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Original article

Analysis of physical and mechanical properties of Cuban Quercus sagraeana wood Nutt from Viñales

Análisis de propiedades físicas y mecánicas de la madera de Quercus sagraeana Nutt. procedentes de Viñales

Análise das propriedades físicas e mecânicas da madeira de nogueira-da-Índia Quercus sagraeana. de Viñales

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SUMMARY

The diversification of wood use has gained importance on the global stage due to the fact that it replaces products from non-renewable sources of resources, strengthening the multipurpose of this renewable matrix. Therefore, the objective of this work is related to determining the radial variation of physical and mechanical properties of *Quercus sagraeana wood*, from areas of the Viñales Science and Technology Unit, in the province of Pinar del Río, Cuba. Ten 54-year-old trees are used and the physical-mechanical properties of the wood are determined from logs obtained at 1.30 m height from each tree, using the standards NC-43-37-87; ISO 13061-2; ISO 3787; ISO 3132 and ISO 3133. Measurements were made at three different radial positions in the pith-to-bark direction. The results show a strong effect of the pith-to-bark distance parameter on all the wood characteristics studied. Therefore, the radial variation in wood characteristics indicates that *Q. sagraeana* tends to develop a significant positive relationship between the strength properties of the wood and its density. It can be applied to sawing schemes for logs of *Q. sagraeana.* The opening cut dimensions to obtain the highest volumes of quality wood. Taking into account the variation in the properties studied in the radial direction of the logs.

Keywords: evaluation, density, contraction, compression, bending

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RESUMEN

La diversificación del uso de la madera ha ganado importancia en el escenario mundial por el hecho de sustituir los productos oriundos de fuentes de recursos no renovables, fortaleciendo el multiuso de esta matriz renovable. Por lo que el objetivo del presente trabajo está relacionado con determinar de la variación radial de propiedades físicas y mecánicas de la madera de *Quercus sagraeana*, procedente de áreas de la Unidad de Ciencia y Tecnología Viñales, en la provincia de Pinar del Río, Cuba. Se utilizan 10 árboles de 54 años de edad y las propiedades físico-mecánicas de la madera se determinan a partir de trozas obtenidas a 1.30 m de altura de cada árbol, al emplear las normas NC-43-37-87; ISO 13061-2; ISO 3787; ISO 3132 e ISO3133. Las mediciones se realizaron en tres posiciones radiales diferentes en dirección médula corteza. Los resultados obtenidos permiten concluir que se aprecia un fuerte efecto del parámetro distancia de la médula a la corteza en todas las características de la madera estudiadas, por lo tanto, la variación radial de las características de la madera indica que *Q. sagraeana* tiende a desarrollar una importante relación positiva, entre las propiedades de resistencia de la madera y su densidad. Aplicar en los esquemas de aserrado de trozas de *Q.sagraeana* las dimensiones de corte de apertura para obtener los mayores volúmenes de madera de calidad. Al tener en consideración la variación de las propiedades estudiadas en la dirección radial de las trozas.

Palabras clave: evaluación, densidad, contracción, compresión, flexión

RESUMO

A diversificação do uso da madeira tem ganhado importância globalmente ao substituir produtos de fontes não renováveis, reforçando a polivalência desse recurso renovável. Portanto, o objetivo deste trabalho está relacionado à determinação da variação radial das propriedades físicas e mecânicas da madeira de *Quercus sagraeana*, proveniente de áreas da Unidade de Ciência e Tecnologia de Viñales, na província de Pinar del Río, Cuba. São utilizadas dez árvores com 54 anos de idade e as propriedades físico-mecânicas da madeira são determinadas a partir de toras obtidas a 1,30 m de altura de cada árvore, utilizando as normas NC-43-37-87; ISO 13061-2; ISO 3787; ISO 3132 e ISO3133. As medições foram feitas em três posições radiais diferentes na direção da medula e do córtex. Os resultados obtidos permitem concluir que se observa um forte efeito do parâmetro distância da medula à casca em todas as características da madeira estudada, portanto, a variação radial das características da madeira indica que *Q. sagraeana* tende a desenvolver uma importante relação positiva entre as propriedades de resistência da madeira e sua densidade. Aplique as dimensões de corte de abertura aos esquemas de serragem para toras de *Q .sagraeana* para obter os maiores volumes de madeira de qualidade. Levando em consideração a variação das propriedades estudadas na direção radial dos troncos.

Palavras-chave: avaliação, densidade, contração, compressão, flexão

INTRODUCTION

Demand for raw materials continues to rise, while the supply of wood is even more limited. A key role is played by the diversification of fast-growing species that, in addition to adapting to soil and climate conditions, are highly productive and produce good-quality wood.

The global trend toward using forest products or byproducts, especially those from natural forests, has driven the introduction of species with high productive potential, hence the need to adapt the forestry industry to meet this growing demand.

The great variability between forest species must also be considered, as well as their different properties, among them, those that indicate possibilities of using wood for the most diverse purposes, including the production of furniture and the levels of customer satisfaction based on the psychological well-being that wood provides (Lipovac & Burnard, 2020).

In the primary and secondary wood processing industry, reductions in maintenance and production costs are evident, along with optimized production and maximized revenue. The constant change in sawing techniques, as well as the mechanical characteristics of forest species, influence the quality of the product obtained from primary wood processing. The variation in the physical and mechanical characteristics of wood and the cutting parameters, focused on wood quality, are proportional (Torkghashghaei). *et al.*, 2023).

In Cuba, although there are important technological advances in the sector of the use of wood as a raw material, there is still a need to improve the level of knowledge in the area of wood properties to increase the levels of efficiency of mechanical transformation processes and their use (Álvarez *et al.* 2020; Guera *et al.* 2021; Valdés *et al.* 2022). Therefore, the objective of this work was to determine the radial variation of physical and mechanical properties of *Quercus sagraean wood.*

MATERIALS AND METHODS

Working conditions

The research begins with the selection of individuals, using the species *Quercus sagraeana* Due to its complexities, its introduction into the secondary wood processing industry has not been the most effective. Individuals were selected in areas of the Viñales Basic Science and Technology Unit, part of the Agro-Forestry Research Institute (Figure 1).

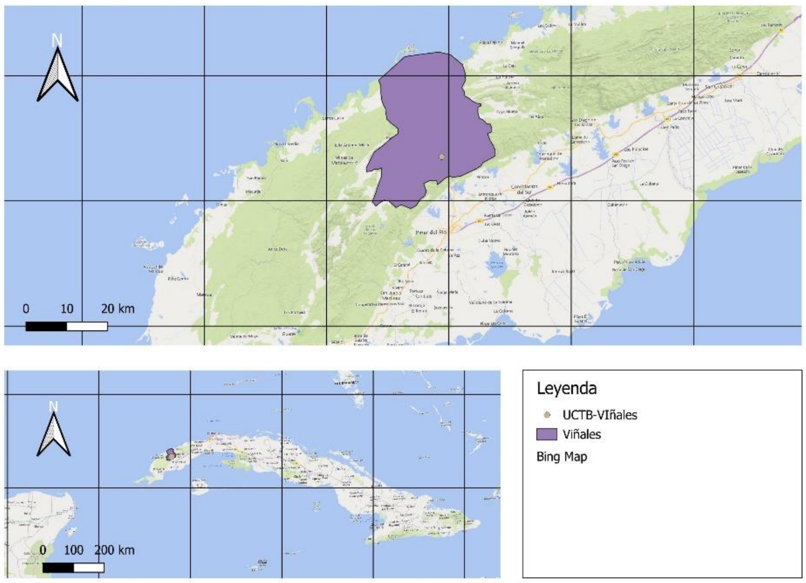

Figure 1. *- Location of the study area. Source: Prepared by the authors, QGIS 3.34*

Located in the north-central part of Pinar del Río province, it borders the Bahamas Strait to the north, the municipalities of Pinar del Río and Consolación del Sur to the south, the municipality of La Palma to the east, and the municipality of Minas de Matahambre to the west. Since the last quarter of the 18th century, the region's vegetation has been severely depleted, always in pursuit of economic and social development. This deforestation was most severe in the valleys and northern plains, and less severe in the limestone mountain ranges and mogotes (Guerra *et al.*, 2019).

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Sample preparation

Determining the number of samples used in the research

Simple random sampling is used, using ten trees, with the diameter at 1.30 m height as the viable tree of interest, according to the methodology proposed by Álvarez *et al.* (2020) and Pupo *et al.* (2023) ; which use the following equations 1 and 2:

$$n=\frac{t^2 s_x^2}{E^2} \qquad (1)$$

$$E=(LE^*\overline{X})(2)$$

Where:

n = number of samples;

t^2= *Student* '*s t* -squared

statistic; LE = limit of permissible sampling error.

This resulted in a sample of ten trees, which were selected completely at random, avoiding edge effects and trees smaller than 20 cm in diameter. At a height of 1.30 m, two 50 cm long logs were extracted and numbered. Twenty test pieces were taken from each log. The determination of the physical and mechanical properties of each sample in each log is carried out from the core to the bark; in agreement with Álvarez *et al.*, (2020) Figure 2.

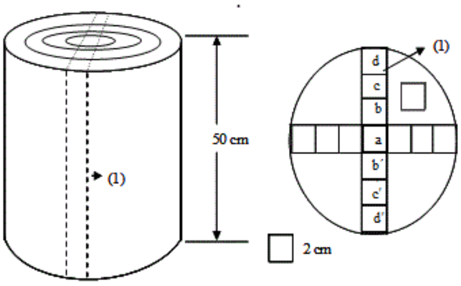

Figure 2. *- Sample preparation*

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Q. cubana wood

In the Materials Strength Laboratory in Pinar del Río, belonging to the Ministry of Construction, the obtained test specimens are placed in a climate-controlled environment with a temperature of 20 ° C and a relative humidity of 65 % (ASTM-D13, 2009) , until an equilibrium humidity of approximately 12 % is obtained; the methodology proposed by Virgen *et al.* was taken into consideration. (2022) and Aramburu *et al*. (2023)

Table 1 shows aspects related to the dimensions of the test pieces used to determine the physical and mechanical properties of wood depending on the different standards used.

Table. *I - General information on the mechanical tests analyzed*

Properties of wood	Standard used	Dimensions of the test pieces (mm)	Number of test tubes used
Wood shrinkage (volumetric, β_v; tangential, β_t; radial β_r and axial β_a).	ISO 3133 (E)-75	20x20x20	100
Green Density (DENS $_v$).	ISO 3133 (E)-75	20X20X25	100
Compression parallel to the fibers (MORCpl).	ISO 3787	20x20x50	100
Compression perpendicular to the fibers. (MORCpp)	ISO 3737	20x20x50	100
Static Flexion (FE).	ISO 3133-75	20x20x340	100

To determine the magnitudes of the physical and mechanical properties studied, the following mathematical expressions are used according to the methodology developed by Marini *et al.* (2020) ; Knapic *et al.* (2022); Virgen *et al.* (2022) and Costa *et al.* (2023) Equation 3:

Total volumetric shrinkage

$$\beta v = \frac{V_S - V_O}{V_s} * 100 \quad (3)$$

Where:

B - total volumetric contraction;

%; V_s - saturated volume, cm^3;

V_o - volume in anhydrous state, cm^3

Tangential shrinkage (β_t), Radial shrinkage (β_r) and Axial shrinkage (βa)

According to Ibáñez and Gherscovic (2021) , the expressions that define the Tangential Contraction, Radial Contraction and Longitudinal Contraction, are defined as follows equations 4; 5; 6; 7 and 8:

$$\beta_{(t,r,l)} = \left[\frac{d_s - d_o}{d_s}\right] X\ 100 (4)$$

Anisotropy (CA)

$$CA = \frac{\beta_t}{\beta_r} (5)$$

Green Density (DENSv)

$$DENS_v = \frac{P_v}{V_v} (6)$$

Where:

$DENS_{12}$ - Green density, $cm^3 * g^{-1}$;

P_v - weight of green wood,

g; V_{12} - Volume of green wood, cm^3.

Compression parallel to the fibers (MORC)

$$MORC = \frac{F_{max}}{a*b} (7)$$

Where:

F_{max} - Force applied to the test pieces at the limit of proportionality, kgf ; a - Width of the test pieces, cm;

b - Thickness of the test pieces, cm.

Static Flexural Strength (FE)

Taking into account the results presented by Carmona *et al.* (2020) , the static bending resistance is determined from the following mathematical expression:

$$FE = \frac{3*P*L}{2*a*b^2} (8)$$

Where: P- Maximum breaking load, kgf ; L- Distance between supports, cm; a- Width of the specimen; b- Thickness of the specimen, cm.

Statistical analysis

Statistical differences in wood properties are determined by analysis of variance (ANOVA), with a significance level of $p < 0.05$; this is consistent with the methodologies proposed by Modes. *et al.* (2020) .

RESULTS AND DISCUSSION

Table 2 shows the average values obtained related to the physical properties studied of *Quercus sagraeana wood* where results are higher than those obtained by Nazari *et al.* (2020), for *Quercus brantii* Lindl. The average tangential shrinkage is 9.4%, radial shrinkage 6.40%, and longitudinal shrinkage 4.55%, which suggests that the species does not suffer severe deformation due to moisture loss.

Table 2. *- Descriptive statistics of the physical properties.*

Properties	Number of test tubes	Average	Standard deviation
Green Density (DENS $_v$), g*cm $^{-1.}$	100	1.21	0.039
Contraction total volumetric (β $_v$), %.	100	9.58	1.401
Contraction tangential, %.	100	9.40	2.70819
shrinkage, %.	100	6.40	1.38569
shrinkage; %.	100	4.55	0.4572
Anisotropy.	100	1.47	0.12354

It is noteworthy (Table 2) that the green density of the wood of *Quercus sagraeana* is 1.21 g/cm ^{3}, higher than the results obtained by Nazari *et al.* (2020), when these authors present values of 0.78 g/cm ^{3}. Density values that are considered high according to the classification proposed by the aforementioned group of authors, for which the species is classified as very heavy.

Honorato and Fuentes (2021) obtained density values of 0.72 g/cm ^{3} in the wood of white oaks in the state of Guanajuato, Mexico; they also analyzed the volumetric shrinkage values, where they concluded that the species classifies as low-nerve wood. The average value obtained in terms of shrinkage, in this research, shows that the species *Quercus sagraeana* presents low contraction, coinciding with the results obtained by Nazari *et al.* (2020).

Quercus sagreana wood in the radial direction

The analysis of variance performed allows the comparison of means of the three contractions studied using the Duncan test. It is observed that there are statistically significant differences between the magnitudes of the contraction for the axes that are manifested in wood, as an orthotropic material; this coincides with the results obtained by Erdene-Ochir. *et al.* (2021).

It is also worth considering the variation that is evident in the cross section of the wood, such behavior of the measured physical properties, reflects the differences in the anatomical elements that form the late wood and early wood, as well as the appearance of juvenile wood and adult wood, agreeing with the results proposed by Winck. *et al.* (2022). Table 3 shows the behavior of the physical properties of the studied wood in the pith-bark direction.

Table 3. - *Analysis of the mean comparison of the physical properties of Quercus sagraeana wood in the pith-to-bark direction. Duncan test*

Property	Position of the samples in the medulla-cortex direction			
	TO	B	C	D
Volumetric contraction, %.	10.32a	9.96b	8.51d	9.53c
Tangential Contraction, %.	10.42a	9.94b	8.01d	9.25c
Shrinkage, %.	7.34a	7.30a	4.81c	6.15b
Anisotropy.	1.42b	1.36b	1.67a	1.50a
Green density, $g*cm^{-1}$.	1.68a	1.35b	0.70d	1.11c

Results with different letters express that there is a significant difference for $p < 0.05$

Obviously, the contraction towards the three fundamental axes of the wood varies depending on the anisotropy that it presents, in this sense, the axial and radial contraction present significant differences, but not so for the longitudinal contraction, this tendency corresponds to the results obtained by Nazari *et al.* (2020) .

This increasing growth in contractions in the medulla-cortex direction is related to the increase in green density in the same direction; this coincides with Nazari *et al.* (2020), establishing that the magnitude of the dimensional variation is proportional to the quantity of wood per volume analyzed.

The anisotropy coefficient of *Q. sagraeana,* according to Table 3, it is 1.45; this is significant because the greater the anisotropy ratio, the greater the tendency for cracks to develop in the wood, as well as deformations due to variations in moisture content as a result of desorption.

It is in agreement with Álvarez *et al.* (2020); it is shown that density is one of the factors with the greatest influence on wood quality. Many of its properties, such as hardness, mechanical properties, shrinkage, and resistance to biodegradation, are strongly affected by density (Herrera *et al.*, 2017) . Therefore, the radial variation in the physical properties of *Q. sagraeana wood,* shown in Table 2, corresponds to the growth of density from the pith to the bark; this corroborates the results obtained by Loiola. *et al.* (2021) and Winck *et al.* (2022) , which suggest a greater presence of adult wood as the section moves away from the medulla.

Analysis of mechanical properties

Mechanical properties allow us to determine the potential strength of a wood species and its potential value. Their radial behavior is a determining factor in the mechanical processing of wood, as well as in increasing its added value as a raw material. These aspects are consistent with the work developed by Vega *et al.* (2020) .

Among these, the responses to compression parallel to the fiber, perpendicular to the fiber, and static bending in the radial direction were analyzed, revealing a notable increase in their magnitudes in favor of the corresponding strength and modulus of rupture; in this respect, this coincides with the work developed by Belleville *et al.* (2020) and Fos *et al*. (2023) (Table 4).

Table 4. *- Analysis of comparison of means of the physical properties of Q. Sagraeana wood in the medulla-cortex direction. Duncan test*

Property	Position of the samples in the medulla-cortex direction			
	TO	B	C	D
Parallel compression to the fibers, kgf /cm ².	520.24d	600.01c	708.32b	1004.25a
Perpendicular compression to the fibers, kgf /cm ².	281.21d	311.34c	382.87b	542.84a
Static Flexion, kgf /cm ².	846.45c	976.47b	1154.32b	1633.94a

The values obtained for the three properties analyzed are in correspondence with the results presented by Jiang *et al.* (2014) and Aydin (2020); are superior to those presented by Carmona *et al.* (2020 ; denote the high resistance present in this species, which enables it to be used for engineering purposes according to Guerra *et al.* (2019), who classifies the species as very resistant.

Based on the above, it is defined that for a better use of *Quercus sagraeana* logs in the sawmill; in order to obtain different wood products, it is necessary to develop a sawing methodology that optimizes the opening cut for greater use of the wood close to the bark, which means that this section of wood is more resistant and of higher quality.

From what is explained below, how with the use of descriptive geometry and differential calculus, the proposed result can be achieved for decision-making during the production process.

This is why it is crucial to find a mathematical expression that guarantees the maximum volume of a rectangular base beam to be obtained from a log identified as a truncated cone. In solving this problem, the theory of extremes of functions of a real variable is used.

Therefore, a log of length "l" has a conical shape depending on the variation in the diameters at the base and the diameter at the tail; this results in a reduction in the efficiency of the primary wood processing process in sawmills. The goal is to find a rectangular-based prism with the largest possible volume, using the conical log (Figures 3 and 4, Equation 9).

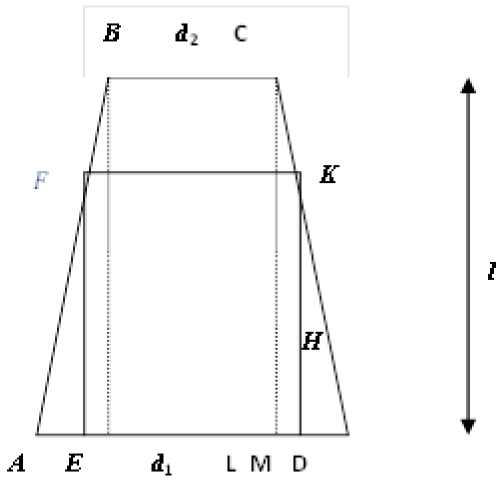

Figure 3. *- Cross section of the log and the largest possible volume prism to be extracted from it*

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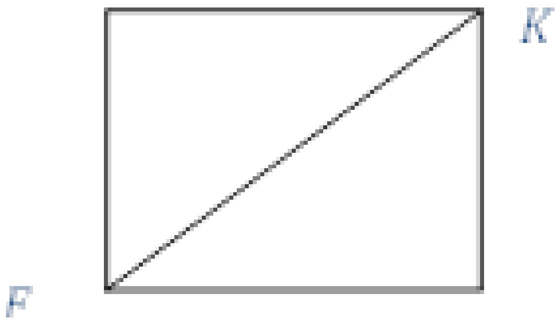

Figure 4. *- Cross section of the rectangular base prism*

$$Fk = em = d1 - 2\,md \qquad (md = ea).\ (9)$$

$$d:\ diámetro\ \ de\ la\ base.$$

$$si\ \Delta\, cld \sim \Delta kmd$$

$$\Delta\, kdm = \Delta\, cdl\ (\Delta\ comunes).$$

$$\Delta\, kmd = \Delta\, cld\ 90^{0}\ \ (cl \perp ad\ y\ km \perp ad)$$

It is true that:

Since Fk is the diagonal of the cross section of the rectangular base prism, the function to be optimized is Equation 10:

$$V = Ab * H(10)$$

It is taken into account that in a circle the rectangle with the largest area that can be inscribed is the square, it is considered that the prism of greatest interest has a square base.

It is taken into account that the solution values must be in the interval (0, l), the point is discarded, then the point Equation 11 is analyzed;

$$,h = \frac{d_1 l}{(3d_1 - 3d_2)} \qquad (11)$$

$$\mathbf{0} \qquad \frac{l}{3} \qquad \frac{d_1 l}{(3d_1 - 3d_2)} \qquad \frac{2d_1 l}{(3d_1 - 3d_2)} \qquad \frac{\boldsymbol{d_1 l}}{(\boldsymbol{d_1 - d_2})}$$

$$\frac{d_1 l}{(3d_1 - 3d_2)} < \frac{2ld_1}{3d_1 - 3d_2} < \frac{ld_1}{d_1 - d_2}$$

$$\left.\frac{dV}{dh}\right|_{h=\frac{2ld_1}{3d_1-3d_2}} = (\frac{d_1}{3}).(-\frac{3d_1}{6}) < 0$$

Therefore, it is enough to take $h = \frac{d_1 l}{(3d_1-3d_2)}$, so that the volume of the square-based prism is maximum.

After determining the optimal height, the cutting distance is calculated in order to obtain the greatest possible volume of wood from the log Figure 5.

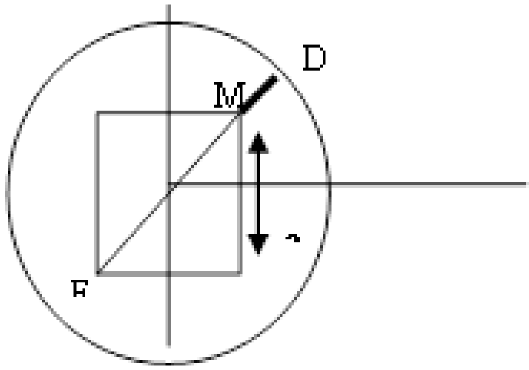

Figure 5. *- The prism within the diameter of the base*

These equations provide the results for calculating cutting length by diameter class for the species under study. It is noteworthy that, in the case of the species under study, sawing methods are not necessary due to factors such as growth stress.

The cutting length (lc) for the opening cut of the log according to the diameter classes is shown in Table 5.

The results of the calculation of the cutting length by diameter classes are obtained from equations. It is noteworthy that in the case of the species under study, it is not necessary to apply sawing methodologies due to factors such as growth stresses.

The cutting length (lc) for the opening cut of the log according to the diameter classes is shown in Table 5.

Table 5. *- Calculation of the cutting length of Quercus sagreana*

CD	db (m)	dr (m)	l (m)	lc (cm)
18.0 - 23.9	0.2093	0.1658	4	4,019
24.0 - 28.9	0.2605	0.2027	4	5,007
29.0 - 33.9	0.3142	0.2352	4	6,057
34.0 - 38.9	0.3863	0.2697	4	7,487

CONCLUSIONS

The results show a strong effect of the parameter distance from the pith to the bark on all the characteristics of the wood of *Quercus sagraeana. An* important positive relation can be seen between the strength properties of wood and its density.

Application in sawing schemes of *Quercus sagraena* logs and the opening cut dimensions provide greater volumes of quality wood, considering the variation of the properties studied in the radial direction of the logs.

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***Conflicts of interest*:**

The authors declare no conflicts of interest.

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The authors have participated in the writing of the work and analysis of the documents.