tank was 115°C; however, after 24 hours, the internal temperature of the log increased faster in logs with smaller diameters and slower in those with bigger

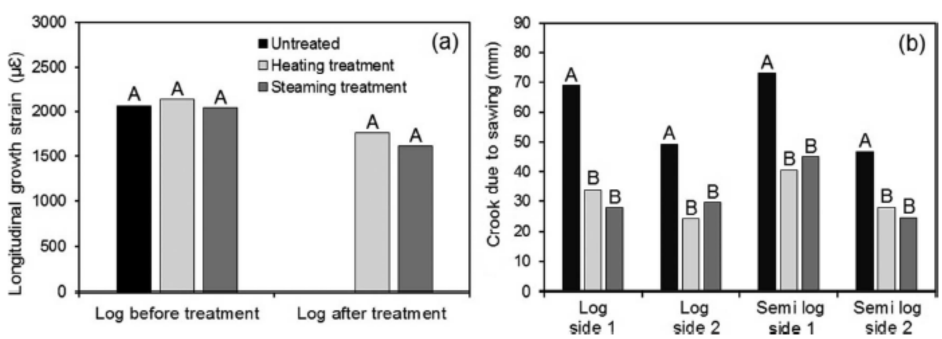

Figure 4.—(a) Longitudinal surface growth strain and (b) crook measured in logs and semilogs of Dipteryx panamensis *wood from a fast-growth plantation under different treatments. Different letters between treatments mean that there are statistical differences ($P < 0.05$) between log treatments.*

Table 4.—Color parameters measured in Dipteryx panamensis *lumber from a fast-growth plantation under different treatments.*

Treatment	Color parameters in heartwood			Color parameters in sapwood		
	L*	a*	b*	L*	a*	b*
Untreated	51.05 B (14.73)[a,b]	8.23 B (31.36)	24.00 B (20.49)	75.66 A (8.64)	6.30 A (45.17)	24.09 B (18.05)
Heating	56.88 A (14.01)	9.48 A (25.22)	27.56 A (17.68)	74.62 A (6.02)	5.76 AB (24.77)	25.90 A (6.81)
Steaming	53.13 B (10.23)	9.88 A (21.65)	25.04 B (13.37)	74.08 A (6.03)	5.00 B (23.87)	25.73 A (8.42)

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

diameters, but after 21 hours all the logs reached approximately 89°C (Fig. 3a). Meanwhile, in the steaming, logs with smaller diameters reached temperatures close to the target and medium sized logs reached close to 89°C, while logs with bigger diameters reached only 70°C internal temperature after 24 hours (Fig. 3b).

As said, the glass transition temperature of the wood varies from 80°C to 100°C, releasing LGS (Kong et al. 2017). Since *D. panamensis* logs under heating and small-diameter logs under steaming reach a temperature range of 80°C to 90°C, it means the glass transition was achieved. As a result, LGS parameters were reduced in 25%, as shown by the reduction of crook (Fig. 4) and of the magnitude of bow (Table 5; Fig. 5c).

In logs that reach the adequate glass transition temperature such as logs under the heating treatment and smaller logs under steaming, softening of the cellulose and the matrix that forms the lignin (Lenth and Kamke 2001, Pelozzi et al. 2014) and the hemicellulose (Kelley et al. 1987, Kong et al. 2017) occurs. This softening alleviates the internal strain through the molecular and microstructural reorganization of the wood (Nogi et al. 2003; Gril et al. 2017; Rodrigues et al. 2018). Stress relief produces warp reduction during sawing, as observed in crook in lumber of *D. panamensis* in the present study (Fig. 4; Table 5).

Heating and steaming treatments are used to reduce LGS (Tejada et al. 1997; Nogi et al. 2003; Severo et al. 2010; Pelozzi et al. 2014; Rodrigues et al. 2018), as evidenced in the present study (Fig. 4a). However, these two treatments showed few differences regarding *D. panamensis* lumber. The values of LGS (Fig. 4a), crook measured in logs and semilogs (Fig. 4b), color parameter a* in heartwood, the three color parameters in sapwood (Table 4), and values and incidence of crook, bow, twist, and split (Table 5; Figs. 5a and 5b) presented no differences between heating and steaming. Differences were only observed in color parameters L* and b* in heartwood (Table 4), and less presence of checks in lumber under the heating (Fig. 5a).

The above results indicate that for *D. panamensis* logs, steaming and heating treatments are appropriate for reducing LGS and related parameters, such as incidence of warps, splits and checks, contradicting studies on other species, such as *Hieronyma alchorneoides*, *Hevea brasiliensis* or some Eucalyptus (Severo et al. 2010; Pelozzi et al. 2014), which indicate that the steaming treatment creates better conditions for relaxation of the different polymers that compose wood. This is so because the internal conditions of temperature and moisture inside the chamber in the steaming treatment allow moisture saturation of the environment, improving conditions for polymer relaxation in the logs (Kong et al. 2017). In addition, the crystalline zones of the hemicellulose tend to decrease, increasing the amorphous areas (Kong et al. 2017), which translates into improved conditions for relaxation of the growth strain (Li et al. 2020). However, the steaming treatment did not render the expected results in *D. panamensis* logs, probably because the logs are very thin and quickly reach the glass transition temperature inside in both treatments.

A negative aspect of heating is the loss of moisture of the log, especially at its ends, because the conditions that are created (high temperature and low humidity) cause greater incidence of checks during the sawmill process, as warping problems or additional growth strains problems (Nogi et al. 2001, 2003), as occurred in this work (Fig. 5).

The variation that occurred in the color parameters, mainly in heartwood of lumber coming from steam- and heat-treated logs in relation to wood from untreated logs (Table 4), is attributed to the effect produced by the temperature on the chemical composition (Kocaefe et al. 2008, Salca et al. 2016), specifically the hydrolysis of hemicelluloses and extractives in this type of wood (Salca et al. 2016). The increase in temperature due to steam or heat causes an increase in the white and yellowish hue (increase in L* and b*), specifically in heartwood (Table 4), which is attributed to degradation or modification of the more abundant extractive agents in heartwood, through reactions such as oxidation, dehydration, decarboxylation, and hydrolysis (Kocaefe et al. 2008), and the darkening of lignin, associated with the parameter a* (increase in a*), which is associated with the generation of chromophore

Table 5.—Magnitude and incidence of crook, bow and twist defects in lumber from Dipteryx panamensis *logs from a fast-growth plantation under different treatments.*

Log treatment	Board total	Bow		Crook		Twist	
		Value	Incidence (%)	Value	Incidence (%)	Value	Incidence (%)
Untreated	88	11.88 A (76.82)[a,b]	86.36	9.41 A (69.98)	75.76	2.48 A (69.98)	21.21
Heating	66	11.26 A (79.30)	88.64	7.60 AB (77.62)	67.05	3.58 A (30.90)	20.45
Steaming	57	8.75 A (87.85)	85.96	5.70 B (69.13)	70.18	3.01 A (35.52)	22.81

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

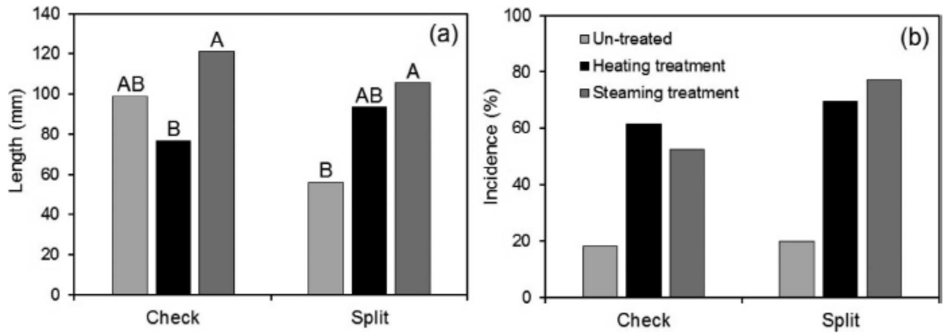

Figure 5.—Length (a) and incidence (b) of check and split defects in Dipteryx panamensis *wood from a fast-growth plantation. Note: Different letters between treatments mean that there are statistical differences (P < 0.05) between log treatments.*

groups (Salca et al. 2016), which causes darker color changes at high temperatures (Table 4).

The values of the parameters L* and b* in heartwood extracted from steam-treated logs surpassed those of -reated lumber (Table 4). This was probably due to slightly higher steaming temperature than heating temperature which results in changes in wood components associated with L* and a* parameters.

Although previous researchers presented different methods for reducing the effects of the presence of GS in trees on wood quality, few have been presented in a tropical commercial wood species with importance in the market, such as *D. panamensis* with its high density and many problems associated with GS. Likewise, this work presents a practical, industrially viable, and economical option to reduce GS, and thus has real effects on wood quality. The reactor (tank) built with steaming or heating applications can be utilized in sawlogs from fast-grown trees from commercial plantations in tropical regions, which have few options for such trees.

Conclusion

LGS diminishs in steam- and heat-treated logs. Quality of the lumber obtained from these logs increases. Specifically, crook due to sawing is reduced in logs and semilogs; there are changes in color parameters and in the value and incidence of warps, splits, and checks in lumber. In both treatments (steaming and heating), the temperature reached probably permitted softening of chemical components, thus promoting LGS diminution. Likewise, both treatments applied to *D. panamensis* logs showed few differences regarding LGS, crook due to sawing measured in logs and semilogs, and in the values and incidence of crook, bow, twist, and split. Therefore, both treatments are appropriate for reducing the LGS and both improve the quality of wood from *D. panamensis*.

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Artículo 2: 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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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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Received: 14 July 2020 / Accepted: 26 July 2021

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 $\mu\varepsilon$ (micro-deformations) before the treatment to 1000 $\mu\varepsilon$ 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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Keywords Log treatment · Warps · Lumber quality · Tropical species · Fast-growth plantation

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)	–

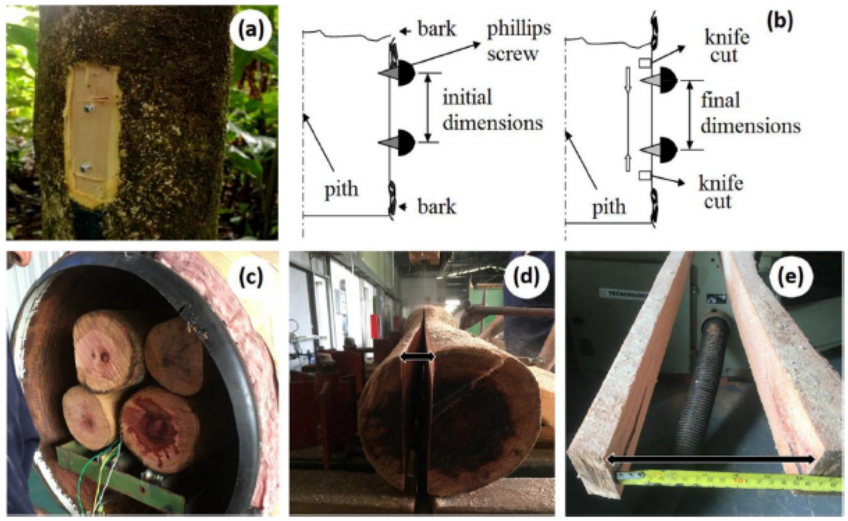


Fig. 1 Longitudinal surface growth residual stresses (LRGS) on the surface of logs or cambial zone measured in a standing tree (**a**), representation diagram of centre deflection measuring of micro-strain by knife cut (**b**), logs located in a steam or heat chamber (**c**), sawlog crooking (**d**)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

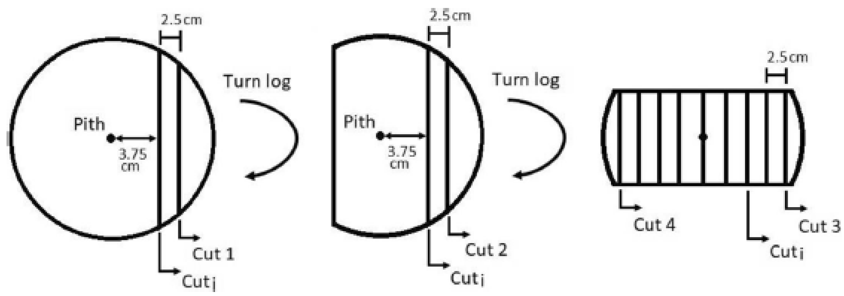
2.6 Crooking due to sawing determination

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 alchornoides* 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

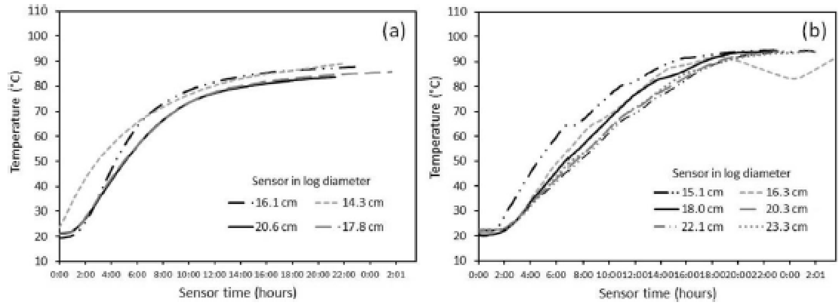


Fig. 3 Temperature variation inside the logs of *Hieronyma alchorneoides* in relation to time for $heating_{treatment}$ (**a**) and $steaming_{treatment}$ (**b**)

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 $LRGS_{stand\text{-}tree}$ and $LRGS_{before\text{-}treatment}$ (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 $LRGS_{after\text{-}treatment}$ at all heights (Table 3); therefore, differences between the treatments evaluated were observed, and logs under the $heating_{treatment}$ 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 $crooking_{due\text{-}to\text{-}sawing}$ obtained in logs and semi-logs according to height and treatment. In the three treatments for logs and semi-logs, the value of $crooking_{due\text{-}to\text{-}sawing}$ side 1 was greater than in $crooking_{due\text{-}to\text{-}sawing}$ side 2. However, a tendency to increase or diminish the value of $crooking_{due\text{-}to\text{-}sawing}$ 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 $crooking_{due\text{-}to\text{-}sawing}$ 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 $crooking_{due\text{-}to\text{-}sawing}$ in logs and semi-logs on side 1 and side 2 at all heights, the $steaming_{treatment}$ presented the lowest values relative to $heating_{treatment}$ and untreated, except for $crooking_{due\text{-}to\text{-}sawing}$ 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

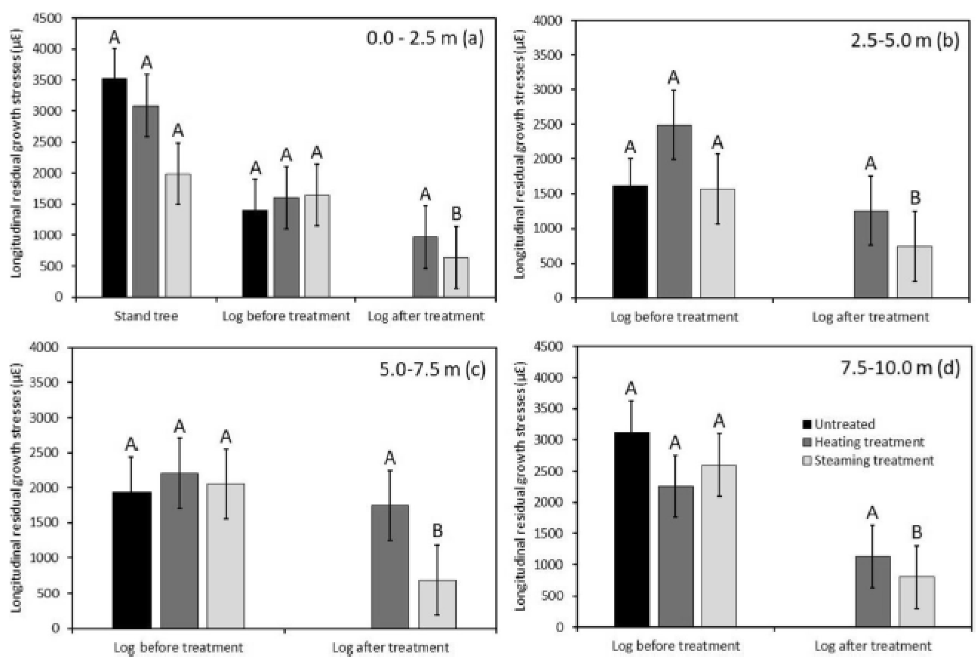


Fig. 4 Longitudinal growth stress per the height of *Hieronyma alchorneoides* wood from the fast-growth plantation

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 heating$_{treatment}$ and steaming$_{treatment}$ 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 heating$_{treatment}$ and steaming$_{treatment}$ (Table 5). As for parameter a* of heartwood, the steaming$_{treatment}$ wood presented the statistically highest values for most of the heights, followed by heating$_{treatment}$ 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 heating$_{treatment}$ and steaming$_{treatment}$. 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 heating$_{treatment}$ and steaming$_{treatment}$. At most heights, no differences were observed between heating$_{treatment}$ and steaming$_{treatment}$ 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 heating$_{treatment}$ and steaming$_{treatment}$ (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 heating$_{treatment}$ and steaming$_{treatment}$ (Table 6). On the other hand, the lumber with treatments heating$_{treatment}$ or steaming$_{treatment}$ 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 heating$_{treatment}$ and steaming$_{treatment}$ 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)
	Heating$_{treatment}$	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)
	Steaming$_{treatment}$	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)
	Heating$_{treatment}$	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)
	Steaming$_{treatment}$	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)
	Heating$_{treatment}$	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)
	Steaming$_{treatment}$	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)
	Heating$_{treatment}$	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)
	Steaming$_{treatment}$	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
	Heating$_{treatment}$	36	11.8^{B} (53.9)	72.2	6.5^{A} (35.2)	97.2	2.0^{A} (50.2)	11.1
	Steaming$_{treatment}$	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
	Heating$_{treatment}$	29	10.4^{B} (82.4)	86.2	6.2^{A} (48.3)	86.2	0.9^{B} (101.9)	13.8
	Steaming$_{treatment}$	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
	Heating$_{treatment}$	16	11.1^{B} (65.1)	81.3	5.2^{B} (44.1)	100.0	1.7^{A} (60.4)	12.5
	Steaming$_{treatment}$	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
	Heating$_{treatment}$	13	14.4^{B} (56.4)	84.6	3.8^{B} (42.2)	69.2	1.5^{B} (68.6)	30.8
	Steaming$_{treatment}$	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)

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

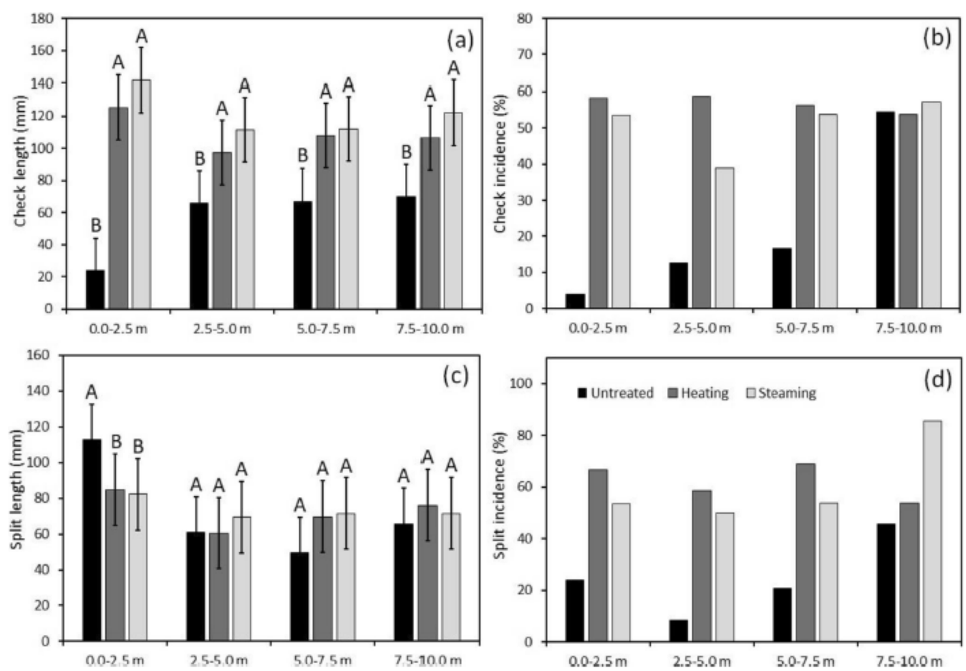


Fig. 5 Length and incidence of check and split defects per height in *Hieronyma alchorneoides* wood from the fast-growth plantation

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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Artículo 3: Application of the steaming step during kiln drying of lumber of two tropical species with high growth stress presence

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Application of the steaming step during kiln drying of lumber of two tropical species with high growth stress presence

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ABSTRACT
The relaxation of growth stress in trees from plantation forests of tropical areas is manifested in the quality of wood after the sawing and the relaxation of drying stress is expressed during the drying process, producing low wood quality. The present study aims to evaluate the lumber quality in logs by heating and steaming application before sawing as pretreatment to reduce growth stress and the application of steaming step during drying of *Dipteryx panamensis* (almendro) and *Hieronyma alchorneoides* (pilón) wood. The results showed that the variation of moisture content and drying rate concerning drying time in wood from logs steamed before or during drying led to a quick increase in the drying rate and a decrease in the moisture content. The steaming application to the logs or during drying decreased the incidence and magnitude of drying defects and increased the quality of dried lumber, especially bow, split, crook, and check defects.

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Drying defects; tropical wood; log treatment; drying improvement

Introduction

One of the main problems of trees from fast-growth plantations is that the logs extracted from them show a high manifestation of growth stress,[1] which is evidenced during the sawing process and they are manifested in warps, log split, and checks. Besides, the moisture gradients and intensity of drying stress are accentuated during the drying process, thereby producing low-quality dried lumber.[2–4] Then, lumber quality can be attributed to two aspects: growth stress and drying stress.

The effect of growth stress on log-processing has been extensively studied.[5–7] Growth stress refers to the mechanical stress permanently endured by the wood of the living tree during its growth.[6] The magnitude of these defects depends on the species and can result in considerable economic losses for the forester and sawyer.[6] Different treatments on logs and lumber have been implemented to enhance lumber quality and diminish the effect of growth stress.[5,8] As such, the application of heat and steam are techniques that reduce growth stress during the sawing or drying process.[9,10] Both processes have been applied to a wide variety of purposes, besides reducing growth stress levels, such as changing color, improving dimensional stability, increasing permeability, improving drying rate, and reducing the initial moisture content and drying defects.[8,11,12]

There are two noteworthy phenomena during drying: the movement of heat occurs from the surface of the boards toward the inside of it, while the movement of moisture occurs in the opposite direction from the inside to the external of boards, resulting in the surface of the piece of wood being drier on the inside, thus causing drying stress due to the shrinkage difference.[8,11] Then, the drying stress is manifested during drying as defects called checks, splits, casehardening, and honeycombing. An alternative to reducing the frequency and intensity of drying defects is to follow a suitable kiln schedule or to apply one or more steaming steps during oven drying.[11,12]

Temperature and steaming application allow softening of the physical structure of wood because reaching the glass transition temperature.[9,13] When the wood reaches this temperature, its polymers are softened, and thus, molecular rearrangement and microstructure of the material occurs and consequently the relief of internal stresses.[6,10]

Specifically, during drying, the application of steaming improves wood permeability due to (1) increased permeability of the warts layer and accessibility to the S3 layer from the cell wall; (2) acid

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hydrolysis of the chemical components of the cell walls; (3) mobilization and partial removal of extractives during steaming, which allows greater access of water molecules to the cell walls, thus, resulting in faster radial and tangential diffusion during wood drying.[10,14] In addition, there is an increase in the diffusion coefficient of water within the wood, thus, preventing the occurrence of dried-lumber defects.[9,10,15]

Conversely, several tropical species have acquired importance in commercial reforestation based on the knowledge of their genetics, reproduction, and plantation management in Costa Rica.[16] Fast-growing species (with rotation periods of less than 25 years), such as *Dipteryx panamensis* and *Hieronyma alchorneoides* have excellent growth and production in forest plantations.[17] Further, recent studies on these species in relation to the quality of wood indicate two types of problems:[2,3,18] (i) during the sawing process and (ii) high incidence of drying defects after the drying process.

Very few studies have examined tropical species where the effect of the application of heat and steam a priori in logs on the quality of wood after sawing processing or during drying the process is evaluated for relaxing growth stress and drying stress, respectively. Thus, the present work aims to evaluate the effect on the quality of dried lumber after the application of two treatments on logs (heating and steaming treatments) and the use of steam application during the drying process, of *Dipteryx panamensis* and *Hieronyma alchorneoides* wood from forest plantations trees.

Materials and methods

Site and plantation characteristics

Two fast-growth plantations of *Hieronyma alchorneoides* and *Dipteryx panamensis* were sampled. The *H. alchorneoides* plantation was 12-year old and had a density of 450 trees/ha at the time of sampling; the *D. panamensis* plantation was 16-year old with a 550 trees/ha density. Moya et al.[19] provide more details on the conditions of the plantations.

Sampling and sawing of trees

Trees of *H. alchorneoides* and *D. panamensis* close to the average diameter at breast height of each plantation, with 19.6 cm and 15.5 cm respectively, which showed little stem deformation, were sampled. Logs were sawn using a cutting pattern typical for lumber production in Costa Rica, where a semilog was obtained, sawn into 2.5 cm thick boards and the boards obtained with sewing patterns are mostly tangential sawn patterns. The sawing was carried out using a band saw and a single blade re-saw.

Treatments used for the relaxation of growth stress in logs

Two treatments were used on the logs with the objective of relaxing growth stress and so increasing lumber quality: (1) application of a temperature of 115 °C for 24 h ($Log_{heating}$) and (2) application of steam for 24 h at a pressure of 70 Pa ($Log_{steaming}$). As a complement and comparison, logs without heating or steaming were used ($Log_{un\text{-}treated}$). In both treatments, 4–6 logs were placed inside a horizontal tank. Moya et al.[19] provide the tank description and conditions of application for heat and steam in extensive detail.

Treatment for the relaxation of drying stress during the drying process

The drying schedules detailed in Table 1 were used to relax the drying stress in sawn-lumber. These schedules were developed by Moya et al.[2] for each species. The time for equalization and conditioning was 4 h for each.

The drying wood testing was performed in a conventional kiln with a 2 m^3 capacity pilot chamber (NARDI, Italy) using an electrical power source to heat the resistance inside the chamber. Step steam application for relaxation of drying stress during the drying process was used on the sawn-wood of both species and these methods have yielded good results in other timber from Costa Rican forest plantations[20,21] (Figure 1). As a complement and comparison, a treatment without steaming was used.

The treatments used on the logs and during drying to enhance wood quality are detailed in Figure 1b and as follows: $Drying_{steam}$ and $Drying_{un\text{-}steam}$: the green lumber was stacked in packages of 10 wide boards and 30 tall pieces, obtaining 300 pieces per drying charge. Cross-sectional pieces of 2.5 × 2.5 cm were used as stickers between the layers. When the stacking reached a height of 10–12 rows, a board was placed, which at the time of steaming during drying formed a totally closed box with the help of double-lined walls and internally filled with fiberglass as insulation (Figure 1). The steaming process was applied in the schedule when the MC reached 40% for 24 h in both species (Table 1). The applied steam was produced by a hermetically sealed water storage tank (Figure 1), which was heated with liquefied propane gas (LPG)

Table 1. Drying schedule utilized in lumber from steaming and heating treatments applied to logs of *D. panamensis* and *H. alchorneoides*.

Specie	Stage	DBT (°C)	WBT (°C)	EMC (%)	RH (%)	MC (%)
D. panamensis	Heating	37	–	–	–	–
	Drying before steaming	40	37	15.8	82	Green
		44	38	11.5	68	40
	Steaming (24 h)	44	–	20	100	40
	Drying after steaming	46	38	9.7	60	30
		48	38	8.4	53	20
		50	38	7.4	47	15
	Equalization	50	42	10	62	–
	Conditioning	50	46	14	79	–
H. alchorneoides	Heating	40	–	–	–	–
	Drying before steaming	40	37	14.8	82	Green
		40	35	12.5	72	40
	Steaming (24 h)	40	–	20	100	40
	Drying after steaming	45	37	9.7	60	30
		50	40	7.9	55	25
		55	42	6.2	47	20
		55	37	5.0	33	15
	Equalization	55	47	10	64	–
	Conditioning	55	51	15	81	–

Note: DBT: dry bulb temperature; WBT: wet bulb temperature; EMC: equilibrium moisture content; RH: relative humidity; MC: moisture content.

(b)

Log treatment	Dry treatment	
Heating ($Log_{heating}$)	Steam	($Drying_{steam}$)
	Un-steam	($Drying_{un\text{-}treated}$)
Steaming ($Log_{steaming}$)	Steam	($Drying_{steam}$)
	Un-steam	($Drying_{un\text{-}treated}$)
Un-treated ($Log_{un\text{-}treated}$)	Steam	($Drying_{steam}$)
	Un-steam	($Drying_{un\text{-}treated}$)

Figure 1. (a) Chamber for steaming process fabricated into kiln chamber with steam production by water heated with LPG. (b) Treatments applied to sawn timber of *D. panamensis* and *H. alchorneoides*, with abbreviations. Source: Moya et al.[20]

generating steam at 115 °C at a pressure of 478 Pa. This steam application procedure is detailed in the study conducted by Moya et al.[20] Lumber inside the chamber and receiving steam during drying is the $Drying_{steam}$ and lumber under the box is the $Drying_{un\text{-}steam}$ treatment.

Moisture control

The moisture content (MC) of wood was determined before and after drying and the variation of MC with drying time was monitored using control kiln samples. For MC before drying, named initial MC (IMC), a cross-section of 2.5 cm thick to 20 cm of the end was extracted from kiln samples[22] and was determined according to ASTM-4442-07 standard.[23] After kiln samples were placed at different heights in the package in the drying chamber according to log and drying treatment, they were weighed twice per day for MC variation and to establish the change in the schedule (steps) applied (Table 1). For the final MC (FMC), again, a cross-section of 2.5 cm thick was extracted from each board after drying and MC was measured using the ASTM-4442-07 standard.[23] The average values for IMC and FMC for these six samples were used to determine the average drying rate for each treatment (6 samples × 3 treatment =18 samples), resulting in moisture loss in percentage determined by Equation (1).

$$\text{Average drying rate}\,(\%/\text{h}) = (\text{IMC} - \text{FMC})/\text{Total drying time(h)} \quad (1)$$

Wood color change

The board color was measured before and after the drying process at the same point on a longitudinal

Table 2. Limits values for classification of drying defects and classification of drying quality according to drying defects utilized in the *D. panamensis* and *H. alchorneoides* dried-lumber.

Drying defects	Limits of quality	Drying quality	Limits of dried-lumber quality index
Cup	not present: 0 mm, slight: 1–3 mm, moderate: 3–5 mm severe: > to 5 mm	Excellent	0.0
Bow	not present: 0 mm, slight: 1–3 mm, moderate: 3–6 mm severe: > to 6 mm	Very good	0.1–0.5
Crook	not present: 0 mm, slight: 1–2 mm, moderate: 2–3 mm severe: > to 3 mm	Good	0.51–1.0
Twist	not present: 0 mm, slight: 1–5 mm, moderate: 5–8 mm severe: > to 8 mm	Satisfactory	1.1–1.5
Checks	not present: 0 mm, slight: 1–10 mm, moderate: 10–25 mm, severe: > to 25 mm	Regular	1.51–2.0
Splits	not present: 0 mm, slight: 1–25 mm, moderate: 25–42 mm, severe: > to 42 mm	Defective	2.1–3.0
		Poor	3.1–5.0
		Very poor	>5.0

Source: Kauman and Mittak.[25]

Table 3. Drying variables for *D. panamensis* and *H. alchorneoides* lumber from different log treatments and with and without steam application during drying.

Specie	Log treatment	Drying treatment	IMC (%)	FMC (%)	Drying rate (%/hours)
D. panamensis	$Log_{heating}$	$Drying_{steam}$	42.3	9.6	0.21
		$Drying_{un\text{-}steam}$	37.3	9.5	0.14
	$Log_{steaming}$	$Drying_{steam}$	41.0	9.6	0.16
		$Drying_{un\text{-}steam}$	46.0	9.7	0.18
	$Log_{un\text{-}treated}$	$Drying_{steam}$	48.9	9.4	0.13
		$Drying_{un\text{-}steam}$	47.8	9.6	0.19
H. alchorneoides	$Log_{heating}$	$Drying_{steam}$	67.1	10.7	0.31
		$Drying_{un\text{-}steam}$	73.6	10.6	0.34
	$Log_{steaming}$	$Drying_{steam}$	112.5	10.2	0.54
		$Drying_{un\text{-}steam}$	138.3	12.3	0.66
	$Log_{un\text{-}treated}$	$Drying_{steam}$	111.6	12.2	0.52
		$Drying_{un\text{-}steam}$	111.3	11.6	0.52

Legend: IMC: initial moisture content; FMC: final moisture content.

surface. Measures were taken in both heartwood and sapwood. The color was measured using a HunterLab Mini Scan XE Plus spectrophotometer. The CIEL*a*b* system was used to measure the reflectance spectra. The spectral range was between 400 and 700 nm, with an 11 mm opening at the measurement point. After drying, the color was re-measured in the same selected area, to obtain the values of the color change (ΔE^*). Detailed information on the color measurement conditions and ΔE^* determination are described in Tenorio et al.[3]

Evaluation of drying defects

The defects were measured before and after drying and the parameters evaluated were warp (twist, crook, bow, and cup), splits, and checks. The methodologies detailed in Tenorio et al.[24] were used to evaluate all the drying defects. Concerning quality assessment, each defect was analyzed based on an index of quality after drying (IQ_{after}).

The official Chilean standard Nch993EO72 was used to determine IQ_{after}, which was computed for the twist, crook, cup, bow, check and split according to Equation (2).[3] The values close to 0 in this index mean the lower presence of defects and values close to 5 indicate higher presences of defects. This standard sets limit quality values for the different parameters (Table 2). For splits and checks, the classification was done according to American Softwood Lumber Standard PS20-05[26] which establishes four different categories (Table 2). Finally, dried-lumber index quality was classified using the Kauman and Mittak[25] methodology (Table 2).

$$QI_{after} = \frac{(Na \cdot 0 + Nb \cdot 0.5 + Nc \cdot 2.0 + 2.5 \cdot Nd)}{\text{Total boards dried}} \quad (2)$$

where:
QI_{after} = quality index after drying; Na = number of pieces without any presence of warp; Nb = number of pieces with a slight presence of warp; Nc = number of pieces with a moderate presence of warp; Nd = number of pieces with a severe presence of warp.

Results

Initial and final moisture content, drying time, and drying rate

The IMC, FMC, and drying rate for the two species tested are presented in Table 3. *D. panamensis* lumber presented the following data: IMC varied from 37% to 48%, and lumber from $Log_{Heating}$ and $Log_{Steaming}$ presented lower values than $Log_{un\text{-}tretated}$; FMC ranged 9.6% to 9.6 and drying rate from 0.13%/h to 0.21%/h. Notably, the application of steam during drying

Table 4. The quality index after drying (IQ_{after}) and classification of dried-lumber obtained for log treatment and steam for increasing lumber quality of *D. panamensis* and *H. alchorneoides*.

Specie	Log treatment	Steam application	Bow	Crook	Twist	Cup	Check	Split
D. panamensis	$Log_{heating}$	$Drying_{steam}$	1.52 (Regular)	1.56 (Regular)	0.50 (Good)	0.00 (Excellent)	1.94 (Regular)	1.29 (Satisfactory)
		$Drying_{un\text{-}steam}$	1.53 (Regular)	1.97 (Regular)	0.37 (Very good)	0.00 (Excellent)	1.26 (Satisfactory)	1.55 (Regular)
	$Log_{steaming}$	$Drying_{steam}$	1.75 (Regular)	1.39 (Satisfactory)	0.39 (Very good)	0.00 (Excellent)	1.25 (Satisfactory)	1.53 (Regular)
		$Drying_{un\text{-}steam}$	1.64 (Regular)	1.67 (Regular)	0.28 (Very good)	0.00 (Excellent)	1.36 (Satisfactory)	1.67 (Regular)
	$Log_{un\text{-}treated}$	$Drying_{steam}$	1.63 (Regular)	2.37 (Defective)	0.37 (Very good)	0.00 (Excellent)	0.53 (Good)	0.50 (Very good)
		$Drying_{un\text{-}steam}$	1.38 (Satisfactory)	1.88 (Regular)	0.00 (Excellent)	0.00 (Excellent)	2.08 (Defective)	0.63 (Good)
H. alchorneoides	$Log_{heating}$	$Drying_{steam}$	2.00 (Regular)	2.06 (Defective)	0.71 (Good)	0.35 (Very good)	1.62 (Regular)	1.09 (Good)
		$Drying_{un\text{-}steam}$	1.77 (Regular)	2.47 (Defective)	0.85 (Good)	0.33 (Very good)	1.47 (Satisfactory)	1.37 (Satisfactory)
	$Log_{steaming}$	$Drying_{steam}$	2.05 (Regular)	2.49 (Defective)	0.76 (Good)	0.57 (Good)	1.30 (Satisfactory)	1.63 (Regular)
		$Drying_{un\text{-}steam}$	1.94 (Regular)	2.50 (Defective)	0.71 (Good)	0.62 (Good)	1.14 (Satisfactory)	1.15 (Satisfactory)
	$Log_{un\text{-}treated}$	$Drying_{steam}$	1.96 (Regular)	2.50 (Defective)	0.36 (Very good)	0.38 (Very good)	0.71 (Good)	1.13 (Satisfactory)
		$Drying_{un\text{-}steam}$	1.95 (Regular)	2.37 (Defective)	0.13 (Very good)	0.11 (Very good)	1.32 (Satisfactory)	0.95 (Good)

decreased the drying rate of lumber from $Log_{steaming}$ and $Log_{un\text{-}treated}$, but steaming application increased the drying rate in lumber from $Log_{Heating}$ (Table 4).

For the *H. alchorneoides* lumber, IMC ranged from 67.1% to 138.4%, FMC from 10.2% to 12.3%, and drying rate ranged from 0.31%/h to 0.66%/h (Table 3). Lumber from $Log_{heating}$ had a lower FMC than the other log treatments and lumber from $Log_{steaming}$ had the highest FMC. The steaming application during the drying process did not affect the drying rate of lumber from $Log_{un\text{-}treated}$, while the use of steam decreased the drying rate of lumber $Log_{steaming}$ and $Log_{heating}$ (Table 3).

Variation of moisture content and drying rate in relation to drying time

With respect to the variation of MC with time (Figure 2), *D. panamensis* (with 220 h) and *H. alchorneoides* lumber (with 180 h) showed similar behavior in all treatments. Some changes occurred in three treatments with $Drying_{steam}$ of *D. panamensis*, which showed an increase in MC between 80 h and 100 h (Figure 2a) and 100 h and 120 h in the lumber from $Log_{heating}$ and $Log_{steaming}$ (Figure 2b). In relation to the variation of the drying rate with time, it is observed that for *D. panamensis*, the lumber from $Log_{heating}$ presented a higher drying rate than the other log treatments ($Log_{steaming}$ and $Log_{un\text{-}treated}$) in the first four days of the drying process; the drying rate was found to be lower in the last hours (Figure 2c). A greater variation in the drying rate was observed in the treatments that did not receive steaming during the first six days of the drying process of *H. alchorneoides* lumber (Figure 2d).

Drying defects

The cup defect did not occur in *D. panamensis* lumber from $Log_{heating}$ and $Log_{steaming}$ treatments. After drying, this defect did not occur in lumber from $Drying_{steam}$ and $Drying_{un\text{-}steam}$ (Table 4).

In the classification of dried-lumber by quality using the quality index after drying (IQ_{after}) for *D. panamensis*, it was observed that for cup defect, the lumber was classified as excellent for any type of log treatment or the application (or not) of steaming during drying (Table 4). For bow defect, the wood was classified as fair to satisfactory and it was not observed that steaming during drying increased the IQ_{after} this defect in lumber from any treatment. For crook defect, the steam application only increased the

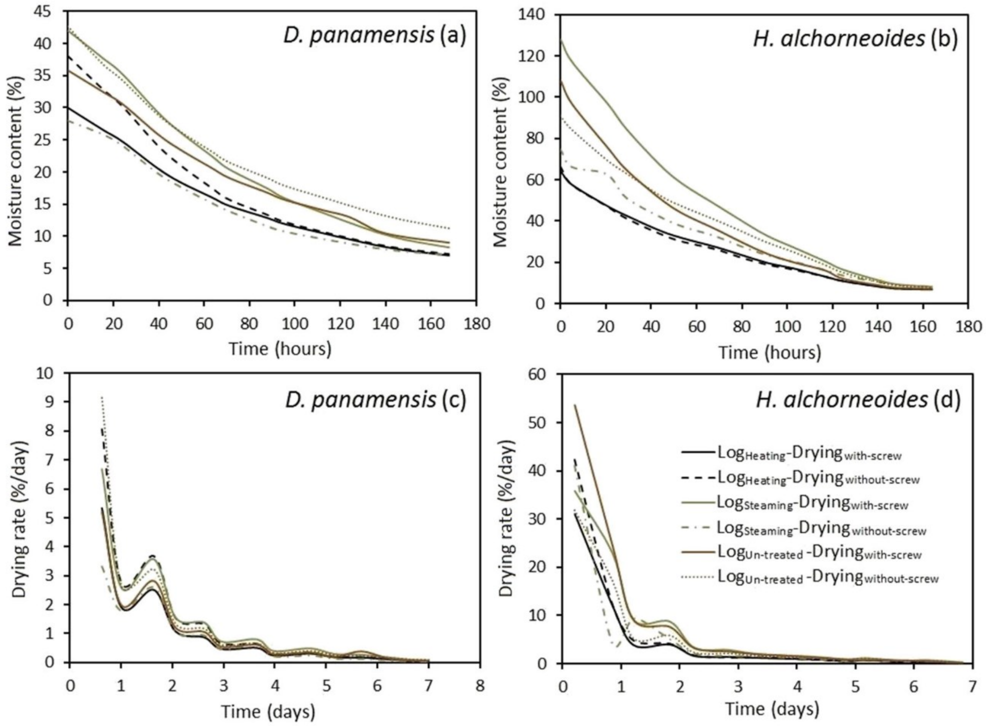

Figure 2. Variation of the moisture content and the drying rate in relation to time for *D. panamensis* (a and c) and *H. alchorneoides* (b and d) lumber with treatment.

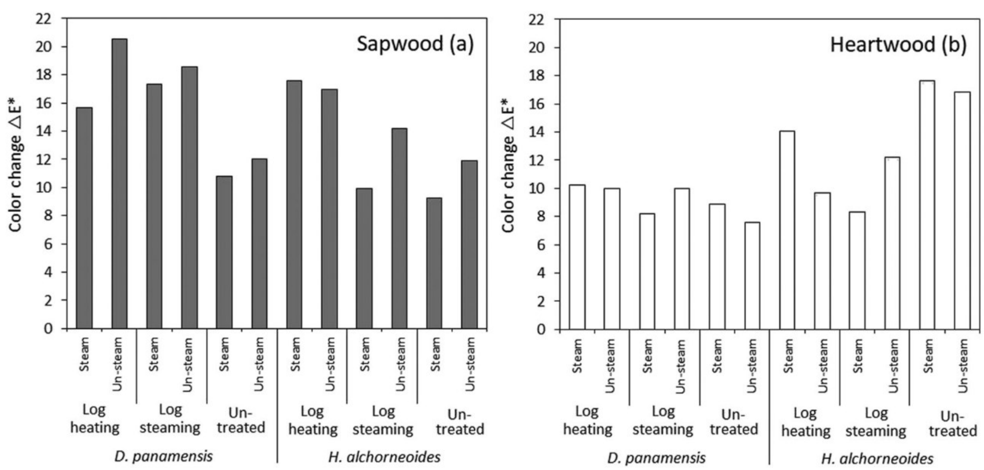

Figure 3. Color change in *D. panamensis* and *H. alchorneoides* lumber from different log treatments with and without steam application during drying.

quality in lumber from $Log_{steaming}$. *D. panamensis* wood in the twist defect is graded superior to good and steaming did not affect lumber from three log treatments (Table 4). Check and split defects did not increase with the application of steaming on drying in lumber from $Log_{heating}$ or $Log_{steaming}$; an increase was only observed in lumber from $Log_{un\text{-}tretated}$ (Table 4).

For the *H. alchorneoides* lumber, IQ_{after} was regular for bow defects, defective for crook defects, good or very good for twist as well as cup defects for the six treatments; wood quality did not improve with the application of steam during drying (Table 4). Most treatments were satisfactory and the split defects ranged from fair to good, but the application of steam in drying increased the quality in check defects in lumber from $Log_{un\text{-}treated}$ and in the split defect in lumber from $Log_{heating}$ (Table 4).

Color change

Color change ($\triangle E^*$) in *D. panamensis* lumber was lower in heartwood than sapwood for all six treatments (Figure 3). The sapwood lumber from $Log_{heating}$ and $Log_{steaming}$ presented a $\triangle E^*$ greater than 12 and the $\triangle E^*$ values in $Log_{un\text{-}treated}$ was lower than this value (Figure 3a). Then, $Log_{heating}$ and $Log_{steaming}$ treatment resulted in a large color change in relation to $Log_{un\text{-}treated}$ in the sapwood. While heartwood presented a $\triangle E^*$ value ranging from 6 to 12. With respect to steam application in the drying process in this species, the steam decreased $\triangle E^*$ in sapwood in all treatments (Figure 3a), then the color change was lowest in wood from $Log_{heating}$ and $Log_{steaming}$. While heartwood, $\triangle E^*$ value was not affected in $Log_{heating}$, in lumber from $Log_{steaming}$, $\triangle E^*$ value decreased and in lumber from $Log_{un\text{-}treate,}$ $\triangle E^*$ value increased (Figure 3b).

For *H. alchorneoides* wood, $Log_{heating}$ and $Log_{steaming}$ presented again lower values in heartwood than sapwood, but not in $Log_{un\text{-}treated}$ (Figure 3). The values of $\triangle E^*$ were lower in wood of Log_{steam} and $Log_{un\text{-}treated}$ than wood from $Log_{heating}$ in sapwood, but the highest values of $\triangle E^*$ were found in $Log_{un\text{-}treated}$ in the heartwood. The effect of steaming application during the drying process was irregular. The steaming during the drying process was not affected by sapwood from $Log_{heating}$, while sapwood from Log_{steam} and $Log_{un\text{-}treated}$ presented the lowest values in wood dried with steam (Figure 3a). But in heartwood, the steaming during the drying process increased the $\triangle E^*$ value only in wood from $Log_{heating}$ (Figure 3b).

Discussion

A relationship was observed between IMC and log treatment (heating or steaming). The IMC of lumber from $Log_{steaming}$ and $Log_{heating}$ treatments was lower than $Log_{un\text{-}treated}$, especially in *D. panamensis* wood from $Log_{steaming}$ (Table 3). This decrease of IMC in lumber from de $Log_{heating}$ or $Log_{steaming}$ is attributed to two phenomes, which could occur during the application of steaming or temperature, (i) part of liquid water contained in the log could change of state, turning to water vapor (a gas); the pressure inside the anatomic elements of the log will increase, pushing the liquid water out the log and (ii) the heating (mainly with steam) will increase lumber permeability, facilitating the liquid water movement. Then these phenomena result in the water coming out at the ends and because when the wood cools down, there is a greater loss of moisture due to evaporation.[27,28] This result agreed with those found by Severo et al.[14] for *Eucalyptus dunnii* and Rodrigues et al.[10] for *Hevea brasilensis*, who found that IMC decreased in lumber from logs with pre-steaming treatments prior to the drying process.

In relation to the average drying rate (Table 3), no effect of steaming during drying was observed. However, these results should be considered with caution, since steaming treatment was evaluated in the same drying bath, so drying ended when all treatments reached the same FMC value (Table 3). Rodrigues et al.[10] with *Hevea brasilensis*, also found that either steaming in the logs or steaming during drying did not improve the drying rate, while Berrocal et al.[21] disagreed with those results in *Tectona grandis* wood, and found that the drying rate increased with steaming during drying.

The variation of MC and drying rate with time showed that for two species were similar, although there were large differences in IMC (Table 3). These differences can be attributed to the permeability of the two species during drying, *H. alchornoides* presented a lower permeability than *D. panamensis*, the time and the behavior were similar (Figure 2). So, the steaming application during drying increased the MC slightly and there was a decrease in the time of drying, but little differences were found between species (Figure 2). The $Log_{heating}$ treatment showed a higher drying rate than the other log treatments ($Log_{steaming}$ and $Log_{un\text{-}treated}$) in the first 4 days of the drying process in the wood of *D. panamensis* (Figure 2c), but in the lumber of *H. alchorneoides*, a large variation in the drying rate was observed in lumber without steaming during the first six days (Figure 2d). These results indicate that a priori steaming of the logs has effects in the first few days of drying, probably before reaching the fiber saturation point (FSP). This result agreed with that of Theppaya and Prasertan,[29] who indicate an important effect of steaming on the wood and the drying rate before reaching PSF.

The presence of warps, split, and check before drying of these two species (Table 4) is attributed to the fact that the trees used to come from the condition of the fast-growth tree with a high percentage of juvenile wood[30] and high levels of growth stresses,[6] or transversal tension for the check, resulting in lumber distortions during the sawing process.[19,31] Conversely, the cup defect was not presented in dried lumber and both species were classified as excellent (Table 4). However, the sawing pattern applied to log produced quarter and flat sawn pattern, the sawn pattern is flat. We believe that the dimensions in width (7.5 cm) do not permit the development of cup defects. Then, the presence of cup defects was the low presence. However, this result can be changed if the width of boards increases.

The stemming and heating treatment applied as pretreatments before sawing logs or during drying, as in this study for *H. alchornoides* and *D. panamensis* lumber, aims to relax the residual longitudinal stress of the wood and increase its permeability, especially during drying, due to occluded fiber pits.[6] In addition, with the increase in permeability, moisture gradients decreased, thus, improving the quality of the wood concerning the presence of warps, check, and split.[6,9–11] However, the effect of stemming or heating treatment were not congruent in the different types of drying defects of two species studied.

Although some references indicated that $\text{Log}_{\text{steaming}}$ and $\text{Log}_{\text{heating}}$ treatment improved the presence of warps or other defects,[6,9–11] the obtained results can not confirm this improvement. These treatments did not present effects in the incidence or magnitude of warping, splitting, or checking; (Table 4). As expected, the steam treatment creates better conditions for the relaxation of the different polymers in the wood.[19,32–34] Among them, a higher temperature was achieved with the $\text{Log}_{\text{steaming}}$ in the internal part of the log or sawn timber than with the $\text{Log}_{\text{heating}}$. High temperature in $\text{Log}_{\text{steaming}}$ treatment probably makes the entire cross-section of the log reach the glass transition temperature of the wood, allowing greater relaxation.[33]

$\text{Drying}_{\text{Steam}}$ allowed the improvement of the incidence, magnitude, and category of the bow, split, crook, and check defects (Table 4), which was the result of the improvement of wood permeability, lower moisture gradients, and a relaxation of residual longitudinal stress present in the sawn boards.[6,9–11] In addition, it was observed that when the logs were previously steamed, they showed better bow, split, crook, and check defects during drying (Table 4), indicating that a combination of steaming before sawing and during drying improves wood quality.

In relation to color change ($\triangle E^*$), first heartwood presented higher color change than heartwood in two species (Figure). Second, the sapwood and heartwood show different behaviors of both *D. panamensis* and *H. alchornoides* wood (Figure 3). Then $\text{Log}_{\text{heating}}$ and $\text{Log}_{\text{steaming}}$ treatment produced a large color change in relation to $\text{Log}_{\text{un-treated}}$ in the sapwood. The extractives produce a chemical change when the temperature is applied.[35,36] During steaming, the polyphenolic compounds that give it its dark color can migrate into the sapwood and darken it.[19] Subsequently, this theory can explicate the highest color change found in the heartwood. However, the relationship between extractives-temperature effect was not evident in the sapwood of both species, probably for the low quantity of extractives in sapwood[35,36] affected color change and steaming applicated during drying was not affected this part of the tree.

But the effect of extractives in heartwood was evident in lumber dried with steaming and from $\text{Log}_{\text{heating}}$ and $\text{Log}_{\text{steaming}}$ treatment, the values were not affected and the value decreased, respectively in both species (Figure 3a).

Then, according to the previous analysis, sapwood from $\text{Log}_{\text{heating}}$ and $\text{Log}_{\text{steaming}}$ treatment and dried with steaming produced large color change, but color change of heartwood is not affected, Probably, the extractives of heartwood were affected during heating and steaming application before sawing process, then they were not affected during the drying process. So, the color change occurred when the log received steaming before sawing.

Another advantage of steam application during drying is that it can be a treatment to improve color uniformity on the surface of the wood.[37–39] Although color uniformity was not measured in the two species studied, it was visually observed that the wood from temperature or steam treatment in the logs or the drying process turned darker, which is congruent with the findings of Tolvaj and Molnár's[38] and Varga and van der Zee.[39]

Conclusions

The steaming application during drying presented positive changes in quality of drying defects of the bow, split, crook, and check of *D. panamensis* and *H. alchorneoides*; important improvement of these parameters was observed in lumber extracted from the log previously steamed, indicating that a combination of steaming in logs and during drying improves wood quality. In addition, to these parameters, there is an increase in the drying rate and moisture content that decreases more rapidly. Meanwhile, the color change was mainly affected in sapwood but not in the heartwood.

Declaration of interest statement

The authors declare that they have no conflict of interest.

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Artículo 4: Reduction of effect of growth stress presence using endless screw during kiln drying and steaming and heating treatment in log before sawing

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REDUCTION OF EFFECT OF GROWTH STRESS PRESENCE USING ENDLESS SCREW DURING KILN DRYING AND STEAMING AND HEATING TREATMENT IN LOG BEFORE SAWING

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ABSTRACT

The relaxation of growth stress in trees growing in fast-growth conditions, as plantation in tropical areas, affects lumber quality during of sawing or drying process. It was evaluated two pretreatments (heating and steaming application) before sawing process and endless screw use to maintain the boards pressed during drying of *Dipteryx panamensis* and *Hieronyma alchorneoides* wood with objective to reduce the effects of relaxation of growth stress. The results showed endless screw is used to maintain the boards pressed, the moisture content (MC) or drying rate did not vary. The use of endless screws with daily adjustment during drying produced a reduction of cup, check and split defects in lumber and this treatment is accompanied with a pre-treatment before sawing (heating or steaming treatment) decreased the incidence of drying defects. Then the use of both treatments is an opportunity to reduce the effects of relaxation of growth stress on the quality of the wood of *D. panamensis* and *H. alchorneoides* from fast-growth plantation conditions.

Keywords: drying defects, tropical wood, log treatment, drying improvement, drying defects.

INTRODUCTION

One of the main problems of trees from fast-growth plantations is that the logs extracted from those trees show a high manifestation of growth stress (Kojima et al., 2009), which is evidenced during the sawing process, the wood presents a high incidence of warps, checks and splits and they are accentuated during the drying process, producing dried-lumber of low quality (Moya et al., 2013, 2019; C. Tenorio et al., 2016).

The effect of growth stress on wood processing has been extensively studied (Yang and Waugh, 2001; Gril et al., 2017). Growth stress is referred to the mechanical stress permanently endured by the wood of the living tree during its growth (Gril et al., 2017). The magnitude of these defects depends on the species and can be result in considerable economic losses for the forester and sawller (Gril et al., 2017).

Different treatments on logs and lumber have been implemented in order to increase lumber quality and reduce the effect of growth stress (Ratnasinga et al., 2013). The application of heat and steam are techniques that reduce growth stress during the sawing or drying process (Pelozzi et al., 2014; Rodrigues et al., 2018). Both processes have been applied with a wide variety of purposes, besides of reducing growth stress levels, such as changing color, improving dimensional stability, increasing permeability, improving drying rate, and reducing the initial moisture content and reducing of drying defects (Calonego and Severo, 2007; Ratnasinga et al., 2013).

Different techniques have been implemented to reduce drying defects: drying schedule adjusted to relaxed residual growth stress (Kong et al., 2018), drying techniques such as temperature and steaming application (A. Lenth and A. Kamke, 2001). frequency-vacuum drying systems (Avramidis and Liu, 1994), microwave pretreatment (He et al., 2017) and drying schedule with high temperature (Baranski, 2018).

Recently, a mechanical system has been tested to reduce drying defects, which consists in the placement of endless screws with plates that traversed the pile of wood from side to side (Fig. 1b). Every 12 hours the nuts on screws are adjusted in order to maintain the pressed boards and to avoid formation of twists in the wood (Berrocal et al., 2017).

On the other hand, several tropical species have acquired importance in commercial reforestation based on the knowledge of their genetics, reproduction, and plantation management in Costa Rica (Murillo, 2018). Fast-growing species (with rotation periods of less than 25 years), such as *Dipteryx panamensis* and *Hieronyma alchorneoides* have excellent growth and production in forest plantations (Redondo-Brenes and Montagnini, 2006). Recent research on these species in relation to the quality of wood indicate two types of problems (Moya and Muñoz, 2010; Carolina Tenorio et al., 2016; Moya et al., 2019): (i) problems during sawing process and (ii) high incidence of drying defects after drying process.

There are few studies in tropical species where the effect of the application of heat and steam a priori in logs on the quality of wood after sawing processing or during drying process is evaluated for relaxation of growth stress. Thus, the present work aims to evaluate the effect on the quality of dried-lumber after the application of four treatments, two applied on logs (heating and steaming treatments) and two applied during the drying process (steam application and endless screw is used to maintain the boards pressed,), of *Dipteryx panamensis* and *Hieronyma alchorneoides* wood from forest plantations trees.

MATERIAL AND METHODS

Site and plantation characteristics

A plantation of *Hieronyma alchorneoides* and a plantation of *Dipteryx panamensis* were sampled for this study. Plantation age were 12 and 16 years old, respectably. A plantation of *Hieronyma alchorneoides* had a density of 450 N/ha, while the *D. panamensis* plantation had 550 N/ha at sampling time. More details on the conditions of the plantations can be consulted in Moya et al. (2021).

Sampling and sawing of trees

Sampled trees were cut close to the average diameter breaks height of each plantation. Logs were sawn using a cutting pattern typical for lumber production in Costa Rica (Serrano and Moya, 2011), where a semi-log was obtained and this sawn into 2.5 cm thick boards.

Treatments used for relaxation of growth stress in logs

Two treatments were used on the logs with the objective of relaxation of growth stress: (1) application of a temperature of 115 °C for 24 hours ($Log_{heating}$) and (2) application of steaming for 24 hours at a pressure of 70 Pa ($Log_{steaming}$). As a complement and comparison, logs without heating or stemming were used ($Log_{un\text{-}treated}$). 4-6 logs were placed inside a horizontal tank in both treatments. Conditions of application and tank description for heating and steaming are extensively detailed in Moya et al. (2021).

Treatments for relaxation of residual growth stress in during drying process

The relaxion of residual growth stress during drying in sawn-lumber were used drying schedules detailed in Tab. 1 for two species studied according to Moya et al. (2019).

A conventional kiln with a 2 m^3 capacity pilot chamber (NARDI, Italy) was used for drying. Conventional kiln uses an electrical power source to heat the resistance inside the chamber. For maintain the relaxation of residual growth stress was used endless screw in during drying process of both species, which had shown appropriated performance for reducing drying defects ($Dyring_{with\text{-}screw}$). The endless screws consisted in the placement of endless screws with plates that traversed the pile of wood from side to side (Fig. 1a) in three different positions: extremes and middle of length pile. They were two twice adjusted with the aid of the nuts on the screw in order to maintain the boards pressed and thus avoid formation of twists in the wood, according to proposed by Denig *et al.* (2000). As a complement and comparison, a treatment without endless screw was tested ($Drying_{without\text{-}screw}$). The treatments used on the logs and during drying to increase wood quality are detailed in Fig. 1b.

Tab. 1: Drying schedule utilized in lumber from steaming and heating treatment log for *D. panamensis* and *H. alchorneoides*.

Specie	Stage	DBT (°C)	WBT (°C)	EMC (%)	RH (%)	MC (%)
D. panamensis	Heating	37	-	-	-	-
	Drying	40	37	15.8	82	Green
		44	38	11.5	68	40
		46	38	9.7	60	30
		48	38	8.4	53	20
		50	38	7.4	47	15
	Equalization	50	42	10	62	-
	Conditioning	50	46	14	79	-
H. alchorneoides	Heating	40	-	-	-	-
	Drying	40	37	14.8	82	Green
		40	35	12.5	72	40
		45	37	9.7	60	30
		50	40	7.9	55	25
		55	42	6.2	47	20
		55	37	5.0	33	15
	Equalization	55	47	10	64	-
	Conditioning	55	51	15	81	-

Note: DBT = dry bulb temperature, WBT = wet bulb temperature, EMC = equilibrium moisture content, RH = relative humidity and MC = moisture content.

(b)

Log treatment	Dry treatment
Heating ($Log_{heating}$)	With screw ($Drying_{with\text{-}screw}$)
	Without screw ($Drying_{without\text{-}screw}$)
Steaming ($Log_{steaming}$)	With screw ($Drying_{with\text{-}screw}$)
	Without screw ($Drying_{without\text{-}screw}$)
Un-treated ($Log_{un\text{-}treated}$)	With screw ($Drying_{with\text{-}screw}$)
	Without screw ($Drying_{without\text{-}screw}$)

Fig. 1: (a). Endless screw location in lumber stacked in piles for adjustment during drying and (b). Treatments applied to sawn timber of *D. panamensis* and *H. alchorneoides*
Source for Fig. 1(a): Berrocal et al. (Berrocal et al., 2017)

Moisture control

Moisture content (MC) was monitored using control or kiln samples and was determined before and after drying. MC before drying, named initial MC (IMC), a cross section of 2.5 cm thick to 20 cm of the end was extracted from kiln samples (Simpson, 1991) and was determined according to ASTM-4442-07 standard (ASTM, 2007). After kiln samples were placed at different heights in the package in drying chamber according to log and drying treatment. Kiln samples were weighed two twice per day for MC and to establish the change in the schedule (steps) applied (Tab. 1) and MC decreasing during drying process. For final MC (FMC), again, a variation cross section of 2.5 cm thick was extracted from each board after drying. The average values for IMC and FMC for theses six samples were used to determine the average drying rate for each charge, which means moisture loss in percentage determined by Equation 1.

$$Average\ drying\ rate\ (\%/\mathrm{hr}) = (\mathrm{IMC-FMC})/Total\ drying\ time\ (hr) \quad (1)$$

Wood color change

Wood color was measured before and after the drying process in the same point in a longitudinal surface. Measures were taken in both heartwood and sapwood. Color was measured using a HunterLab Mini Scan XE Plus spectrophotometer. The CIEL*a*b* system was used to measure the reflectance spectra (from 400 to 700 nm), with an 11 mm opening. Color change (ΔE*)ΔE* was determined by the values L*, a* and b* before and after drying and calculated according to the formula laid down in the standard ASTM D 2244 (ASTM, 2005).

Evaluation of drying defects

The defects measured were warp (twist, crook, bow and cup), splits and checks and were determined before and after drying. The methodology detailed in Salas and Moya (Salas and Moya, 2014) and Tenorio et al. (Tenorio et al., 2012), were used to evaluate all the drying defects. The radio of incidence ($Incidence_{ratio}$) and Index of quality after drying (IQ_{after}) were determined. $Incidence_{ratio}$ was calculated before and after drying and ratio was calculated for relation to quantity of boards with defects between total boards (Equation 2). Then the variation of $Incidence_{ratio}$ (Equation 3) was presented in three different form: “+” when variation of incidence was positive, which means the incidence increased after drying process, “-” when variation of incidence was negative, which means the incidence decreased after drying process and “=” when variation of incidence was cero, which means the incidence was similar to value before drying.

The official Chilean standard Nch993EO72 was used to determine IQ_{after}, which was computed for twist, crook, cup, bow, check and split according to Equation 4 (C. Tenorio et al., 2016). The values close to 0 in this index means lower presence of defects and values close to 5 higher presences of defects. This standard sets limit quality values for the different parameters (Tab. 2). For splits and checks the classification was done according to American Softwood Lumber Standard PS20-05 (NIST-National Institute of Standards and Technology, 2005) which establishes four different categories (Tab. 2). Finally, dried-lumber index quality was classified using Kauman and Mittak (1966) methodology (Tab. 2).

$$Incidence_{ratio} = \frac{Quantity\ of\ boards\ with\ determined\ defect}{Total\ boards\ dried} \mathrm{x}\ 100 \qquad (2)$$

$$Variation\ of\ Incidence_{ratio} = (Value\ of\ Incidence_{ratio}\ after\ drying - Value\ of\ Incidence_{ratio}\ before\ drying) \qquad (3)$$

$$QI_{after} = \frac{(Na\cdot 0 + Nb\cdot 0.5 + Nc\cdot 2.0 + 2.5\cdot Nd)}{Total\ boards\ dried} \qquad (4)$$

Where:

QI_{after} = quality index after drying; Na = number of pieces without any presence of warp; Nb = number of pieces with a slight presence of warp; Nc = number of pieces with a moderate presence of warp; Nd = number of pieces with a severe presence of warp.

Tab. 2: Limits values for classification of drying defects and classification of drying quality according to drying defects utilized in the *D. panamensis* and *H. alchorneoides* dried-lumber.

Drying defects	Limits of quality	Drying quality	Limits of dried-lumber quality index
Cup	not present: 0 mm, slight: 1-3 mm, moderate: 3-5 mm severe: > to 5 mm	Excellent	0.0
Bow	not present: 0 mm, slight: 1-3 mm, moderate: 3-6 mm severe: > to 6 mm	Very good	0.1-0.5
Crook	not present: 0 mm, slight: 1-2 mm, moderate: 2-3 mm severe: > to 3 mm	Good	0.51-1.0
Twist	not present: 0 mm, slight: 1-5 mm, moderate: 5-8 mm severe: > to 8 mm	Satisfactory	1.1-1.5
Checks	not present: 0 mm, slight: 1-10 mm, moderate: 10-25 mm, severe: > to 25 mm	Regular	1.51-2.0
Splits	not present: 0 mm, slight: 1-25 mm, moderate: 25-42 mm, severe: > to 42 mm	Defective	2.1-3.0
		Poor	3.1-5.0
		Very poor	>5.0

Source: Kauman and Mittak (Kauman and Mittak, 1966)

RESULTS

Initial and final moisture content, drying time and drying rate.

IMC ranged from 28% to 43%, the FMC ranged from 9% to 11%, the drying time was 168 hours for all treatments and the drying rate ranged from 0.13 to 0.20 %/hr in *D. panamensis* lumber (Tab. 3). For *H. alchorneoides* lumber, IMC ranged from 64% to 128%, FMC 7.0% to 8.2%, drying time for all six treatments was 164 hours and drying rates were lowest in lumber from $Log_{Heating}$ (about 0.35 %/hour), while the highest value in $Log_{Steaming}$ with 0.73 %/hour (Tab. 3).

Tab. 3: Drying variables for *D. panamensis* and *H. alchorneoides* lumber with and without endless screw use during drying process.

Specie	Log treatment	Screw use in drying	IMC (%)	FMC (%)	Drying time (hours)	Drying rate (%/hours)
D. panamensis	$Log_{heating}$	$Drying_{with\text{-}screw}$	29.98	7.01	168	0.14
		$Drying_{without\text{-}screw}$	38.05	7.20	168	0.18
	$Log_{steaming}$	$Drying_{with\text{-}screw}$	41.99	8.27	168	0.20
		$Drying_{without\text{-}screw}$	28.07	7.05	168	0.13
	$Log_{un\text{-}treated}$	$Drying_{with\text{-}screw}$	35.80	9.01	168	0.16
		$Drying_{without\text{-}screw}$	42.74	11.27	168	0.19

H. alchorneoides	$Log_{heating}$	$Drying_{with-screw}$	64.08	7.88	164	0.35
		$Drying_{without-screw}$	66.36	7.00	164	0.36
	$Log_{steaming}$	$Drying_{with-screw}$	127.85	8.20	164	0.73
		$Drying_{without-screw}$	74.85	8.17	164	0.41
	$Log_{un-treated}$	$Drying_{with-screw}$	107.91	7.24	164	0.61
		$Drying_{without-screw}$	90.84	7.78	164	0.51

Note: IMC= initial moisture content, FMC= final moisture content.

Variation of moisture content and drying rate in relation drying time

The variation of MC with time of *D. panamensis* and *H. alchorneoides* lumber showed a homogeneous behavior of decreasing MC with time in all treatments (Fig. 3). It was observed that were no differences in the behavior of MC variation between $Drying_{with-screw}$ and $Drying_{without-screw}$ (Fig. 3a-b). The variation of drying rate showed homogeneous behavior time in all treatment of *D. panamensis* (Fig. 3c), there was more differences in the lumber from $Log_{Steaming}$ and $Drying_{without-screw}$ in *H. alchorneoides* lumber, which presented a higher value of drying rate during the first two days (Fig. 3d), due to its high IMC (Tab. 3).

Drying defects

Dried-lumber of *D. panamensis* did not show $Incidence_{ratio}$ de cup in the different log treatments (Tab. 4). It was also observed that endless screw use in the wood pile ($Drying_{with-screw}$ treatment), there is a reduction of $Incidence_{ratio}$ de bow, crook and twist of lumber from any of the three log treatments ($Log_{steaming}$, $Log_{heating}$ or $Log_{un-treated}$), but the effects of endless screw in the pile were (Tab. 4). $Incidence_{ratio}$ of check decreased in $Drying_{with-screw}$ in lumber from $Log_{steaming}$ and $Log_{un-treated}$, but $Drying_{with-screw}$ treatment increases $Incidence_{ratio}$ of check in lumber from $Log_{heating}$ (Tab. 4). $Incidence_{ratio}$ of split decreased with the use of endless screw in lumber from $Log_{heating}$ and $Log_{steaming}$, but there was no difference in $Incidence_{ratio}$ when the lumber came from $Log_{un-treated}$ (Tab. 4).

The use of endless screw decreased $Incidencia_{ratio}$ of cup, check and split defect in lumber from $Log_{steaming}$ y $Log_{un-treated}$, but the $Incidencia_{ratio}$ of these 3 parameters was not affected in lumber from $Log_{heating}$ in dried-lumber of *H. alchorneoides* (Tab. 4). In the case of bow $Incidence_{ratio}$, it decreased in lumber from $Log_{heating}$ and $Log_{un-treated}$, but in lumber from $Log_{steaming}$ there was no difference in $Drying_{with-screw}$ and $Drying_{without-screw}$ (Tab. 4). For crook $Incidence_{ratio}$, there was only a decrease in lumber from $Log_{heating}$, while the other treatments $Log_{steaming}$ and $Log_{un-treated}$) did showed not difference between $Drying_{with-screw}$ and $Drying_{without-screw}$ (Tab. 4). Incidence of twist decreased in lumber from $Drying_{with-screw}$.

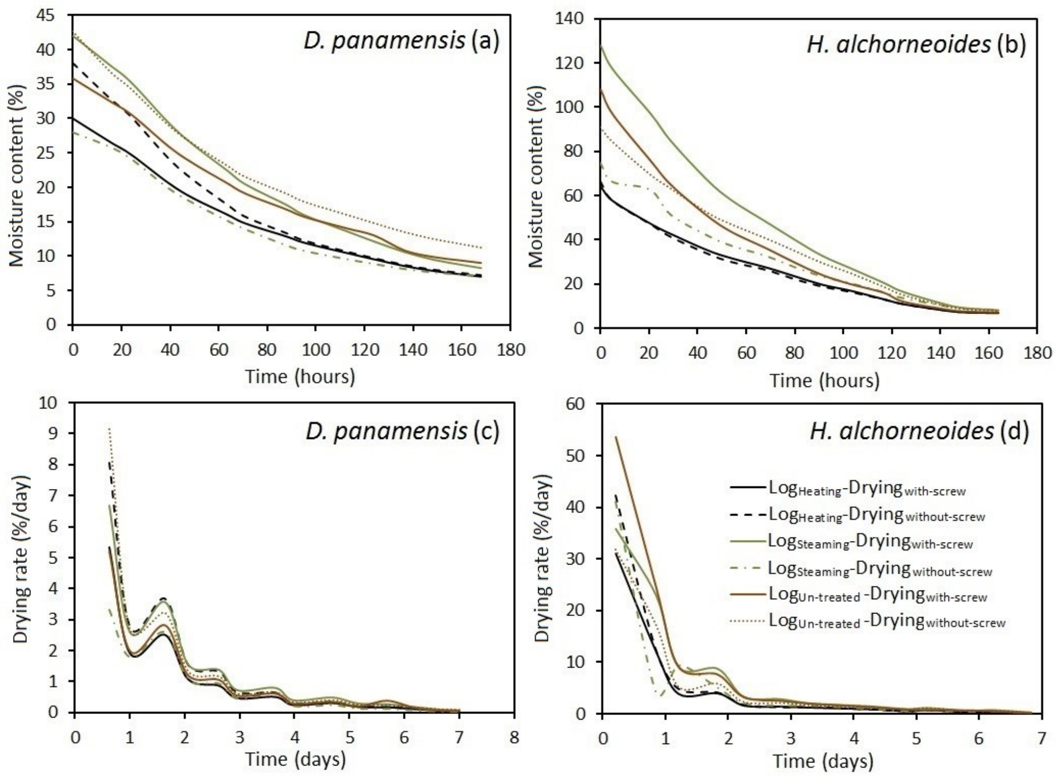

Fig. 3: Variation of moisture content and drying rate in relation to time for *D. panamensis* (a and c) and *H. alchorneoides* (b and d) lumber with endless screw use.

The quality classification of dried-lumber considering IQ_{after} cup of *D. panamensis* showed that lumber was classified as excellent in the different treatments (Tab. 5). The use of endless screw increased IQ_{after} of bow in lumber from $Log_{heating}$ and $Log_{un-treated}$, thus there was a decreasing the quality in $Drying_{with-screw}$. IQ_{after} of crook increased in $Drying_{with-screw}$ in lumber from $Log_{heating}$. The IQ_{after} of twist increased in lumber from three different log treatments. For IQ_{after} of checks, only dried-lumber from $Log_{un-treated}$ increased, while IQ_{after} of split increased in lumber from $Log_{heating}$ and $Log_{steaming}$ (Tab. 5).

For the *H. alchorneoides* lumber, the IQ_{after} of bow increased only in lumber from $Log_{heating}$ and $Log_{steaming}$, but IQ_{after} of crook did not increase lumber-dried quality (Tab. 5). For twist and check, the IQ_{after} increased in lumber from $Log_{steaming}$ and $Log_{un-treated}$ in $Drying_{with-screw}$ (Tab. 5). In the case of cup defects, the IQ_{after} increased the quality of the lumber when steaming treatment is applicated during drying. For split defects, the use of endless screw decreased wood quality in all log treatment (Tab. 5).

Tab. 4: Warp, check and split variation of $Incidence_{ratio}$ and color change in *D. panamensis* and *H. alchorneoides* lumber from different log treatments and with and without steam application during drying.

Specie	Log treatment	Endless screw used	$Incidence_{ratio}$ (%)						Color change △E*	
			Cup	Bow	Crook	Twist	Check	Split	Sapwood	Heartwood
D. panamensis	$Log_{heating}$	$Drying_{with-screw}$	0.0 (=)	31.6 (-)	21.1 (+)	10.5 (-)	15.8 (+)	0.0 (=)	11.8	10.9
		$Drying_{without-screw}$	0.0 (=)	10.5 (+)	21.1 (+)	21.1 (+)	5.3 (-)	5.3 (+)	10.8	11.3
	$Log_{steaming}$	$Drying_{with-screw}$	0.0 (=)	0.0 (=)	4.5 (+)	4.5 (+)	4.5 (-)	13.6 (-)	10.4	10.0
		$Drying_{without-screw}$	0.0 (=)	14.3 (-)	14.3 (+)	42.9 (+)	7.1 (+)	0.0 (=)	10.5	10.7
	$Log_{un-treated}$	$Drying_{with-screw}$	0.0 (=)	22.7 (-)	4.5 (+)	13.6 (-)	9.1 (+)	4.5 (+)	8.6	7.8
		$Drying_{without-screw}$	0.0 (=)	5.3 (+)	5.3 (+)	10.5 (+)	42.1 (+)	5.3 (+)	7.8	8.8
H. alchorneoides	$Log_{heating}$	$Drying_{with-screw}$	66.7 (+)	0.0 (=)	0.0 (=)	29.2 (+)	12.5 (+)	4.2 (+)	13.3	9.2
		$Drying_{without-screw}$	50.0 (+)	31.3 (+)	6.3 (+)	75.0 (+)	0.0 (=)	0.0 (=)	16.5	8.8
	$Log_{steaming}$	$Drying_{with-screw}$	63.0 (+)	14.8 (+)	7.4 (+)	55.6 (+)	0.0 (=)	18.5 (+)	15.8	14.0
		$Drying_{without-screw}$	73.3 (+)	13.3 (+)	6.7 (+)	66.7 (+)	6.7 (+)	20.0 (+)	17.9	13.1
	$Log_{un-treated}$	$Drying_{with-screw}$	19.0 (+)	4.8 (-)	4.8 (+)	38.1 (+)	28.6 (+)	28.6 (+)	9.8	12.8
		$Drying_{without-screw}$	50.0 (+)	0.0 (=)	0.0 (=)	57.1 (+)	42.9 (+)	50.0 (+)	9.8	12.9

Legend: "+" when variation of incidence (Equation 3) is positive, which means the Incidence increased after drying process, "-" when variation of incidence (Equation 3) is negative, which means the Incidence decreased after drying process and "=" when variation of incidence (Equation 3) is cero, which means the Incidence was similar to value before drying

Tab. 5: Quality index after drying (IQ_{after}) and classification of dried-lumber obtained for log treatment and used or not of endless screw for increasing lumber quality of *D. panamensis* and *H. alchorneoides*.

Specie	Log treatment	Screw use in drying	Cup	Bow	Crook	Twist	Check	Split
D. panamensis	$Log_{heating}$	$Drying_{with\text{-}screw}$	0.00 (Excellent)	1.39 (Satisfactory)	1.32 (Satisfactory)	0.03 (Excellent)	1.87 (Regular)	1.82 (Regular)
		$Drying_{without\text{-}screw}$	0.00 (Excellent)	2.05 (Regular)	1.71 (Regular)	0.74 (Good)	0.79 (Good)	2.24 (Defective)
	$Log_{steaming}$	$Drying_{with\text{-}screw}$	0.00 (Excellent)	2.18 (Defective)	2.25 (Defective)	0.41 (Very good)	1.11 (Satisfactory)	1.68 (Regular)
		$Drying_{without\text{-}screw}$	0.00 (Excellent)	1.57 (Regular)	2.11 (Defective)	1.14 (Satisfactory)	1.07 (Good)	2.32 (Defective)
	$Log_{un\text{-}treated}$	$Drying_{with\text{-}screw}$	0.00 (Excellent)	1.59 (Regular)	1.93 (Regular)	0.02 (Excellent)	1.02 (Good)	0.57 (Good)
		$Drying_{without\text{-}screw}$	0.00 (Excellent)	2.29 (Defective)	1.84 (Regular)	0.58 (Good)	1.58 (Regular)	1.05 (Good)
H. alchorneoides	$Log_{heating}$	$Drying_{with\text{-}screw}$	0.33 (Very good)	1.88 (Regular)	2.50 (Defective)	0.83 (Good)	1.77 (Regular)	1.90 (Regular)
		$Drying_{without\text{-}screw}$	0.25 (Very good)	2.22 (Defective)	2.28 (Defective)	1.06 (Good)	1.72 (Regular)	1.50 (Satisfactory)
	$Log_{steaming}$	$Drying_{with\text{-}screw}$	0.50 (Very good)	1.96 (Regular)	2.48 (Defective)	0.63 (Good)	1.20 (Satisfactory)	1.69 (Regular)
		$Drying_{without\text{-}screw}$	0.57 (Good)	2.27 (Defective)	2.33 (Defective)	1.17 (Satisfactory)	1.50 (Satisfactory)	1.17 (Satisfactory)
	$Log_{un\text{-}treated}$	$Drying_{with\text{-}screw}$	0.17 (Very good)	2.17 (Defective)	2.50 (Defective)	0.31 (Very good)	0.83 (Good)	1.55 (Regular)
		$Drying_{without\text{-}screw}$	0.36 (Very good)	2.14 (Defective)	2.32 (Defective)	0.89 (Good)	1.18 (Satisfactory)	1.21 (Satisfactory)

Color change

Color change (△E*) was similar between in dried-lumber of heartwood and of sapwood in the 3 log treatments of *D. panamensis* (Tab. 4). In addition, it was observed that the △E*, both of sapwood and heartwood, was higher in the lumber from $Log_{heating}$ and $Log_{steaming}$ than the lumber from de $Log_{un\text{-}treated}$ (Tab. 4). For *H. alchorneoides*, lumber from $Log_{heating}$ and $Log_{steaming}$, the △E* was lower in heartwood than sapwood in both de $Drying_{with\text{-}screw}$ and $Drying_{without\text{-}screw}$. But contrary result was presented in lumber from $Log_{un\text{-}treated}$, where heartwood presented the highest △E* value compared to sapwood (Tab. 4). Likewise, no effect of endless screw during drying was observed in △E* value in all treatments (Tab. 4). An important aspect to note is that △E* of two species studied was categorized as very evident, this because the △E* values are in the range of 6 to 2 (Cui et al., 2004).

DISCUSSION

Although the IMC was not related with endless screw use during drying, the influence of the log treatment (heating or steaming) on this parameter was observed. IMC of lumber of $Log_{steaming}$ and $Log_{heating}$ treatments were lower than $Log_{un\text{-}tretaed}$ (Tab. 3). This decreasing of IMC in lumber is attributed to the fact that during the application of steaming or temperature, there is an expansion of the water inside the wood, resulting in the wood coming out at the ends and also because when the wood cools down, there is a greater loss of moisture due to evaporation of this moisture (Zhang and Cai, 2008).

In relation to the average drying rate, no effect of the use of screws during drying ($Drying_{with\text{-}screw}$ treatment) was observed (Tab. 3). Berrocal et al. (2017) agreed those results in *Tectona grandis* wood, who found that drying rate was not affected the use of screws during drying.

The variation of the MC and drying rate with time of the *D. panamensis* and *H. alchorneoides* lumber in all treatments showed a homogeneous decreasing of MC with time (Fig. 3a-c). This situation is to be expected, since the use of endless screw has the objective of keeping the boards fixed within the pile (Denig et al., 2000; Berrocal et al., 2017). Therefore, the drying rate and MC will not be affected over time, as occurred in the two species studied (Fig. 3a-c).

The presence of warps, split and check before drying of these two species (Tab. 4) is attributed to the fact that the trees used come from fast-growth trees condition with a high percentage of juvenile wood (Zobel and Sprague, 1998) and high levels of growth stresses (Gril et al., 2017). Stemming and heating treatment applied as pre-treatments before sawing logs aims to relax the residual longitudinal stress of the wood and increase its permeability (Gril et al., 2017). In addition, with the increase in permeability, moisture gradients decrease and thus there is improving the quality of the wood in relation to the presence of warps, check and split (A. Lenth and A. Kamke, 2001; Gril et al., 2017; Rodrigues et al., 2018). However, in the case of the two species studied, the effect was not congruent with the different types of drying defects present in dried-lumber (Tab. 4-5).

$Log_{steaming}$ and $Log_{heating}$ treatment were not presented effects in the incidence or magnitude of warping, splitting or checking, although a slight reduction in the incidence of these quality parameters was observed in $Log_{steaming}$ (Tab. 4-5). This difference was attributed to the fact that steam treatment creates better conditions for the relaxation of the different polymers in the wood (Kong et al., 2017; Moya et al., 2021). Among them, the higher temperature reached with the $Log_{steaming}$ in the internal part of the log or sawn timber than with the $Log_{heating}$. High temperature reached in $Log_{steaming}$ treatment is probably making the entire cross section of the log reach the glass transition temperature of the wood, allowing greater relaxation (Kong et al., 2017) and as well, the steaming reduces the crystalline zones of cellulose, therefore the amorphous zones increase (Kong et al., 2017).

Endless screw has objective to reduce check and split defects due to the application of temperature during drying and variations in the moisture content in the cross-section of a piece of wood during drying (Berrocal et al., 2017). The use of this system (Fig. 1b) allows the wood pile to be held in place to prevent movement and to have a positive influence when applied to wood above the FSP in combination with high temperatures (Vansteenkiste et al., 1997). In this case, the improvement of wood quality using endless screw to maintain wood quality was irregular and each defect behaves differently; the values obtained for incidence and magnitude of the defect increased or decreased according to the defect (Tab. 4). However, the effect of the use of the endless screw was reflected in the value of IQ_{after}, this value decreased, therefore, there was an increase in the quality of dried-lumber (Tab. 7). The reduction of these defects by endless screws used is due to the fact that this forces for maintaining pile working in the direction of the tangent of the growth rings could reduce the development of internal checking. Besides, this force can be viewed as a counteracting force for stresses developed during drying or as a restraining force to internal stresses in the wood that give it a great tendency to accumulate drying defects (Denig et al., 2000).

Likewise, the use of endless screws for daily adjustment during drying produced a lower percentage of dried-lumber classified as "low drying stress", in relation to the lack of screws in the wood pile (Tab. 5). This result, together with good pretreatment before sawing (heat or steam treatment) reduced the incidence of warping, checking and cracking (Tab. 4-5).

In relation to color change (△E*), the sapwood and heartwood show different behaviors of both *D. panamensis* and *H. alchornoides* wood (Tab. 4). Heartwood has a higher amount of extractives than sapwood (Hillis, 1987), which produce a chemical change when temperature is applied (Tolvaj et al., 2012; Berrocal et al., 2016). During steaming, the polyphenolic compounds in the heartwood that give it its dark color can migrate into the sapwood and darken it (Tolvaj et al., 2012), as was evident in heartwood of both *D. panamensis* and *H. alchornoides* of present study. The highest color change was obtained when log received steaming before sawing. Tolvaj et al. (Tolvaj et al., 2012) based on studies of *Robinia pseudoacacia* indicated that the color changes are attributed to the fact that parameter L* decreased and the parameters a* and b* increased with temperature and steaming.

Endless screw use during drying does not change the chemical structure of the wood and the chemical composition of wood (Tolvaj et al., 2012; Berrocal et al., 2016), then no effects on the change in color or △E* was not evidenced (Tab. 4). Therefore, the changes observed in the color of lumber whose drying process included endless screw treatment are related to the pretreatments ($Log_{steaming}$ and $Log_{heating}$) of the logs prior to sawing.

CONCLUSIONS

The use of endless screw during drying, being a treatment that does not change the chemical structure of the wood, but are external supports to maintain the shape of the board, has no effect on color change, drying time or drying rate, but its main benefits are related to the improvement of the magnitude, incidence and quality category of cup, check and split defects. In addition, this decreasing of defects is favored again when the use of endless screw in the wood piles was accompanied with a pre-treatment of the logs such as steaming and heating before sawing.

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Artículo 5: Structural and design values of timber of solid wood and glued laminated timber of *Dipteryx panamensis* and *Hieronyma alchorneoides* wood from fast-growth plantation

Roger Moya Roque

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Enviado el:	jueves, 20 de enero de 2022 00:52
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The manuscript of your submission for DRVIND:

DRVIND.0007 Structural and Design Values of Solid Timber Beams and Glued Laminated Timber Beams of Dipteryx panamensis and Hieronyma alchorneoides Wood From Fast-Growth Plantation

-

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Structural and design values of solid timber beams and glued laminated timber beams of *Dipteryx panamensis* and *Hieronyma alchorneoides* wood from fast-growth plantation

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Structural and design values of solid timber beams and glued laminated timber beams of *Dipteryx panamensis* and *Hieronyma alchorneoides* wood from fast-growth plantation

Abstract

Dipteryx panamensis and *Hieronyma alchorneoides* are two species of high specify gravity and used in reforestation programs in Costa Rica, but they lack products with structural value for commercialization. In order to introduce the wood of these two species in the market, the objective was established to study the behavior of solid timber beams and glued laminated timber beams of two cross sections (2 cm x 10 cm and 2 cm x 15 cm) and establish the design values in bending test. The results showed that the bending design values (fb) ranged from 10 to 26 MPa in glued laminated timber beams, but in solid timber beams, fb ranged from 3 to 16 MPa. In the shear design values (fv) the variation was from 0.33 to 0.65 MPa in glue laminated timber beams and from 1.81 to 2.59 MPa in solid timber beams. It was also found that the species *D. panamensis* beams presented higher values than *H. alchornoides* beams. Finally, it was established that glued laminated timber beams showed better performance in bending parameters and higher design values, resulting in wider span values than solid timber beams when used in floor and roof.

Keywords: tropical species, bending, shear, mezzanine, gluelam, mass timber.

Introduction

Costa Rica is a small Central American country, that is currently characterized by the conservation of its natural resources, especially natural forests (Allen and Vásquez, 2017). However, the country has gone through several stages in the harvesting of natural forests, the most critical point occurred in the 1980s, when forest cover decreased to critical levels (Stan and Sanchez-Azofeifa, 2019). The selective harvesting of natural forests resulted in the production of bigger logs (Johns, 1988), where large cross sections lumber was obtained (Bello, 2020). It was possible to find in the market lumber for furniture fabrication with dimensions of 2.5 cm thickness, over 40 cm in widths and lengths over 3.36 meters, while in the case of timber, the dimensions could be 10 cm in thickness and over 15 cm in wide and lengths of up to 5.5 m. Thus, before the 1980s, buildings (houses and buildings) were characterized by the use of wood in all elements of high structural demand, such as beams and columns (Serrano-Montero and Moya, 2011).

After this critical period, the government encouraged reforestation programs through forestry incentives, with the aim to reduce the pressure on natural forests and to increase a source of sawlog supply for the country (Quesada-Mateo and Solis-Rivera, 1990). These programs were maintained for several years, resulting in the fact that commercial plantations currently supply 60% of the volume of sawlog consumed in Costa Rica (Ugalde, 2021). Throughout this process, about 20 forest species have shown adequate results in terms of growth and production. So, farmer had accepted many species to establish commercial plantations (Nichols and Vanclay 2012). Fast-growing species, with rotation periods of less than 25 years, such as *Dipteryx panamensis*, *Terminalia amazonia*, *Vochysia guatemalensis, Cordia alliodora* and *Hieronyma alchorneoides* (native species) *and Tectona grandis, Cupressus lusitanica, Acacia mangium* and *Gmelina arborea* (exotic species), have been extensively studied (Petit and Montagnini, 2006) and have shown excellent results in forest plantations in Costa Rica (Petit and Montagnini, 2006; Nichols and Vanclay 2012). However, it has been observed that most of the above species are concentrated in moderate density wood, used as lumber for furniture manufacturing (Moya et al., 2021).

D. panamensis (almendro) and *H. alchorneoides* (pilon) are two species utilized in reforestation programs due to their high specify gravity and therefore their high values in structural properties. However, in wood from forest plantations, three main problems have been identified: (i) presence warp during sawmilling process, (ii) high incidence of drying defects in the drying process and (iii) lack of product development for marketing. The first two have been recently addressed by Moya et al. (2021) and Moya and Tenorio (2021). The lack of products for the commercialization of these species is associated with two aspects: (i) they have a density greater than 0.5 g/cm^3, so they are classified as high-density timber, so they cannot be used in the manufacture of furniture and pallets fabrication, which are the main markets for plantation sawlog, and (ii) the other most influential aspect is that the heartwood color of plantation timber has lighter color in relation to natural forest wood (Moya and Tenorio, 2021; Moya et al., 2021).

D. panamensis and *H. alchornoides* are classified as high wood density considering their characteristics of trees from natural forests in Costa Rica (Moya et al., 2021). The wood from these trees has an established market and is used for the construction of trusses, floors and columns to support walls, bridges, and truck, among others, that is, in uses where there is an important demand for structural strength (Moya and Tenorio, 2021). However, wood from trees growing in fast growth plantations presented a decreasing in specify gravity in relation to wood from natural forests (Senft et al., 1985). However, this decrease should not be a problem for plantation wood to be introduced in the same market sector established for wood from trees from natural forest (Moya et al., 2021).

One way to mitigate these limitations of these species is to develop new processing options not only to minimize problems during the sawing or drying process (Moya et al., 2021, Moya and Tenorio, 2021&2022), but also in the development of highly engineered products that allow to wood from these species growing in fast growth plantation to competitively enter new markets (Zobel, 1981). For example, the fabrication of glued laminated timber beams (Moody and Hernandez, 1997). This type of product is manufactured with laminates of limited thickness, with a certain degree of structural grading of its layers, and glued with structural adhesives (Kitek Kuzman et al., 2010), but may present some differences in structural values in relation to solid wood (Falk and Colling, 1995). For example, elements in compression are of higher strength, but in bending test present a higher modulus of elasticity but a lower shear strength than solid timber beams (Ndong Bidzo et al., 2021).

Although glued laminated timber beams and solid timber beams are produced from wood of relatively uniform quality, variations are always present (Moody and Hernandez, 1997), so it is necessary to standardize in order to establish different design values (Morin-Bernard et al., 2021). Thus, the present work aims to study the behavior of solid timber beams and glued laminated timber beams fabricated with *D. panamensis* and *H. alchorneoides* wood from fast growth plantation conditions in two cross sections (2 x 10 cm and 2 x 15 cm) and stablish the design values in bending test.

Methodology

Site and characteristics of the plantation

Two fast-growth plantations were sampled: one of *H. alchorneoides* and another of *D. panamensis*. The *H. alchorneoides* plantation at the time of sampling was 12 years old and had a density of 450 trees/ha, while the *D. panamensis* plantation was 16 years old and had a density of 550 trees/ha. More details on the characteristics of the plantations can be found in Moya and Tenorio (2021) and Moya et al. (2021).

Sampling and sawing trees

Approximately 70 trees of each species were sampled, close to the average diameter of each plantation, 19.7 cm for *H. alchornoides* and 17.9 cm for *D. panamensis*. Half of the logs were sawn using a typical cutting pattern for timber production in Costa Rica (Serrano-Montero and Moya 2011), where a semi-log was obtained, which was sawn into 2.5 cm thick timber (Figure 1a). From the other half of the logs, a 6.2 cm thick central block was obtained across the width of the log (Figure 1b). Log was sawn using a band saw and a single-cut resaw. The 2.5 cm and 6.2 cm timber were dried using a drying schedule proposed by Moya and Tenorio (2022).

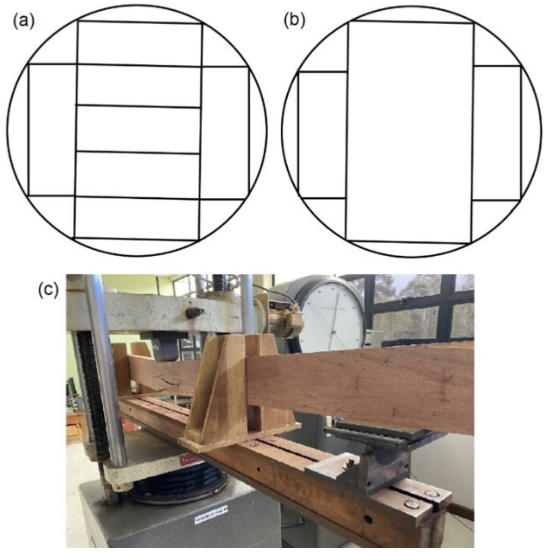

Figure 1. Sawing pattern utilized for obtaining 2.5 cm in thickness for fabricated glued laminated timber beams (a), sawing patter utilized for obtaining 6.2 cm thickness in solid timber beams (b) and bending test in three-point (c).

Timber dimension and beams fabrication

The timber was dried using the drying schedule proposed by Moya and Tenorio (2022) with a target moisture content of 12 %. Extensive details of the drying process for the two species can be found in Moya and Tenorio (2022). After drying, timber of 2.5 cm in thickness was planned to 2 cm x 6.5 cm x 270 cm, while timber of 6.2 cm was planned to 5.0 cm. Two type of timber beams (solid and glued laminated) were prepared with length of 270 cm of two different cross dimensions: (i) 5 cm x 10 cm and (ii) 5 cm x 15 cm. For solid timber beams, the dried-timber with 5 cm in thickness were cut in width of 10 cm and 15 cm. Each cross-section was prepared 15 solid timber beams. Meanwhile, glued laminated timber beams were fabricated two cross sections and a length of 270 cm: (i) 5 cm x 10 cm with 6 lamellas of 20 cm in thickness and (ii) 5 cm x 15 cm with 8 lamellas of 20 mm in thickness. A total of 15 glued laminated timber beams were constructed for each cross section, for a total of 60 beams (2 different type of beams x 2 cross-section x 15 beams). Advantage EP-950A® isocyanate polymer emulsion (EPI)+catalyst 200 Franklin® (isocyanate polymer) adhesive system (Franklin Adhesives and Polymers, OHIO, USA) was used. The adhesive was applied at a weight of 200 $g \cdot m^{-2}$ on one side of lamellas. The lamella was placed on a balance and the required amount of adhesive was applied with micropore rollers. The pressing was performed with an ITALPRESSE PL/9/SCF/8 hydraulic press (Italpresse S.A., Bergamo, Italy), at a pressure of 8.0 MPa for a time of 3600 s.

Bending test

The solid and glued laminated timber beams were tested in third-point static bending over a span of 2.50 m as shown in Figure 1c. Testing was conducted with a Tinus Olsen Super L universal testing machine, with 60 tons in capacity. The test conditions, load speed and deflection determination were compliant with ASTM D198-21a (ASTM, 2021a). A displacement sensor (LVDT) was placed at the center of the beam under the king post, to measure the vertical displacement at the time of load application, then load and displacement was measured each 30 μs. From the results of these tests, the modulus of elasticity (MOE) and modulus of rupture (MOR) were determined using equations 1 and 2, respectively. The shear stress (τ) in bending was determined according to equation 3.

$$\text{MOE (GPa)} = \frac{0.852 * F_{LP} * L^3}{24 * I * y} \text{ x } 0.0000981 \qquad (1)$$

$$\text{MOR (MPa)} = \frac{\text{Fmax} * \text{L} * \frac{\text{H}}{2}}{6 * \text{I}} \text{x } 0.0981 \qquad (2)$$

$$\tau\ (\text{MPa}) = \frac{3 \cdot \text{Fmax}}{4 \cdot \text{b} \cdot \text{H}} \cdot 0.0981 \qquad (3)$$

Where: F_{LP} = load at proportional limit (kgf), Fmax = rupture load (kgf), L = span (cm), I = moment of inertia (cm^4) for rectangular form, y = deflection (cm), b= width of beam H = depth of the beam (cm), 0.0000981 conversion units from kgf cm^{-2} to GPa and 0.0981 = conversion units from kgf cm^{-2} to MPa. And 0.852 is derived from general equation for MOE for one load (Equation 3).

In addition, the type of failure that occurred in the two types of beams was determined. For glued laminated timber beams, the type of failure was first categorized according to the location of the failure in the lamina number, with L1 being the lamina where the load is applied and Ln being the lamina farthest away from the load, L6 for the 10 cm high beams and L8 in the 15 cm high beams (Figure 2a-b). Second, it was determined if the failure was due to delamination (Figure 2c), which refers to the separation of the glueline between two lamellae, or if any lamellae that make up the beam failed, this type of failure can be of two types: tension and shear (Figure 2d-e). Meanwhile, for solid timber beams, 5 types of failure were established according to ASTM D-143 standards (ASTM, 2021b): simple tension (Figure 2f), cross-grain tension (Figure 2g), splintering tension (Figure 2h), brash tension (Figure 2i) and horizontal sheer (Figure 2j).

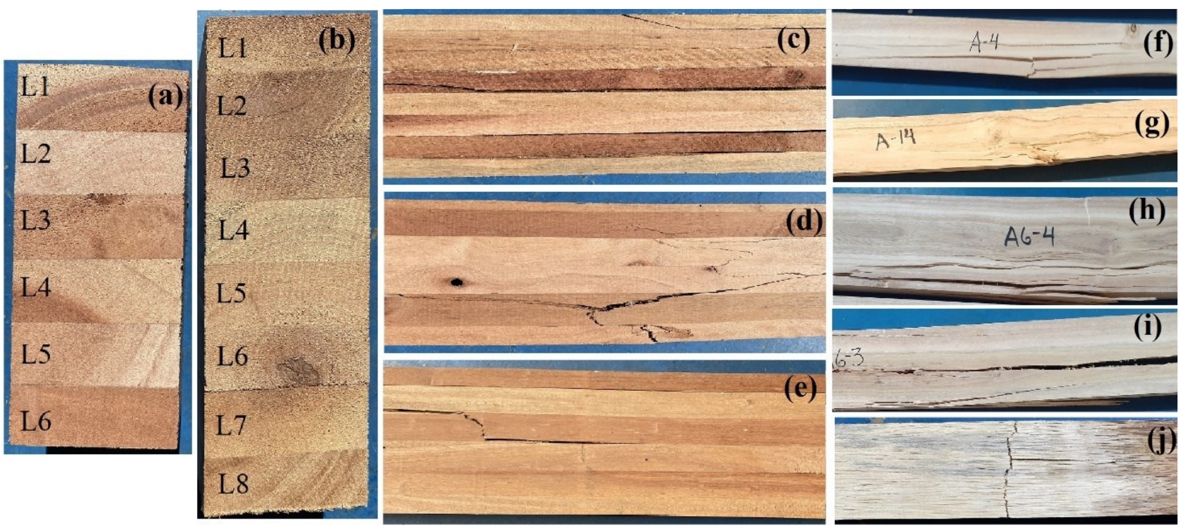

Figure 2. Number of laminates in glued laminated timber beams of 5 cm x 10 cm (a) and 5 cm x 15 cm (b), types of failures in glued laminated timber beams: delamination of glued line (c) and failure in lamina by tension (d) or shear (e), and failure in solid timber beams: simple tension (f), cross-grain tension (g), splintering tension (h), brash tension (i), and horizontal sheer (j) in static bending.

Density, moisture content and stress in shear parallel to the grain determination

Following bending tests, a 5-cm cross-section was extracted from each beam. Its volume and its weighed were measured and density (kg m^{-3}) was calculated. After, the sample was oven-dried for 24 hours to 103 °C and moisture content was determined. Density value was later used to calculate total weight of the beam. For glue line test was used for stress in shear parallel to the grain determination in glued laminated timber beam and shear resistance for solid timber beam. On the tested beam, a sample of approximately 20 cm length was taken from each beam, from a section away from the failure area. From this, two samples of 6.5 cm in length were extracted (60 samples in total) and tested according to ASTM D905 (ASTM, 2021c) for glued laminated timber beam (30 samples) and ASTM D143 (2021b) for solid timber beam (30 samples).

Derivation of design values

Design values were derived from MOE and MOR values of glued laminated timber and solid timber beams tested in bending test and its applicability will be shown as beam in flexion applications. In the derivation of design values, the beam was structurally analyzed in two different ways: (i) bending capacity, and (ii) deflection in the span. For bending capacity, the superimposed load in different span was determined, considering only maximum stress of the transverse section.

For the derivation of the design values, a normal distribution of the MOR and MOE obtained for each type of beam was assumed. Then using the t-student statistical distribution function, the basic stress LRFD is obtained according to equation 4 and transformed into ASD stress by applying equation 5 only for MOR to obtain the basic stress LRFD. This step was not performed for the MOE because it is not necessary. Next, the nominal bending strength (ΦMn), nominal shear strength (ΦVn) and bending stiffness (EI) were calculated, considering equations 6, 7 and 8, respectively.

$$F_{LRFD} = \bar{X} \cdot \left(1 - t_f \cdot \frac{CV}{100}\right) \quad (4)$$

$$F_{ASD} = \frac{F_{LRFD}}{K_F \cdot \phi} \quad (5)$$

$$\Phi \mathrm{Mn} = f_b \cdot S \cdot K_F \cdot \phi \quad (6)$$

$$\Phi \mathrm{Vn} = \frac{2}{3} \cdot f_v \cdot A \cdot K_F \cdot \phi \quad (7)$$

$$\mathrm{EI} = MOE \cdot I \quad (8)$$

Where: $\bar{X}$: average value of the data, CV: coefficient of variation of the data (percentage), tf: t Student factor for a 95% exclusion level according to the sample size, KF: format conversion factor, according to the NDS 2018 (American Wood Council, 2018), 2.54 for flexure and 2. 88 for shear, Φ: strength reduction factor, according to the Seismic Code of Costa Rica 2010 revision 2014 (CIFA, 2011; INTECO, 2011), which in this case was 0.85 for bending and 0.75 for shear, fb: bending design values, S: elastic section modulus, fv: shear design values, A: cross-sectional area, E: MOE determined in Equation 1, I: moment of inertia and EI: bending stiffness.

Subsequently, the maximum capacity in terms of overload (distributed load per unit area, w) in supported flexure was calculated, varying span length (L) and the separation between beams (sep) using Equations 9, 10 and 11. From these three calculated values, the lowest one was selected by safety factor, which is the one that determines the design values.

$$\mathrm{w} = \frac{8 \cdot \Phi \mathrm{Mn}}{sep \cdot L^2} \quad (9)$$

$$\mathrm{w} = \frac{384 \cdot \mathrm{Y} \cdot \mathrm{EI}}{5 \cdot sep \cdot L^4} \quad (10)$$

$$\mathrm{w} = \frac{2 \cdot \Phi \mathrm{Vn}}{sep \cdot L} \quad (11)$$

Where: ΦMn: nominal bending strength, Y: maximum allowable deflection (L/240), EI: product of the modulus of elasticity and the second moment of area and ΦVn: nominal shear strength.

Statistical analysis

One-way ANOVA was applied to mechanical parameters in flexure test (load and deflection at proportional limit, maximum load, MOR and MOE) and maximum stress in shear test, in the parameters of the physical (density, MC and WA). The Tukey test was used to test the mean difference at a level of significance of $p<0.01$ per species and each type of beams. The SAS 8.1 statistics program for Windows (SAS Institute Inc., Cary, N.C., USA) was used to carry out the analyses.

Results and discussion

Density and moisture content

Figure 3 presents the MC and density values obtained for the two species by cross section and type of beam. The MC was higher in the glued laminated timber beams for both species and cross section of beams, except for the 5x10 cm cross section of *D. panamensis* (Figure 3a). Wood density of the solid beams of both species presented the highest values, except for 5x10 cm cross section of *D. panamensis*, which showed no differences between the two types of beams. In addition, the beams manufactured with *D. panamensis* timber (solid and laminated) presented higher wood density in relation to the beams of *H. alchorneoides* (Figure 3b).

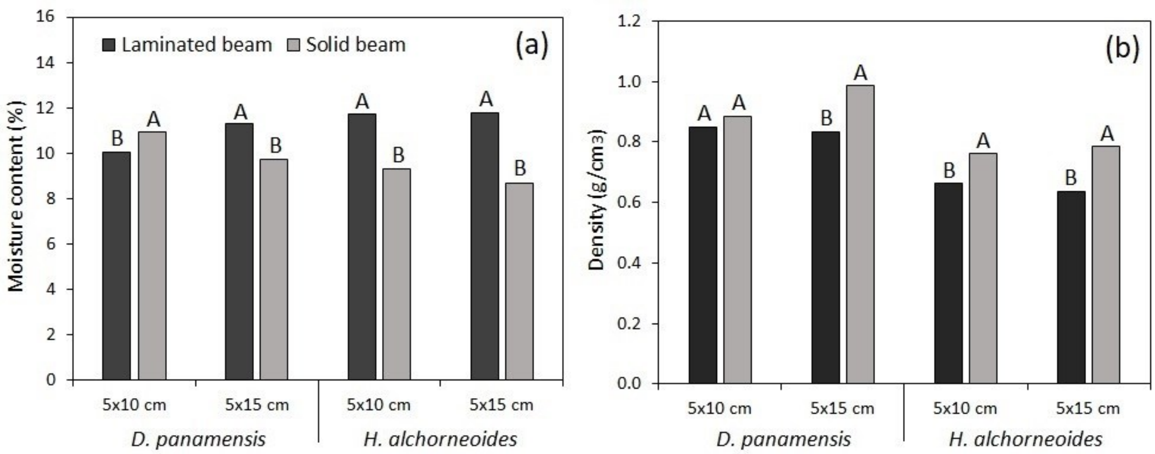

Figure 3. Moisture content (a) and density (b) for laminated and solid beams built with *D. panamensis* and *H. alchorneoides* timber.

Bending and shear test

In the bending test for *D. panamensis* was not presented any statistical differences between laminated timber and solid timber beams in 5x10 cm cross section in terms of load at LP and deflection, but statistical differences were observed in terms of maximum load, where glued laminated timber beams presented the highest values (Table 1). For cross sections of 5x15 cm of the same species, it was observed that there were statistical differences between the two types of beams, in the three parameters evaluated, where the solid timber beams presented the highest values (Table 1). In the case of *H. alchorneoides*, for 5x10 cm in cross section, differences were observed in load at LP and deflection at LP, where the solid timber beams presented the highest value; in the case of maximum load, no statistical differences were observed between the two types of beams (Table 1). For the 5x15 cm in cross section, there were differences in the three parameters evaluated, where the solid timber beams presented the highest values in relation to the glued laminated timber beams (Table 1).

Table 1. Statistical values obtained in the bending test for glued laminated timber and solid timber beams fabricated with *D. panamensis* and *H. alchorneoides* timber.

Specie	Parameter		Type of beam			
			5x10 cm cross section		5x15 cm cross section	
			Glued laminated timber	Solid timber	Glued laminated timber	Solid timber
D. panamensis	Load at PL	Average (kN)	8.38^{A}	9.04^{A}	10.84^{B}	32.43^{A}
		SD (kN)	2.84	4.17	4.61	14.73
		CV (%)	33.82	46.16	42.47	45.42
	Deflection at PL	Average (mm)	35.20^{A}	43.73^{A}	20.58^{B}	64.86^{A}
		SD (mm)	7.55	15.46	7.29	14.40
		CV (%)	30.74	35.36	35.41	22.20
	Maximum load	Average (kN)	17.81^{A}	12.83^{B}	24.96^{B}	35.69^{A}
		SD (kN)	4.73	4.99	7.63	13.19
		CV (%)	26.56	38.91	30.56	36.97
H. alchorneoides	Load at PL	Average (kN)	5.47^{B}	12.67^{A}	7.38^{B}	30.08^{A}
		SD (kN)	2.27	4.16	4.02	6.64
		CV (%)	41.49	32.80	54.49	22.06
	Deflection at PL	Average (mm)	20.48^{B}	56.90^{A}	17.28^{B}	63.00^{A}
		SD (mm)	7.54	11.97	8.18	9.49
		CV (%)	36.83	21.03	47.36	15.06
	Maximum load	Average (kN)	11.03^{A}	14.18^{A}	16.27^{B}	31.95^{A}
		SD (kN)	4.05	4.57	7.70	7.62
		CV (%)	36.75	32.24	47.33	23.84

Note: PL= proportional limit, SD= standard deviation, CV= coefficient of variation.

Figure 4 presents the MOE and MOR values obtained for the bending test for the beams of the two species. For *D. panamensis* in cross section of 5x10 cm, the glued laminated timber beams presented the highest MOE value, while for 5x15 cm in cross section there were no statistical differences in MOE (Figure 4a). For *H. alchorneoides*, the glued laminated timber beams presented the highest MOE in cross section of 5x10 cm but the lowest value of MOE was presented in the cross section of 5x15 cm (Figure 4a). As for the MOE, the solid timber beams presented the highest values for the two species and cross sections of beams, except for the 5x10 cm cross section of *D. panamensis* where the glued laminated timber beams presented the highest value (Figure 4b).

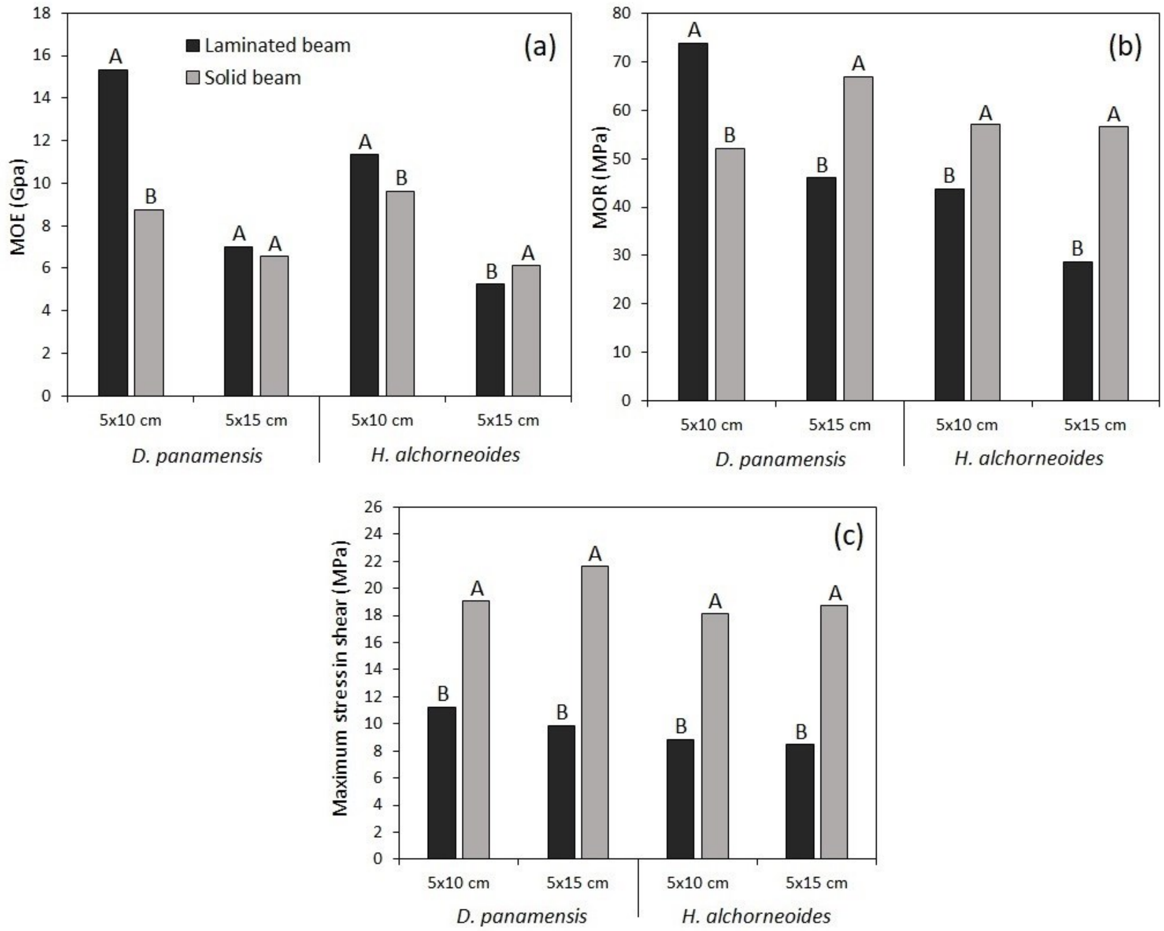

Figure 4. MOE (a) and MOR (b) obtained in the bending test and maximum stress in shear parallel to the grain (c) for glued laminated timber and solid timber beams built with *D. panamensis* and *H. alchorneoides* timber.

In the load vs. deflection curves obtained in the bending test, it is observed that for both species at the same deflection value, the 5x15 cm cross section beams for solid wood and glulam beams present the highest load value, followed by the 5x10 cm cross section beams for glued laminated timber and solid wood beams (Figure 5). In addition, it is observed that the beams made with D. panamensis wood present higher load values in relation to the beams made with *H. alchorneoides* for the same deflection (Figure 5). Regarding the maximum stress in the shear test parallel to the grain, it was observed that the solid timber beams presented the highest values for beams of two species and two cross sections used (Figure 4c).

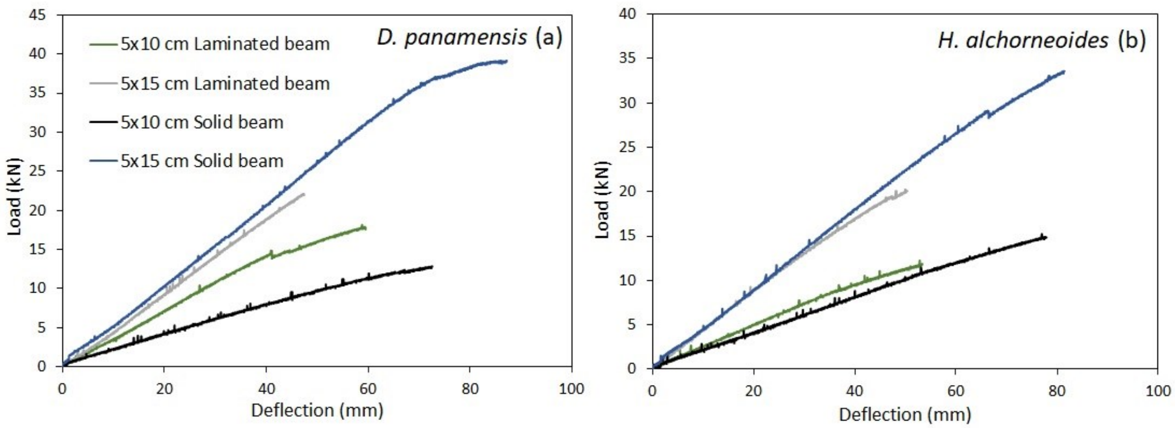

Figure 5. Average load versus deflection plots obtained in the bending test for glued laminated timber and solid timber beams built with *D. panamensis* and *H. alchorneoides* wood.

Types of failures

Due to the different configurations of the two types of beams, the types of failures were different (Table 2). In the case of the solid timber beams, the type of failure was different by species and cross section (Table 2). The type of failure with the highest presence was horizontal shear in the solid timber beams of *D. panamensis* of 5x10 cm of cross section, followed by simple failure and cross-grain tension, while in the 5x15 cm beams, horizontal shear and splintering tension presented the highest percentages. While in the solid timber beams of *H. alchornoides*, cross-grain and splintering tension failure were the highest percentages in the 5x10 cm dimension and splintering tension failure were the highest percentage in the beam of 5x15 cm in cross sections, followed by cross-grain and simple tension failure (Table 2).

Typical failures of solid timber beams are those involving tension (cross-grain, splintering or simple tension) (Nadir and Nagarajan, 2014), as occurred in two species and two cross section of beams tested (Table 2). According to Conrad et al. (2003) the lack of ductility between fibers in a solid timber beams causes the beam to fail in tension, as evidenced by the results of the solid timber beams in the present study.

In the case of glued laminated timber beams, the highest percentage of failures was the delamination type in the beams of *D. panamensis* of two cross sections tested and in cross section of 5x15 cm of *H. alchorneoides*, followed by tensile failure in these dimensions. While in cross section of 5x10 cm of *H. alchorneoides*, the highest percentage of failure was tension failure (Table 2). This behavior was different from that found by Nadir and Nagarajan (2014) for glued laminated timber beams of rubber wood tested in flexure where the highest failure type was tensile and the lowest percentage was delamination. In this regard, these authors explain the different types of failures that occur in glued laminated timber beams tested in flexure and that may explain the results of the present study:

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i. A delamination failure in a glued laminated timber beams can occur when there is a defectively glued area in a part of the lamella, then the cracks start to propagate through the adhesive surface, but when a very strong glued area appears, it passes through the wood and another type of failure occurs (Nadir and Nagarajan, 2014). Thus, the beams of *D. panamensis* of two cross sections tested and in *H. alchorneoides* beams of 5x15 cm of cross section, by the results of high presence of delamination failure (Table 2), indicate that these lamellae presented problems of adhesion between the lamellae.
ii. Tensile failure is the type of failure that is expected to occur, and occurs when the joints are perfectly bonded and there are few defects in the timber that could fail the laminates. This results in failures starting from bottom lamina and spreading to the top (Nadir and Nagarajan, 2014). Then in the *H. alchorneoides* beams of 5x10 cm in cross section, where the highest percentage of failure was of tension type (Table 2), it is the type of beam fabricated without problems of laminate adhesion and therefore present normal failures.

Table 2. Percentage of presence of different types of failure for glued laminated timber and solid timber beams of *D. panamensis* and *H. alchornoides*.

Type of beam	Type of failure (%)	*D. panamensis* beam		*H. alchorneoides* beam	
		5x10 cm cross section	5x15 cm cross section	5x10 cm cross section	5x15 cm cross section
Solid	Cross-grain tension	14.3	20.0	46.7	26.7
	Horizontal shear	57.1	40.0	0.0	6.7
	Simple tension	28.6	0.0	6.7	26.7
	Brash tension	0.0	0.0	6.7	0.0
	Splintering tension	0.0	40.0	40.0	40.0
GLued laminated	Delamination	58.3	90.9	0.0	64.3
	Delamination and shear	0.0	0.0	0.0	7.1
	Shear	0.0	9.3	14.3	0.0
	Tension	41.7	0.0	85.7	14.3
	Tension and shear	0.0	0.0	0.0	14.3

Derivation of design values

Table 3 shows the fv, fb and MOE parameters derived from the bending tests of the two types of beams. These values were used to determine the maximum allowable length for each beam at ΦMn, ΦVn and EI, respectively. The results obtained show that first of all, the two types of beams made of *D. panamensis* timber have higher values than the beams made of *H. alchorneoides* timber (Table 3 and 4). It is also observed that solid timber beams have higher values of fv and MOE than those presented in glued laminated timber beams (Table 3). But in the case of the fb parameter, it is higher in glued laminated timber beams in relation to solid timber beams.

Table 3. Design values for glued laminated timber and solid timber beams built with *D. panamensis* and *H. alchorneoides* wood.

Spicies	Type of beam		fv (MPa)	fb (MPa)	MOE (GPa)
D. panamensis	5x10 cm	Glued laminated timber	0.65	26.42	2.94
		Solid timber	2.59	9.36	5.13
	5x15 cm	Glued laminated timber	0.28	14.74	2.71
		Solid timber	1.83	9.33	2.52
H. alchorneoides	5x10 cm	Glued laminated timber	0.33	10.41	3.95
		Solid timber	2.45	16.61	6.82
	5x15 cm	Glued laminated timber	0.38	3.24	1.95
		Solid timber	1.81	23.13	5.12

With respect to the nominal bending strength (ΦMn), the two species and different cross section of beam presented different behaviors (Table 4). In the beams of *D. panamensis* the glued laminated timber beams presented higher values than the solid timber beams, but in the beams of *H. alchorneoides* the behavior was the opposite, the solid timber beams presented higher values of ΦMn. In the nominal shear strength parameter (ΦVn), the solid timber beams of the two tested species presented higher values than the glued laminated timber beams. The bending stiffness (EI) was higher in the solid timber beams of 5x10 cm cross section of *D. panamensis* and in the solid timber beams of the two cross section of *H. alchorneoides,* but the glued laminated timber beams of 5x15 cm cross section of *D. panamensis* presented the highest value of EI (Table 4).

Table 4. Design values for glulam and solid wood beams constructed with *D. panamensis* and *H. alchorneoides.*

Specie	Type of beam		ΦMn (kN-m)	ΦVn (kN)	EI (kN-m^2)
D. panamensis	5x10 cm	Glued laminated timber	4.75	4.66	12.27
		Solid timber	1.68	18.68	21.39
	5x15 cm	Glued laminated timber	5.97	3.07	38.15
		Solid timber	3.78	19.78	35.37
H. alchorneoides	5x10 cm	Glued laminated timber	1.87	2.36	16.47
		Solid timber	2.99	17.62	28.41
	5x15 cm	Glued laminated timber	1.31	4.15	27.39
		Solid timber	9.36	19.55	71.95

Figure 6 represents the maximum allowable lengths and overload for the use of beams as floors with spans of 40, 60, 80, 100 and 120 cm for the two species and two cross sections of beams, commonly used in Costa Rica. For example, in solid timber beams of *D. panamensis* of 5x10 cm cross sections with a spacing of 40 cm and a load of 500 kg/m^2, it is necessary to use a span of approximately 1.2 m, but if the beam is fabricated in laminated form, the span increases to 1.35 m (Figure 6a). On the other hand, if the cross section of beams in *D. panamensis* is 5x15 cm of cross section, the span for solid timber beams is 1.35 m and 1.95 m for glued laminated timber beams (Figure 6b). This same behavior was present in the beams of *H. alchorneoides*, but with the difference that the span was slightly smaller in the two cross sections of each type of beam (Figure 6c-d).

According to the classification proposed by the Andean Group for the tropical woods of South American countries, Group D can include species with basic specific gravity from 0.56 to 0.70 (Keenan et al., 1987). Thus, the two species studied can be classified in this species group. For the species located in this group, design values in bending of 15 MPa for fb are presented, which is lower or similar to the glued laminated timber beams, but the solid timber beams do not comply with this category, so they are categorized in group C, since they present values close to 10 MPa, which is the range proposed by the classification proposed for the Andean Group. This behavior and the presented overload results (Figure 6) show that glued laminated timber beams, as expected, present a better behavior in bending parameters and therefore in design values, resulting in wider span values than those used for solid timber beams (Ndong Bidzo et al., 2021).

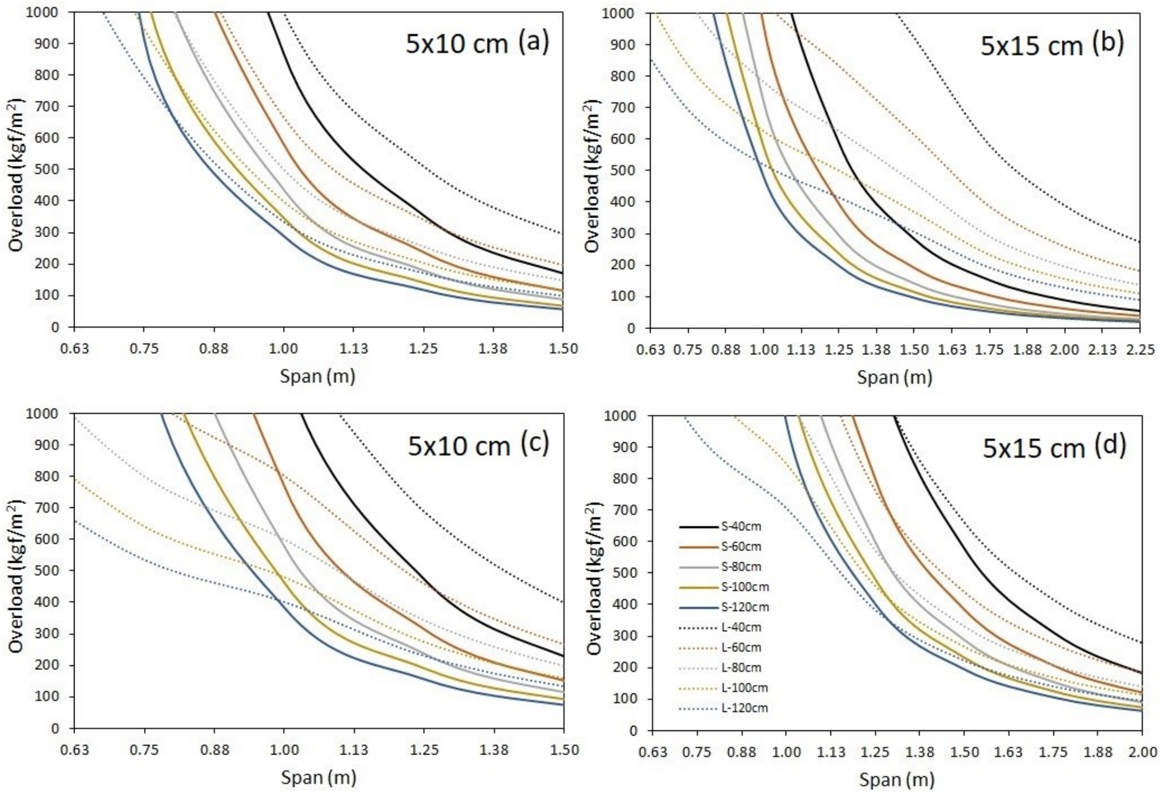

Figure 6. Overload vrs span for glued laminated timber and solid timber beams fabricated with *D. panamensis* (a and b) and *H. alchorneoides* (c and d) wood.

Conclusions

Although problems have been reported for its commercialization due to the lack of products of higher engineering value. Costa Rican plantation timbers such as *D. panamensis* and *H. alchorneoides* whose characteristic is a high basic specific gravity, are a viable option for commercialization and fabricate of glue laminated timber beams thus becoming an engineered product with adequate bending design values when compared to solid timber beams or to design values used for tropical timbers for similar densities, therefore it is possible to reach wider spans, when the proposed glued laminated timber beams are used as floors.

Other conclusions can also be derived from the present study: (1) the glued laminated timber beams fabricated with *D. panamensis* wood present higher bending parameters than the glued laminated timber beams fabricated of *H. alchorneoides* wood and (2) two cross section studied for glued laminated timber beams present different values in the bending strength parameters, so for each one it is necessary to establish the design values separately.

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