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ARTÍCULOS

Historic urban trees: Assessing the trunk's internal integrity

Árboles urbanos históricos: evaluación de la integridad interna del fuste

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SUMMARY

In addition to the general benefits that all trees provide, historic urban trees contribute significant cultural and affective value to the quality of life in cities. As these trees age, their maintenance requires meticulous and consistent attention to reduce associated risks. The objective of the present study was to identify and estimate the extent of internal damage in the trunk of historic urban trees. Forty-five *Eucalyptus robusta* trees located in a popular square in the city of Nova Friburgo-RJ, Brazil were evaluated. A visual analysis of the crown, trunk, and root system was performed, followed by complementary evaluations of acoustic tomography and, when necessary, resistography. Mathematical models were adjusted to infer the relationship and influence of dendrometric characteristics (total height, height to the first branch, diameter at 1.30 m above the ground, and crown diameter) and the mean resistographic amplitude on the mean wave propagation velocity acoustic. Most trees presented some form of external lesion on their trunks, and, generally, trees with severe lesions also exhibited alterations in the propagation velocity of acoustic waves and in the perforation resistance profile. The combination of different techniques allows for the identification of areas with possible internal injuries in the trunks of historic urban trees. However, it is worth noting that the extent of these areas varied among the techniques used.

Keywords: visual analysis, acoustic tomography, resistography.

RESUMEN

Además de los beneficios que aportan todos los árboles, en general, el valor cultural y afectivo que aportan los árboles urbanos históricos contribuye a la calidad de vida de las ciudades. A medida que envejecen, el cuidado con su mantenimiento debe ser cuidadoso y constante, con el objetivo de reducir los riesgos asociados. Así, el objetivo del presente estudio fue identificar y estimar la extensión de las áreas internas lesionadas en el tronco de árboles urbanos históricos. Se evaluaron 45 árboles de *Eucalyptus robusta* ubicados en una plaza popular en la ciudad de Nova Friburgo-RJ, Brasil. Se realizó un análisis visual de la copa, tronco y sistema radicular, seguido de evaluaciones complementarias de tomografía acústica y, cuando fue necesario, resistografía. Se ajustaron modelos matemáticos para inferir sobre la relación e influencia de las características dendrométricas (altura total, altura a la primera rama, diámetro a 1,30 m sobre el suelo y diámetro de copa) y la amplitud resistográfica media sobre la velocidad media de propagación de la onda acústica. La mayoría de los árboles presentó algún tipo de lesión externa en el tronco y, en general, los árboles con lesiones severas también presentaron alteraciones en la velocidad de propagación de las ondas acústicas y en el perfil de resistencia a la perforación. La combinación de diferentes técnicas permite identificar zonas con posibles lesiones internas en los troncos de árboles urbanos históricos. Sin embargo, se observa que la extensión de estas áreas varía entre las técnicas utilizadas.

Palabras clave: análisis visual, tomografía acústica, resistografía.

INTRODUCTION

Urban trees are essential in enhancing the quality of life in cities due to the diverse ecosystem services they provide. With proper maintenance and management, trees provide aesthetic, social, ecological and economic benefits proportional to their size and stage of development.

The morphological diversity exhibited by leaves, flowers, and fruits, combined with the countless aesthetic possibilities presented by urban trees, contributes to visually pleasing environments. These environments, in turn, encourage engagement in recreational physical activities and provide communal spaces, ultimately bolstering the physical well-being of the population and fostering a sense of community (de Vries *et al*. 2003, Arnberger and Eder 2012, Wang *et al.* 2019). In the social context, historic urban trees are especially important for local heritage and the development of affective memory between different generations (Ariffin *et al.* 2019). Urban trees also serve to reduce atmospheric pollution and mitigate climate change through CO_2 assimilation, air temperature regulation and reduction of rainwater runoff (Zhang *et al.* 2015, García-Sánchez *et al.* 2019, Locosselli *et al.* 2019, Ren *et al.* 2019, Rötzer *et al.* 2019). Their presence also translates into economic advantages, with the shade provided by tree canopies leading to reduced energy consumption for ventilation and air conditioning as well as extending the lifespan of asphalt (Mcpherson and Muchnick 2005, Donovan and Butry 2009). Moreover, they enhance property value, significantly increasing the overall worth of residential homes (Donovan *et al.* 2019).

Trees are highly responsive to their surrounding environmental conditions and are subject to constant mechanical stress arising from factors such as their own weight, the presence of inclined or horizontal branches, and the influence of winds (Allison and Wang 2015). In extreme weather scenarios, these stressors can escalate into significant issues. In this regard, biomechanics emerges as a valuable tool in risk management, as it delves into the structural properties of biological organisms and their interactions with the environment (Dahle *et al.* 2017). Parameters like tree morphology, branch distribution, presence of internal lesions, and root system patterns are pivotal in understanding how trees respond to the externa forces. This knowledge serves as a foundation for evaluating potential consequences of structural failures and devising strategies for corrective measures (Vargas-Silva 2019).

In order to preserve the environmental services provided by urban trees and ensure the safety of potential targets, particularly people, it becomes imperative to develop and implement rapid and precise diagnostic methods for managing risks associated with trees. When coupled with adequate urban planning, these techniques can reduce the likelihood of accidents and ensure tailored and proactive management strategies that align with the unique characteristics of each urban setting.

In Brazil, risk assessment is conducted at three distinct levels, taking into account the entirety of the tree's surroundings. Level 1 entails a visual analysis of the trees without the need for specialized equipment. Level 2 involves a more comprehensive visual analysis, encompassing features of the visible root system, root collar, trunk, and crown of the tree, which may necessitate the use of handheld tools. Level 3 assessments require the examination of branches or the application of advanced methods and technologies to assess the presence and extent of internal defects within the tree (ABNT 2019).

Relying solely on visual inspection can lead to underestimation of the risk associated with tree failure. Therefore it is advisable to complement visual assessments with techniques that provide insights into the nature and characteristics of potential defects. Non-destructive wood assessment methods can be used to locate and quantify the occurrence of internal defects within trees, contributing to the monitoring and risk management associated with tree fall hazards (Allison and Wang 2015). Notably, acoustic tomography and perforation resistance are among the commonly employed methods for this purpose.

Acoustic tomography is employed to visualize the internal cross-sections of a tree's trunk by generating color graphics, known as tomograms, which are created based on the transmission time of mechanical waves within the wood. The appearance and diversity of colors in a tomogram depend on the type of lesion or defect within the tree. Generally, areas with slower wave speeds may indicate the presence of decayed wood, hollows or cracks (Allison and Wang 2015). Tomography has proven effective in evaluating defects in urban trees (Wang *et al.* 2007, Carvalho *et al.* 2019), but the number of sensors is crucial in locating and determining the magnitude of defects (Arciniegas *et al.* 2014). To ensure accurate diagnosis, the use of complementary tools is essential.

In certain scenarios, the acoustic tomogram tends to overestimate the size of a lesion, especially when cracks are present (Allison and Wang 2015). In such cases, an analysis of perforation resistance can provide valuable insights for assessing the tree's risk (Wang *et al.* 2007). Resisography involves measuring the wood's resistance to penetration as a drill advances linearly. The presence of hollows, cracks and lesions can be detected by the characteristic reduction in resistance as the drill progresses (Allison and Wang 2015). In risk assessments, resistography is employed subsequente to initial inspection methods to confirm and determine the extent of any identified lesions (Johnstone *et al.* 2007, Rollo *et al.* 2013, Koeser *et al.* 2017).

Applying these techniques can be effective in the management of urban trees, particularly those with historical significance that require meticulous care. When utilized appropriately, these methods contribute to minimizing safety risks by providing guidance on essential corrective actions, such as pruning. In cases where the risks outweigh the benefits, these techniques can also inform recommendations for the replacement of the tree specimen. Therefore, the primary objective of this study is to identify and assess the extent of internal injuries within the trunks of historic urban trees.

METHODS

A total of forty-five centenary *Eucalyptus robusta* Sm. trees were evaluated in Praça Getúlio Vargas, Nova Friburgo, RJ, Brazil (22° 16' 49" S, 42° 31' 56" W). This square, originally designed by the French landscape architect and botanist Auguste François Marie Glaziou at the end of the 19th century, holds significant historical and cultural value. In 1972, it was designated as the "Architectural and Landscape Ensemble of Praça Getúlio Vargas" by IPHAN (National Historical and Artistic Heritage Institute) (Correa 2019).

Initially, a visual analysis of the crown, trunk and visible root system was conducted to identify physical damage, the presence of pathogens, and external cavities. This preliminary assessment guided the subsequent analyses of the stem's internal integrity. The trunk was evaluated for the presence or absence of external lesions. In cases where lesions were present, they were categorized as follows: i) light lesion: referring to superficial lesion on the trunk; ii) moderate lesion: indicating trunk injuries resulting from accidents or previous pruning; iii) severe lesion: denoting trunk cavities and injuries that facilitate pathogen entry and compromise the tree's stability. Additionally, dendrometric variables such as total height (m), height to the first branch (m), diameter at 1.30 m above the ground (DBH) (cm), and crown diameter (m) were measured.

Subsequently, the ARBOTOM® (Rinntech) acoustic tomograph was used to assess the propagation characteristics of acoustic waves within the tree's wood. This process entails positioning eight vibration sensors at the base of each trunk, with sensor 1 oriented towards the north. The sensors were attached by driving nails through the bark until they reached the sapwood. The transmission of acoustic waves was initiated by gently tapping each sensor with a hammer, until the error (delta %) was less than 10 %. In cases where the tomographic results indicated the presence of considerably large lesions with external indications suggesting possible longitudinal extensions, additional evaluations were conducted at various heights. These involved measuring the circumference of the tree at the specified point and determining the distance between sensors at each level.

The data captured by the sensors, specifically the propagation time of acoustic waves later converted into wave velocities, were used to generate color-coded graphs (tomograms) illustrating the wave velocities within the wood. The process involved configuring the software with the following settings: i) Minimum and maximum filter speeds of 50 and 4,000 m s^{-1}, respectively; ii) Rainbow color model; iii) 2D resolution = 5 mm; iv) Selecting distribution analysis and standard deviation correction; v) Maximum standard deviation = 1. Subsequently, the tomograms were processed, and areas exhibiting low propagation speeds (characterized by pink, red and orange colors) were quantified using ArcMap, a component of ArcGIS Pro.

Following the preliminary evaluation of the tomograms, regions of interest were identified for further verification of wood lesions or hollows using perforation resistance analysis, carried out with the RESISTOGRAPH® Rinntech 4452-S. The equipment was positioned perpendicular to the tree's axis, and the drilling depth was determined according to each specific cross section analyzed. In cases where the tomograms did not exhibit significant drops in wave propagation speed, perforation resistance analysis was not conducted. Radial profiles of perforation resistance were constructed using DECOM software version 2.34. These profiles were subsequently analyzed, identifying the regions that overlapped with the tomograms while disregarding the initial millimeters corresponding to the bark fraction.

Data analysis. Following the confirmation of non-normality in the residues (Shapiro-Wilk test at a 5 % significance level), Spearman's correlation coefficient (at a 5 % significance level) was employed to assess the relationships among all the variables under investigation.

Next, four mathematical models (table 1) were evaluated to deduce the relationship and influence of dendrometric characteristics and the mean resistographic amplitude on the mean velocity of acoustic wave propagation. Linear models were fitted using the ordinary least squares method, while non-linear models were adjusted using the Gauss-Newton algorithm (Scolforo 2005). Model validation was carried out by examining residual distribution, calculating the root mean square error (RMSE), and creating validation plots, in which a linear model was established between estimated values and observed values.

The analysis of residual normality and variable correlation was conducted using PAST 4.02 software, while model fitting was carried out in the R 4.0.5 environment, utilizing the nlstools package for the non-linear models (Baty *et al.* 2015).

RESULTS

In general, the trees exhibited significant variation in dendrometric characteristics, primarily attributable to the management practices implemented over the years (figure 1). The height to the first branch displayed the highest coefficient of variation at 52.69 %, followed by DBH, crown

Table 1. Linear and non-linear models selected to assess the causal relationship between the variables of interest.

Modelos lineales y no lineales seleccionados para evaluar la relación causal entre las variables de interés.

Model			Function
Linear	1	Hyperbolic	$Y = \beta_0 + \beta_1 \frac{1}{X}$
	2	Logarithmic	$Y = \beta_0 + \beta_1 lnX$
Non-linear	3	Potency	$Y = \beta_0 X^{\beta_1}$
	4	Exponential	$Y = \beta_0 e^{\beta_1 X}$

Where: Y = propagation speed of acoustic waves; β_0, β_1 = model coefficients; X = independent variable.

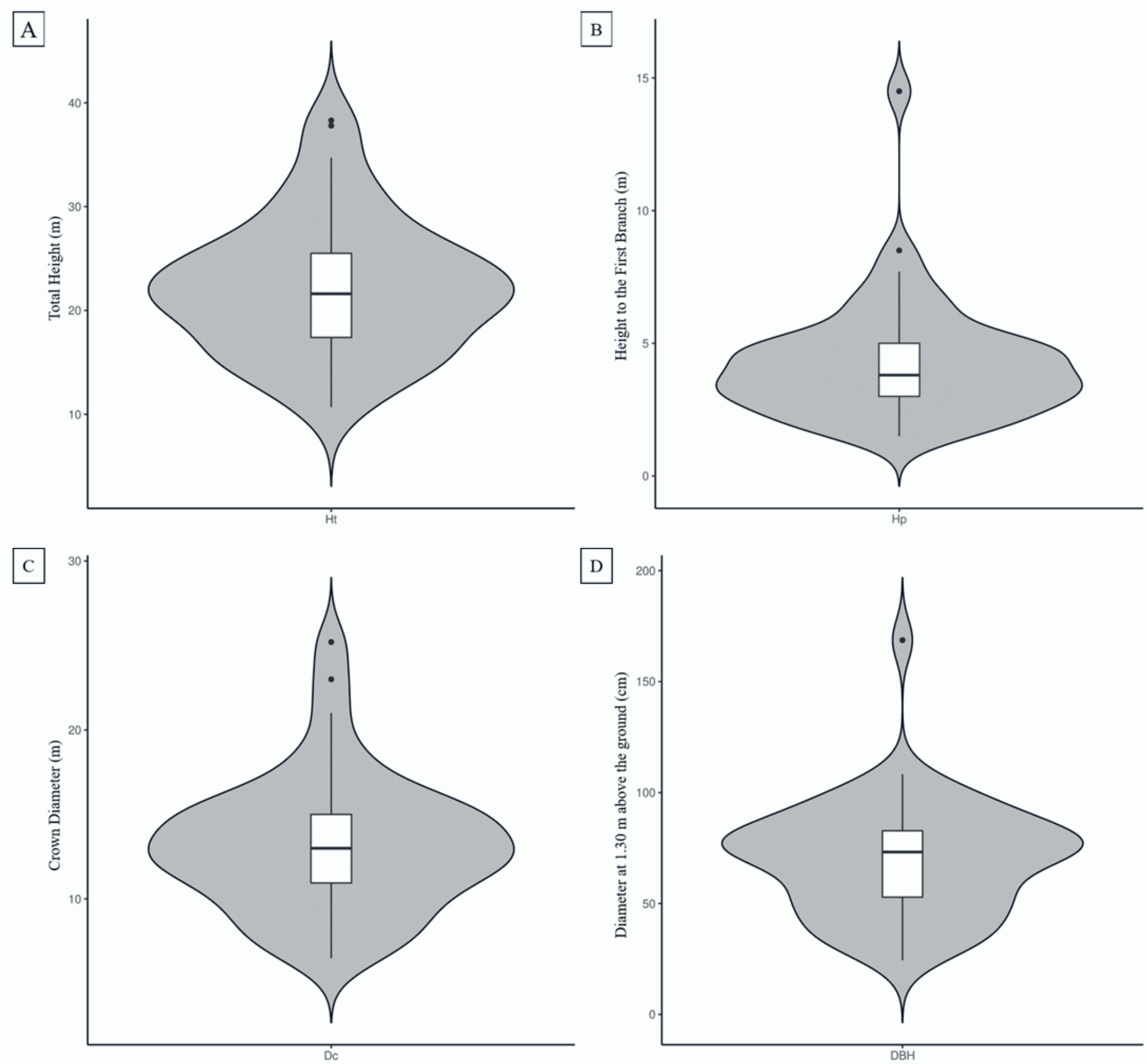


Figure 1. Distribution of dendrometric characteristics of historic urban *Eucalyptus robusta trees*. The central box represents data density and highlights the median (central line) and quartiles (upper and lower limits). Lateral extensions indicate data variation; all variables studied presented skewed data distribution. Black dots indicate outliers, which in this study denote large trees. Where: Ht = total height (m) (A); Hp = height to the first branch (m) (B); Dc = crown diameter (m) (C); DBH = diameter at 1.30 m above the ground (cm) (D).

Distribución de características dendrométricas de árboles urbanos históricos de *Eucalyptus robusta*. El cuadro central representa la densidad de datos y resalta la mediana (línea central) y los cuartiles (límites superior e inferior). Las proyecciones laterales representan la variación de datos; todas las variables estudiadas mostraron una distribución asimétrica de los datos. Los puntos negros indican valores atípicos que, en este estudio, representan árboles grandes. Donde: Ht = altura total (m) (A); Hp = altura a la primera rama (m) (B); Dc = diámetro de copa (m) (C); DBH = diámetro a 1,30 m sobre el suelo (cm) (D).

diameter and total height (37.35 %, 30.70 % and 29.41 %, respectively). All these characteristics exhibited a right-skewed distribution to the right, with the presence of outliers. These values correspond to the largest trees and are not indicative of sampling errors. Most of the trees fell within the following ranges: total height varying between 15 and 35 m, height to the first branch between 2 and 7 m, crown diameter between 7 and 20 m, and DBH between 30 and 100 cm.

Among the evaluated trees, 82.22 % exhibited some form of external lesion on the stem, ranging from light to severe (35.56 % - light lesion, 28.89 % - moderate lesion 17.78 % - severe lesion), often associated with the presence of pathogens and damage from previous pruning. In 87.5 % of trees with severe external injuries, reductions were observed in the propagation speed of acoustic waves and in the perforation resistance profile. Both non-destructive analysis methods exhibited a 72.73 % correspondence, suggesting that more than half of the tomograms that indicated possible material discontinuities were confirmed by the resistance profile. However, in all cases, the size of the regions with low resistance was smaller than the extent of the affected áreas, and thus, the amplitude in these areas was not significantly influenced (table 2).

The minimum values of resistographic amplitude correspond to the initiation of perforation and are associated with the bark region (figure 2).

An example of the combined assessment performed on the trees is shown in figure 2. In this case, all analysis methods indicated external and internal problems. The

Table 2. Descriptive statistics of acoustic wave propagation velocity and resistographic amplitude of historic urban *Eucalyptus robusta* trees.

Estadísticos descriptivos de la velocidad de propagación de ondas acústicas y amplitud resistográfica de árboles urbanos históricos de *Eucalyptus robusta*.

Tree	Velocity of acoustic waves propagation (m s^{-1})				Resistographic Amplitude (%)			
	Min.	Mean	Max.	Affected area (%)	Min.	Mean	Max.	Amplitude in the affected area
1	274	633.3	1,286	0.00	-	-	-	-
2	431	799.6	1,911	9.60	11.7	18.6	30.5	15.8
3	296	737.9	1,626	8.54	18.9	25.9	36.9	25.1
4	265	637.7	2,002	58.83	14.5	35.4	53.6	33.4
5	355	677.2	1,865	34.24	27.1	50.8	66.4	55.9
6	128	734.2	1,980	14.38	26.4	54.1	70.5	64.1
7	461	1,221.8	2,174	0.00	-	-	-	-
8	355	680.9	1,507	13.98	18.6	36.0	57.9	45.2
9	149	484.4	792	5.90	13.2	35.1	49.9	34.6
10	419	730.7	1,563	12.89	15.7	25.5	35.3	26.1
11	296	600.6	1,571	25.59	21.3	32.3	45.2	35.2
12	334	635.9	1,447	13.90	8.9	28.4	40.9	28.4
13	390	700.4	2,005	53.81	18.5	32.9	43.3	38.5
14	266	819.3	1,514	0.00	-	-	-	-
15	288	754.4	3,160	13.42	13.9	41.4	71.1	41.5
16	242	681.6	2,472	21.10	31.6	40.7	53.9	34.8
17	247	998.2	1,624	0.00	-	-	-	-
18	219	494.9	780	0.00	-	-	-	-
19	366	846.5	2,137	4.71	31.5	52.4	71.1	59.1
20	127	692.6	2,518	18.17	15.9	28.8	42.3	27.4
21	214	508.1	2,332	43.84	12.1	18.1	35.5	18.1
22	344	585.1	2,131	76.07	25.9	47.6	64.4	48.1
23	103	528.3	1,932	32.48	16.5	45.7	71.1	45.7
24	347	907.5	2,453	12.71	27.3	40.7	51.7	33.6
25	475	1,754.3	3,712	0.00	-	-	-	-
26	354	1,664.9	3,797	0.00	-	-	-	-
27	423	1,296.2	3,331	5.32	34.5	54.5	71.1	49.4
28	315	1,140.9	2,691	0.00	-	-	-	-

Continue

Table 2. Continued

29	169	461.1	1,070	0.00	-	-	-	-
30	377	745.0	2,102	24.19	13.7	32.5	41.5	33.3
31	455	686.1	1,247	5.96	11.2	38.9	54.0	48.0
32	441	622.8	1,079	3.73	15.3	35.4	50.0	38.1
33	401	677.2	1,346	1.89	22.1	42.2	59.6	51.6
34	189	586.3	2,097	44.25	22.8	42.6	57.7	42.2
35	263	751.8	2,271	22.74	19.3	29.9	42.4	29.9
36	301	897.4	1,743	0.00	-	-	-	-
37	202	481.1	1,039	17.10	10.7	19.0	33.6	19.1
38	396	699.9	1,901	58.45	15.7	35.4	48.5	39.1
39	311	626.6	1,319	19.60	29.3	44.5	69.7	49.1
40	356	929.8	2,078	0.00	-	-	-	-
41	101	474.1	1,641	41.30	11.7	24.3	42.3	24.3
42	225	637.7	1,748	29.82	2.7	19.1	31.5	22.5
43	364	774.0	2,813	46.23	15.7	28.5	36.3	28.5
44	322	622.5	1,018	0.00	-	-	-	-
45	304	1,029.9	3,513	36.14	12.3	21.3	30.1	19.3

The symbol "-" indicates that the perforation resistance analysis was not performed because the tomograms did not indicate a reduction in the wave propagation speed (affected area = 0 %). The affected areas correspond to regions with low velocities (characterized by the colors pink, red and orange in the tomograms).

orange, red and pink areas in the tomograms represent the regions with the lowest propagation speeds of acoustic waves. By analyzing the perforation resistance profile graphs, the corresponding zones were segmented and the mean Resistographic amplitudes were determined. A noticeable alteration in the resistance profile aligns with the low-speed zones.

Correlation analysis indicated a significant positive relationship between the variables DBH and Ht (rs = 0.445; P = 0.002), Dc and Ht (rs = 0.645; P < 0.001) and DBH and Dc (rs = 0.361; P = 0.015) and negative between DBH and Vm (rs = -0.666; P < 0.001) (figure 3).

Since Ht and Dc were directly influenced by the tree management practices, the evaluation of causal effects focused on the DBH and Vm variables. Among the selected models, the hyperbolic model (1) displayed the highest significance and the lowest RMSE (table 3).

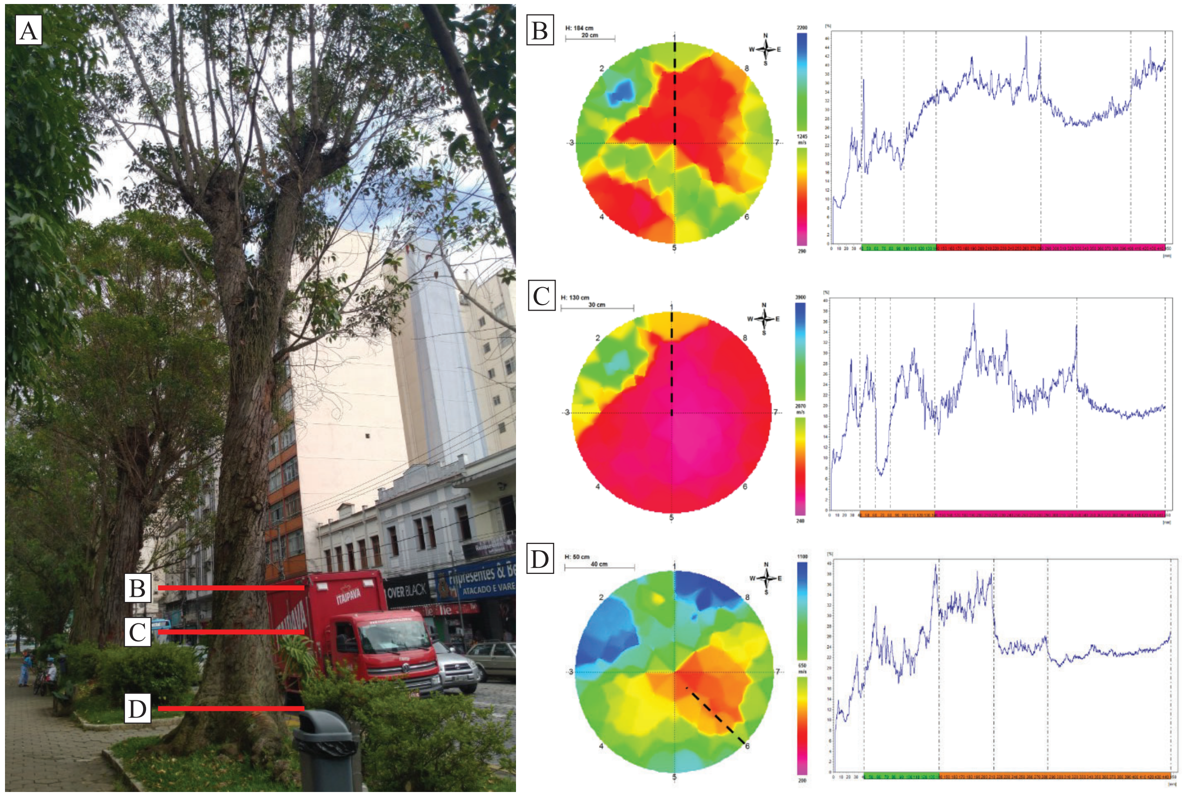
The hyperbolic model provided a better description of the relationship between the variables, and presented a more homogeneous distribution of residuals and a higher coefficient of determination (R^2) between the observed and estimated values (figure 4).

Trees with smaller diameters (< 60 cm) showed a wider range of average speeds (633.3 to 1,754.3 m s^{-1}), whereas an increase in diameter resulted in greater homogeneity of this variable (461.1 to 846.5 m s^{-1}).

DISCUSSION

In 2015, the *Eucalyptus* trees at Praça Getúlio Vargas were subjected to significant pruning (Correa 2019), which directly contributed to the variation in dendrometric characteristics. Furthermore, standard urban afforestation management practices, such as corrective and maintenance pruning, also influence these variables.

Poor urban tree management practices can encourage various degrees of damage. Visual damage may signal internal wood problems that compromise tree integrity and increase associated risks (Wu *et al.* 2018). Advanced techniques like acoustic tomography and resistography help to confirm or rule out these issues. However, tomograms may sometimes indicate potential cavities or lesions that are actually caused by acoustic shadow effects from cracks, which may go unnoticed during Resistograph drilling (Wang and Allison 2008). Although acoustic tomography tends to overestimate damaged areas, particularly with more sensors, its combination with perforation resistance assessment permits a diagnosis of potential internal defects in trees. This is particularly importante for mature trees with high historical and cultural value, which may be susceptible to physical damage (Son *et al.* 2021). The resistance profile of wood is influenced by factors such as the density at the drilling location, growth ring structure



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Visual observations :

Visible root system: root plate lifting.
Trunk: presence of pathogens; trunk with cavities and light lesions that facilitate the entry of pathogens and hinder the stability of the tree.
Crown: presence of dead and/or damaged branches due to previous pruning; presence of drastic pruning with residual stumps, irregular cutting line and splinters.

Figure 2. Example of the evaluation conducted on one of the *Eucalyptus robusta* trees (tree 37). The red dashed lines indicate the locations where the acoustic tomography and perforation resistance analyses were carried out (A). Tomograms and their corresponding perforation resistance profiles at heights of 0.50, 1.30 and 1.84 m are displayed. The black dashed lines indicate the drill bit position (B, C and D). Primary issues visually observed in the root system, trunk and crown of the tree are depicted (E).

Ejemplo de evaluación realizada en uno de los árboles de *Eucalyptus robusta* (árbol 37). Las líneas discontinuas rojas indican los lugares donde se realizaron los análisis de tomografía acústica y resistencia a la perforación (A). Tomogramas y sus perfiles de resistencia a la perforación a alturas de 0,50, 1,30 y 1,84 m, respectivamente. Las líneas discontinuas negras indican la posición de la broca (B, C y D). Principales problemas observados visualmente en el sistema radicular, tronco y copa del árbol (E).

and the angle of drill penetration. Therefore, an understanding of wood's basic anatomical properties is important for accurate interpretation of results (Rinn 2012). Typically, *E. robusta* wood presents basic density ranging from 0.40 to 0.75 g cm^{-3}, diffuse porosity, and often indistinct or absent growth rings (Insidewood 2004, Wheeler 2011). Given these characteristics, a consistent perforation resistance profile is expected, except when wood abnormalities are present.

As expected, trees with larger diameters tend to be taller with more extensive crowns, regardless of the management they've undergone over the years. Moreover, as tree diameter increases, the speed of acoustic waves propagation decreases. This phenomenon arises because trees with larger diameters exhibit greater distances between the sensors. This increases the probability of deviations in wave propagation, consequently resulting in a reduction in final speed. However, various intrinsic tree factors can interfere with wave propagation and should be considered, including the physical and anatomical properties of wood (especially density, moisture content and formation of growth rings), as well as geometric characteristics of the material.

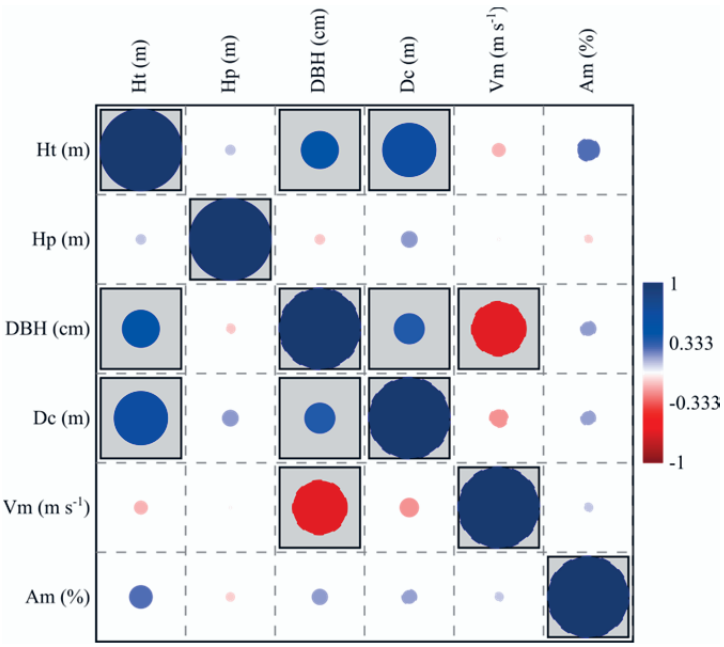

Figure 3. Spearman's correlation (5 % of significance) between the dendrometric variables, mean velocity of acoustic waves propagation (Vm), and mean amplitude of perforation resistance (Am). The size of the circles corresponds to the strength of the correlation between variables. Significant correlations ($P < 0.05$) are shown in the image. Where: Ht = total height; Hp = height to the first branch; DBH = diameter at 1.30 m above the ground; Dc = crown diameter.

Correlación de Spearman (5 % de significación) entre las variables dendrométricas, velocidad media de propagación de ondas acústicas (Vm) y amplitud media de resistencia a la perforación (Am). El tamaño de los círculos es proporcional a la correlación entre las variables. En la imagen se muestran correlaciones significativas ($P < 0,05$). Donde: Ht = altura total; Hp = altura a la primera rama; DBH = diámetro a 1,30 m sobre el suelo; Dc = diámetro de la copa.

Table 3. Equations generated for each model evaluated and their respective *P-values* and RMSE (Root Mean Square Error).

Ecuaciones generadas para cada modelo evaluado y sus respectivos valores *P* y RMSE (Error Cuadrático Medio).

Model	Equation	*P-value*	RMSE
1	$Vm = 31{,}583.14 + 245.09 \frac{1}{DBH}$	< 0.001	169.23
2	$Vm = 3{,}046.19 - 545.08 lnDBH$	< 0.001	184.09
3	$Vm = 15{,}094.52 DBH^{-0.72}$	< 0.001	171.25
4	$Vm = 1{,}756 e^{-0.01 DBH}$	< 0.001	187.57

1 = Hyperbolic model; 2 = Logarithmic model; 3 = Potency model; 4 = Exponential model; Vm = Mean velocity of acoustic waves propagation; DBH = diameter at 1.30 m above the ground

Additionally, environmental conditions, such as average temperature, relative humidity, and the mechanical loads to which the tree is exposed, can also influence the speed of acoustic waves (Bucur 2006).

CONCLUSIONS

In summary, the combined analysis of acoustic tomography and perforation resistance aids in verifying the presence or absence of internal wood issues which were initially identified through visual examination. Acoustic tomography tends to overestimate potentially injured areas; however, when used as a preliminary assessment, it offers a spatial perspective a tree trunk's interior. Per-

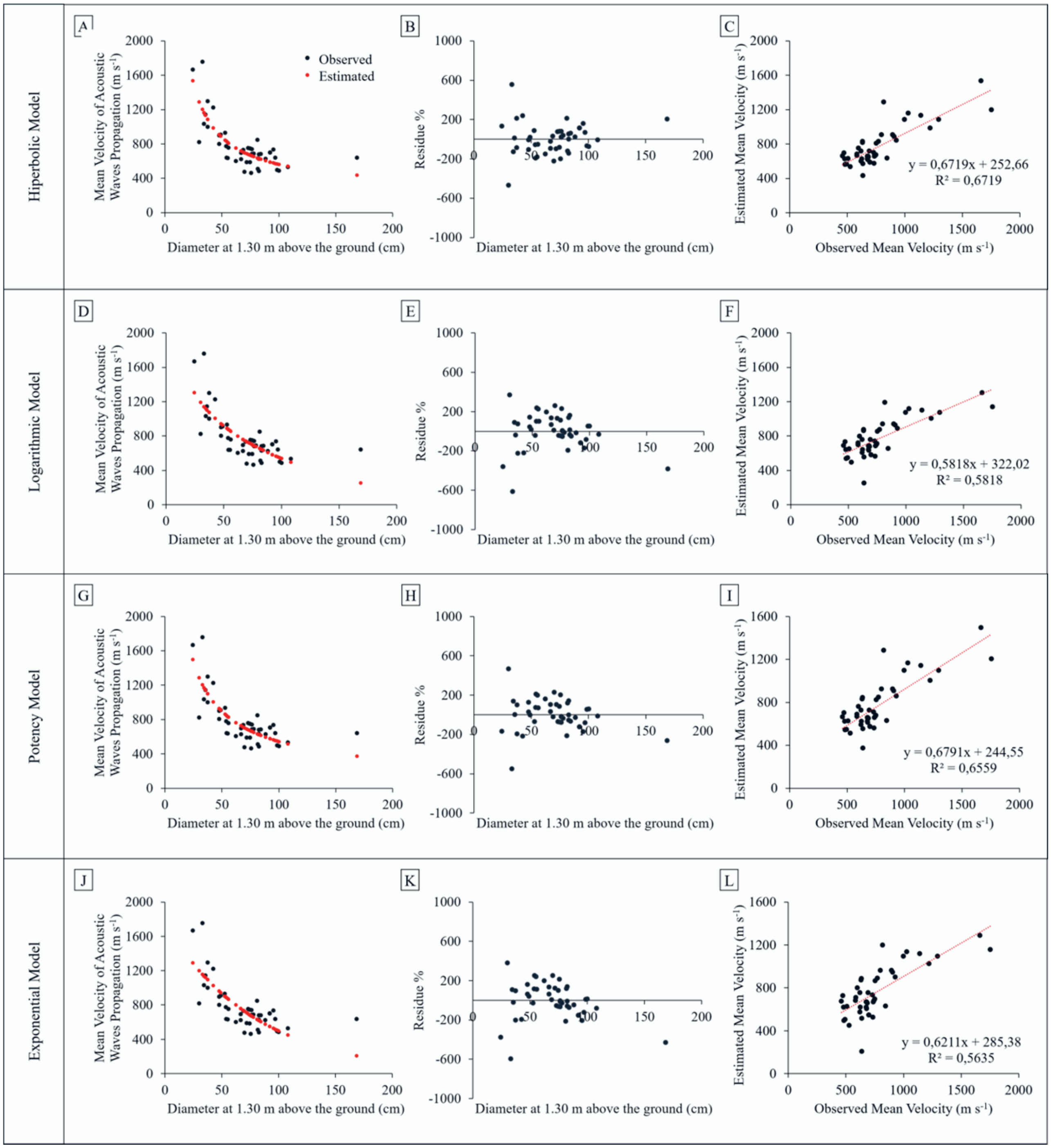

Figure 4. Validation graphs for the models selected to evaluate the effects of causality between the Mean Velocity of Acoustic Wave Propagation and DBH (Diameter at 1.30 m above the ground). Adjustment of models (A, D, G and J); residual distribution (B, E, H and K); validation of estimated values as a function of those observed (C, F, I and L).

Gráficos de validación de los modelos seleccionados para evaluar los efectos de causalidad entre las variables Velocidad Media de Propagación de Ondas Acústicas y DBH (Diámetro a 1,30 m sobre el suelo). Ajuste de modelos (A, D, G y J); distribución residual (B, E, H y K); validación de los valores estimados en función de los observados (C, F, I y L).

foration resistance analysis, being more precise, serves to confirm the existence and extent of injuries. The inclusion of additional drilling paths can increase the likelihood of locating areas with minor injuries. Proper utilization of these tools can facilitate the management of historic trees, while minimizing structural impact and guiding corrective measures to preserve the benefits these trees provide.

AUTHOR CONTRIBUTIONS

GCVSA collected the data, performed the analysis, and wrote the manuscript; DHSA contributed data or analysis tools, and revised and wrote the manuscript; BCM collected the data, and revised and wrote the manuscript; AMC supervised the project; JVFL supervised the project, conceived and designed the analysis, and revised and wrote the manuscript; All authors aproved the final, and submitted version of this manuscript.

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