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Profiles of a Non-Calibrated Resistance Drill Compared with Deteriorated Stem Cross Sections

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Abstract. The drilling resistance test has been widely used in tree inspections and structures since its first demonstration in Germany in 1988. A high correlation to wood density allows a correspondingly clear interpretation and reliable evaluation of the profiles in terms of wood condition. Without such a correlation, it is not clear what the profiles mean. In this study, researchers compared the profiles of a non-calibrated resistance drill with pictures of the surfaces of the drilled stem cross sections in order to find out how defects are revealed. In decayed areas, the profiles mostly dropped down and the results showed that advanced stages of decomposition and voids of significant size can be detected reliably with this device. There were statistical differences between drilling amplitude among the studied species and, in the heartwood, the values of amplitudes were superior and statistically different from those obtained in the sapwood. However, the depth of the drop, or the changes in the profiles of this device, do not allow users to differentiate between various stages of deterioration. Similarly, it is not clear if all rising profile peaks are caused by locally higher wood density, as compatibilizations zones, or by technical artefacts.

Key Words. Decay in Trees; Hazard; Resistance Drilling; Stem Cross Section; Tree Inspection; Tree Risk Assessment.

The drilling resistance measurement is a semi-destructive test in which a fast rotating drilling needle is inserted in the wood under inspection. The method has development considerably since the idea was first introduced in the 1970s (Rinn 2014); it has been widely used in tree inspections and structures since 1988 (Rinn et al. 1989). The needle must be very thin to minimize material damage; the needle, however, cannot be so thin that it could suffer from resonance or buckling problems (Tannert et al. 2013). Most machines use a needle with a 3-mm tip diameter where the cutting edges are located, and a 1.5-mm diameter shaft (Tannert et al. 2013). With the rotation, the needle cuts the wood and perforates the material as it advances (Botelho 2006). The tested drills require manual adjustment of the advance speed of the needle (cm/min), as well as its rotation speed (turns/min). For those drills, this adjustment must be done according to the hardness or the density of the wood (Nutto and Biechele 2015). Besides the velocities, the sharpening of the needle tip is also very important to reduce shaft friction, which causes interpretation problems of this kind of drill results, especially in dense woods (Nutto and Biechele 2015). While drilling, the needed energy is measured depending on the drilling depth of the needle, and registered in a percent-amplitude graph.

The different resistance drills differ strongly in many ways: in handling and practical applicability, in precision and accuracy, and most important, in how their profiles have to be interpreted (Rinn 2012). When drilling at the same spot of a tree with different kinds of resistance drills, the profiles can differ so strongly that users can come to contradictory evaluations of wood condition (Rinn 2015). Consequently, there is need for a criterion for how to evaluate the accuracy and reliability of the profiles obtained by the various kinds of resistance drills in terms of wood condition.

Considering that the equipment measures the resistance offered by the wood to drilling, it is also expected that the equipment's results can be correlated with losses in density caused by deterioration. Several studies have focused on evaluating the correlations between the amplitude of the drilling resistance obtained by the equipment and the wood density (Botelho 2006) or its effectiveness in detecting deteriorations in wood structures (Eckstein 1994; Brashaw et al. 2011; Rinn 2012; Tannert et al. 2013; Rinn, 2016), logs (Brashaw et al. 2011), trees (Johnstone et al. 2007; Wang et al. 2008; Kubus 2009; Johnstone et al. 2010), and damaged wooden poles (Jenkins 2011; Reinprecht and Supina 2015).

Density is a wood material property that describes wood condition, and it differentiates between intact and decayed parts (Means et al. 1985). How important it is to differentiate between the various stages of decomposition becomes clear when realizing that, depending on the type of decay, a loss in density by only 10% can lead to a loss in strength of 90% or even more (Wilcox 1978). Structural stability of wood is thus highly dependent on even slight changes in wood density. Therefore, many research projects have focused on developing a method for non-destructive assessment of the density profiles of standing trees and timber (Rinn 2016). Shortly after the first international press releases described how a German physicist (F. Rinn) drilled thin needles into trees in order to inspect for defects by measuring density (Schubert 1989), many companies worked to develop similar devices. For a few electronically recording resistance drills, a high correlation ($r^2 > 0.9$) of the profiles to wood density was found, even in standing trees (Brashaw et al. 2013); and because density is the most important material parameter for this technique, there is a need for studies to evaluate the accuracy and reliability of the profiles obtained by non-calibrated resistance drills. For resistance drills using mechanical spring-driven recording, the correlation to wood density was found to be weak (r^2 ~0.5; Johnstone et al. 2011), making it correspondingly difficult to evaluate wood condition based on such profiles. Due to this weak correlation, it is impossible to identify and differentiate various stages of decomposition in these profiles (Johnstone et al. 2011). Consequently, only big defects with advanced stages of decay or voids can be identified reliably. For other resistance drills, it is not yet known how well the measured values correlate to wood density, although these drills are frequently used on the market, and have been for several years. Thus, it is not yet clear how to interpret these profiles correctly in terms of wood condition.

To fill this knowledge gap, researchers compared profiles of a non-calibrated resistance drill with pictures of the surface of the drilled stem cross-sections, with a special focus on how the different stages of decomposition are revealed.

MATERIALS AND METHODS

Sampling was composed of logs collected from six tree species: *Centrolobium* sp., *Tabebuia ochracea*, *Liquidambar styraciflua*, *Platanus* spp., *Caesalpinia pluviosa*, and *Copaifera* sp., widely spread in the urban arborization of São Paulo State, Brazil. Six discs approximately 200 mm high were removed from these logs. The discs were conditioned in a place with temperature and relative humidity (RH) controlled (temperature around 25°C and RH around 65%) until reaching equilibrium moisture. When they reached the equilibrium, species heartwood and sapwood presented moisture content around 10% and 11%, respectively. It is important to note that even in green condition, hardwoods tend to exhibit smaller differences in moisture between heartwood and sapwood than softwoods, and in some species, heartwood moisture is higher than sapwood moisture (Haygreen and Bower 1989). Eight equidistant points were marked on each disc perimeter for measurements with the drilling resistance equipment (IML PD 400, Wiesloch, Germany) (Figure 1). The measurements were performed in the perpendicular direction to the grain in the 8 marked points (measurement routes), obtaining 48 graphs of amplitude of drilling resistance. To help with the test, the discs were fixed to a concrete table with sergeants (Figure 1).

The species used in the research had different densities and deterioration conditions (Table 1). The model of equipment used needs the manual choice of

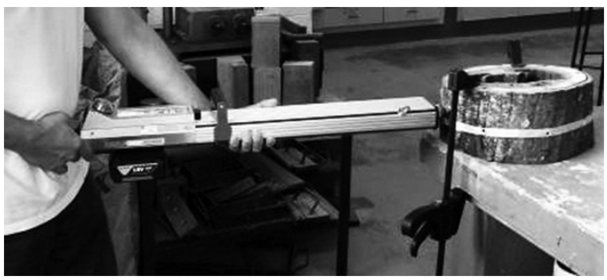

Figure 1. Drilling-resistance test on discs.

Table 1. Short description of disc deterioration.

Species	Description
Centrolobium sp.	Hollow caused by termites.
Tabebuia ochracea	Coleopterans attack.
Liquidambar styraciflua	Near the spinal cord there is a small area with early stage of fungal decay and lateral cracking of the marrow to the bark.
Platanus spp.	Most of the wood shows signs of fungi attack and there are some hollowed areas caused by termites.
Caesalpinia pluviosa	Fungi attack at the center of the disc.
Copaifera sp.	Hollow caused by termites and fungi deterioration around them.

Table 2. Values of basic density (ρbas), feed velocity (V_A), and rotation speed (V_R) adopted for each species.

Species	ρbas kg•m^{-3}	V_A cm/min	V_R rot/min
Liquidambar styraciflua	490[z]	100	2500
Platanus spp.	500[y]	150	2500
Copaifera sp.	575[x]	50	3500
Centrolobium sp.	660[w]	100	2500
Tabebuia ochracea	840[x]	100	2500
Caesalpinia pluviosa	890[w]	50	3500

[z] Lima et al. 2015
[y] Freitas 2012
[x] IPT (www.ipt.br/informacoes_madeiras3.php?madeira=38)
[w] Remade (www.remade.com.br/madeiras-exoticas/116/madeiras-brasileiras-e-exoticas/arariba)

different levels of feed speed (from 15 cm/min to 200 cm/min) and needle rotation (1,500 rpm at 5,000 rotations/min). This adjustment is usually made according to the expected but mostly unknown density of the wood. In light woods, the feeding speed must be higher to provide sufficient amplitude so that the curve variations can be seen. In denser woods, the feed speed must be reduced and the rotation increased so drilling is possible. Considering these aspects of the equipment, feeding and rotation velocities were adopted, manually, according to the expected wood density, and it was also necessary to consider the deteriorating condition of the disc to prevent the needle from breaking (Table 2). Other kinds of resistance drills automatically adapt the drilling speed to wood density while drilling. The user does not need to adjust the drilling speed before drilling with these devices.

The wood condition influenced the choice of feed velocity. Although the species *Liquidambar* and *Platanus* have practically the same density, the feed velocity used in the *Liquidambar* was lower than in the *Platanus* (Table 2). The feed speed used in the *Copaifera* sample could also be 100 cm/min, but it was necessary to reduce it and increase the rotation so that the drill inlet would not break (Table 2).

After the drilling-resistance tests were completed, the discs were cut to the exact position of the drill paths. These sections were detailed through photographic record in order to compare the amplitude plots of drilling resistance with the different zones of the wood through which the drilling occurred. The equipment model used in this research provides two curves, one showing power needed for feedings of the needle, and the other for the rotation of the needle. However, older models provide only the feed curve. Nutto and Biechele (2015) observed that in high-density wood, the feed amplitude tends to increase with the drilling depth because of friction. This increase in amplitude may cause wrong interpretation of the results, since it can camouflage the amplitude drop that would be caused by deterioration.

The discs were macroscopically analyzed to identify the heartwood, sapwood, and deteriorated areas. Descriptions of the species were obtained in the literature (Freitas 2012; Lima et al. 2015; IPT 2016), as well as the support of an expert in visual assessment. For the species in which it was possible to distinguish the heartwood and sapwood regions, the average amplitude of drilling resistance obtained separately in the bark, heartwood, sapwood, and deterioration zones was determined.

For all discs, the drilling-resistance graphs obtained on each route were compared with the photographic images, by image overlay. In the case of discs with heart and sapwood zones, the average amplitudes of rotational drilling resistance were statistically analyzed using multivariate variance analysis. In this research, only the amplitude plots of rotational drilling resistance

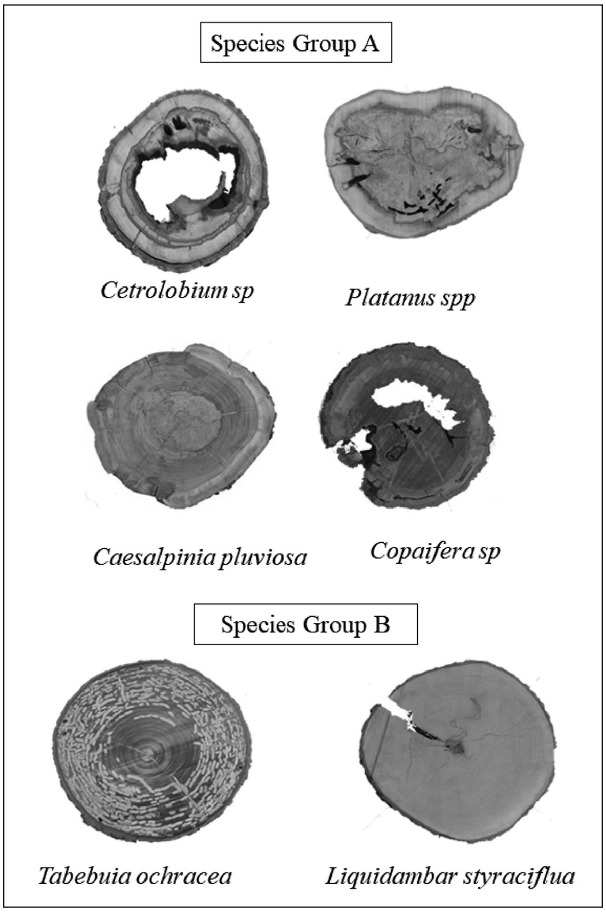

Figure 2. Images of the *Cetrolobium* sp., *Platanus* spp., *Caesalpinia pluviosa*, and *Copaifera* sp. discs with color distinction between heartwood and sapwood (Species Group A) and of the species *Tabebuia ochracea* and *Liquidambar styraciflua*, without distinction of color between heartwood and sapwood (Species Group B).

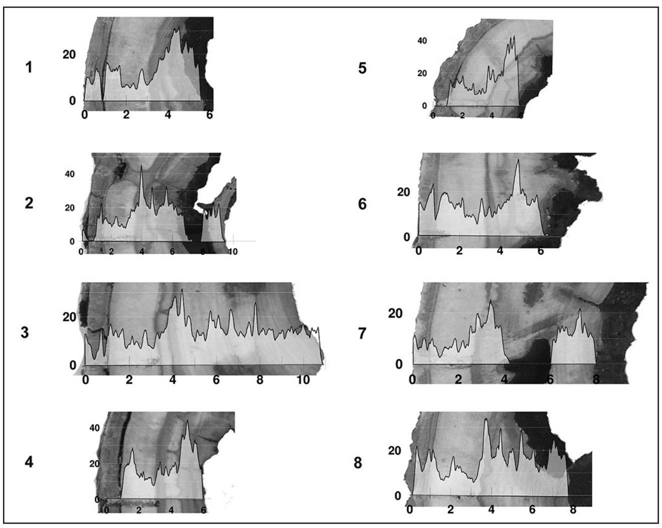

Figure 3. Superposition of the amplitude graph of drilling resistance to the photographic image obtained from the disc, in the position of the needle passage of the resistograph. Species: *Centrolobium* sp.

were used because the use of the two graphs (thrust and rotational resistance to drilling) made the image overlay too difficult.

RESULTS AND DISCUSSION

In the *Centrolobium*, *Platanus*, *Caesalpinia*, and *Copaífera* discs, it was possible to define the heartwood and sapwood zones due to their coloring distinction (Figure 2), whereas in *Tabebuia* and *Liquidambar* species, this distinction was not possible (Figure 2). The characteristics of the heartwood and sapwood differentiation as a function of color differentiation were similar to those proposed in the literature (Freitas 2012; Lima et al. 2015; IPT 2016). Not all of the discs contained voided areas and not all of the discs differed in types and levels of deterioration (Table 1).

Considering the methodology, it was possible to obtain eight images of the amplitude graph of the drilling resistance from each disc, corresponding to the eight measurement routes, which were overlaid with the photographic images (Figure 3). The same result observed in Figure 3 was obtained for the six species studied.

The detailed analysis of the 48 superimposed images allowed researchers to verify the existence of a pattern of behavior of the amplitude of drilling resistance against the different zones of the wood (healthy and with deterioration) traveled by the needle during the drilling.

Considering all studied species, the maximum amplitude ranged from 0% to ≅ 40%, with the 0% sections corresponding to the voids, as expected. Considering the type of machine used (no density calibration), the amplitude range varies among species, being smaller for *Centrolobium* sp. and *Copaifera* sp. (0% to ≅16%) than for *Caesalpinia pluviosa* and *Platanus* (0% to 40%), which was also expected. This result confirms that this tool is adequate to detect the location and the approximate size of voids. The same result was highlighted by Kubus (2009) when analyzing the condition of a large monumental tree in Portland, Oregon, U.S. The author presents records of 10 graphs of resistance to drilling, obtained in different positions of the tree, in which there were several zones with amplitudes close to zero (probably voided zones) and, in the other regions, average amplitudes of resistance to perforation of 16%. In the bark area, the average amplitudes were 6%. Brashaw et al. (2011) obtained drilling resistance that varied

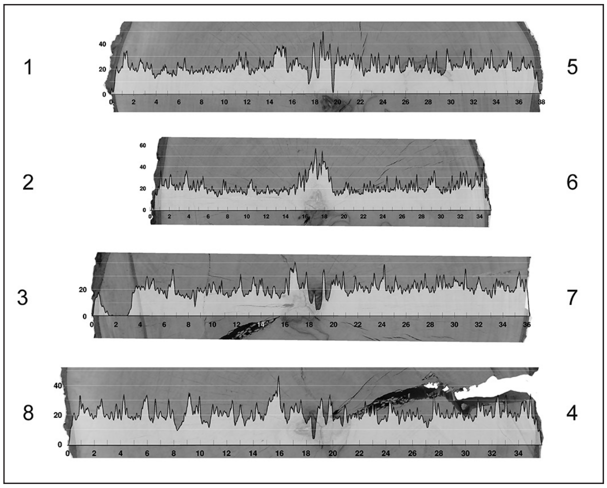

Figure 4. Superposition of the amplitude graph of drilling resistance to the photographic image obtained from the disc, in the position of the needle passage of the resistograph. Species: *Liquidambar styraciflua*.

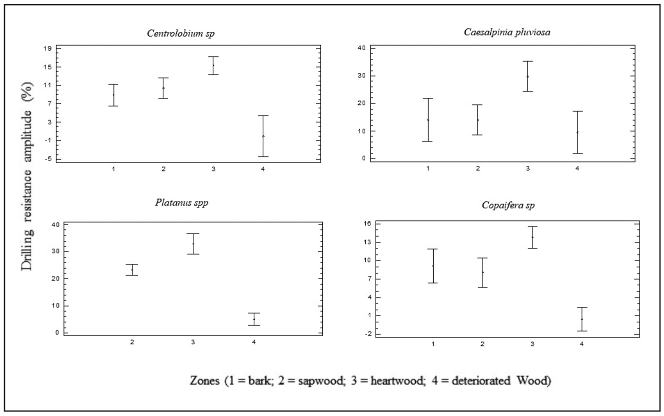

Figure 5. Representative graph of the average values and the variability of amplitude obtained in the different zones of the discs in different species.

from 0% to 25% in zones with different levels of wood degradation.

In this research, in the species for which it was possible to define the heartwood and sapwood regions, there was amplitude variation (Figure 3). In the two species for which it was not possible to visualize the distinction between heartwood and sapwood (*Tabebuia ochracea* and *Liquidambar styraciflua*), the amplitude of the drilling-resistance graph also does not show variations (Figure 4). Similar graphs, without heartwood and sapwood visual distinction, were obtained by Kubus (2009).

In the heartwood, the values of amplitudes were higher than those obtained in the sapwood. For the four species for which it was possible to define the heartwood and sapwood regions (Figure 2), this result was statistically demonstrated (Figure 5). The analysis of variance showed that amplitudes were always lower in deteriorated regions (with or without voids),

Table 3. Average drilling resistance amplitude by species and Multiple Range Test for analyzing statistical differences.

Species	Sapwood	Heartwood
Platanus spp.	23.3 (a)	32.9 (a)
Caesalpinia pluviosa	14.0 (b)	29.8 (a)
Centrolobium sp.	10.4 (bc)	15.3 (b)
Copaifera sp.	8.1 (c)	13.8 (b)

Note: Different letters indicate statistically significant differences at the 95.0% confidence level.

but always higher in the heartwood regions and in sapwood and bark intermediate regions (Figure 5).

Considering only the heartwood and sapwood regions without apparent deterioration, there was a differentiation between species. For sapwood, the amplitudes of drilling resistance were higher and statistically different for *Platanus* spp. and statistically equivalent for the other species (Table 3). For heartwood, the amplitudes of drilling resistance were also higher for *Platanus* spp., but statistically equivalent for *Caesalpinia pluviosa*, and smaller for the other two species (Table 3). This result is not expected, since *Platanus* spp. has the lowest density (Table 2) and the drilling resistance, in general, has a positive correlation with density (Costelo and Quarles 1999; Couto et al. 2013). However, it is noteworthy that the amplitude of drilling resistance in this device type is affected by the selected advance velocity, which for *Platanus* spp. was higher (Table 2), and that in order to properly interpret and compare amplitude results obtained in the resistance test, it was necessary to know, in advance, the profiles obtained in the whole condition (Martinez 2016; Matheny et al. 1999). This is different from resistance drills automatically adopting the speed to the wood, as tested by Brashaw (2013), and resulting in a high correlation to wood density ($R^2 > 0.9$), because a high correlation to wood density is necessary to allow for reliable evaluations of the profiles concerning the wood condition.

For *Tabebuia ochracea*, which sustained a beetle insect attack (Figure 2), the amplitude of drilling resistance did not show variations that allowed, in an inspection, researchers to visualize the wood state (Figure 6).

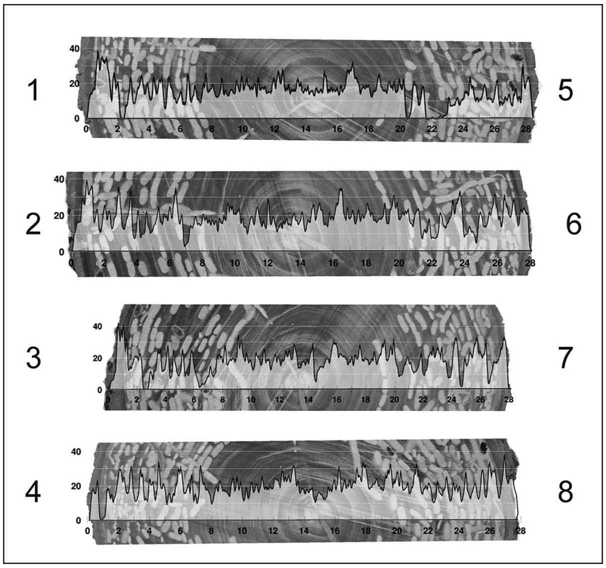

Figure 6. Superposition of the amplitude graph of drilling resistance to the photographic image obtained from the disc, in the position of the needle passage of the resistograph. Species: *Tabebuia ochracea*. Deterioration caused by *Coleoptera* insects.

In the *Liquidambar styraciflua* disc there was a significant crack (Figure 2) that was not identified in any drilling resistance amplitude graph, because no needle route passed through the crack site (Figure 4). This result highlights the fact that this type of inspection is punctual, and it is important to know where it should be applied. Botelho (2006) and Tannert et al. (2014) had the same conclusion.

It was possible to observe in some discs the contour of the fungi deteriorated zone, a darker-colored region. In these cases, an increase peak in the amplitude of the drilling resistance was observed (Figure 7). A similar result was obtained by Rinn (1996) and was explained by the compartmentalization process promoted in the trees' tissue to protect them from the advance of the deteriorated zone. In this process, the tree develops a thicker cell wall tissue, in addition to obstructing cell voids, causing this tissue to act as a deterioration barrier (Shigo 1977; Shortle 1979; Fraedrich 1999). The darker color is due to the antimicrobial substances produced (Shigo 1977; Shortle 1979). The *Platanus* spp. disc was the only one that presented these peaks in the sapwood zone, which may have influenced the average value of amplitude of drilling resistance, making this species present the highest values of amplitude, although with lower density. Compartmentalization is an assertive hypothesis for the behavior of the amplitude resistance; however, seeing as researchers did not know the correlation of the profile with density (non-calibrated device), it is not possible to affirm that all rising profile peaks are caused by this higher wood density.

Rinn (1996) observed that differentiated patterns of behavior of the drilling resistance plot may help the inspection interpretation. The author clarifies that in fungi-deteriorated wood, the amplitudes are low and approximately homogeneous, while in termite-deteriorated areas or with cracks present, the graph is more variable and has higher amplitudes (surrounding wood in good condition) followed by amplitude values much smaller and localized. In the *Platanus* spp. and *Caesalpinia pluviosa* discs, in which there was a large fungus-deteriorated zone (Figure 2 and Table 1), the drilling-resistance graph shows a continuous

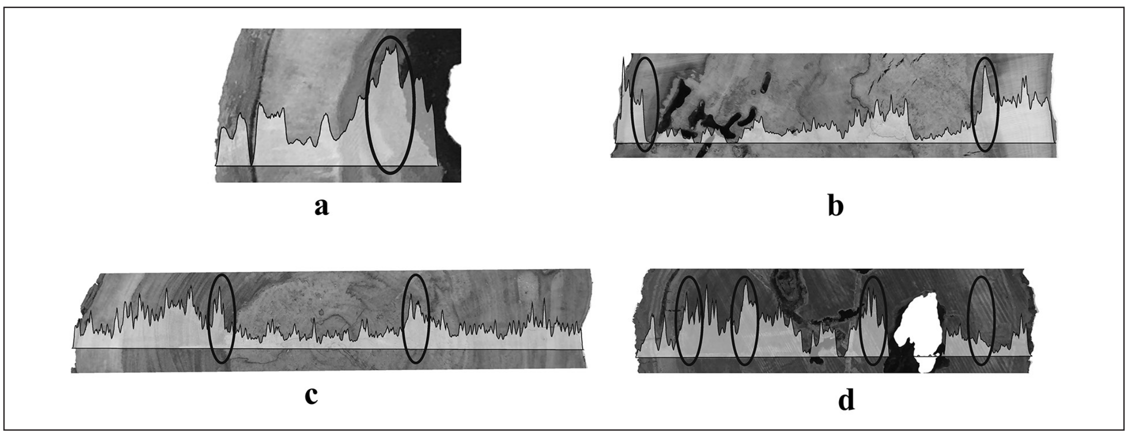

Figure 7. Details of amplitude peak observed in zones close to fungal decay: a) *Centrolobium* sp., b) *Platanus* spp., c) *Caesalpinia pluviosa*, d) *Copaifera* sp.

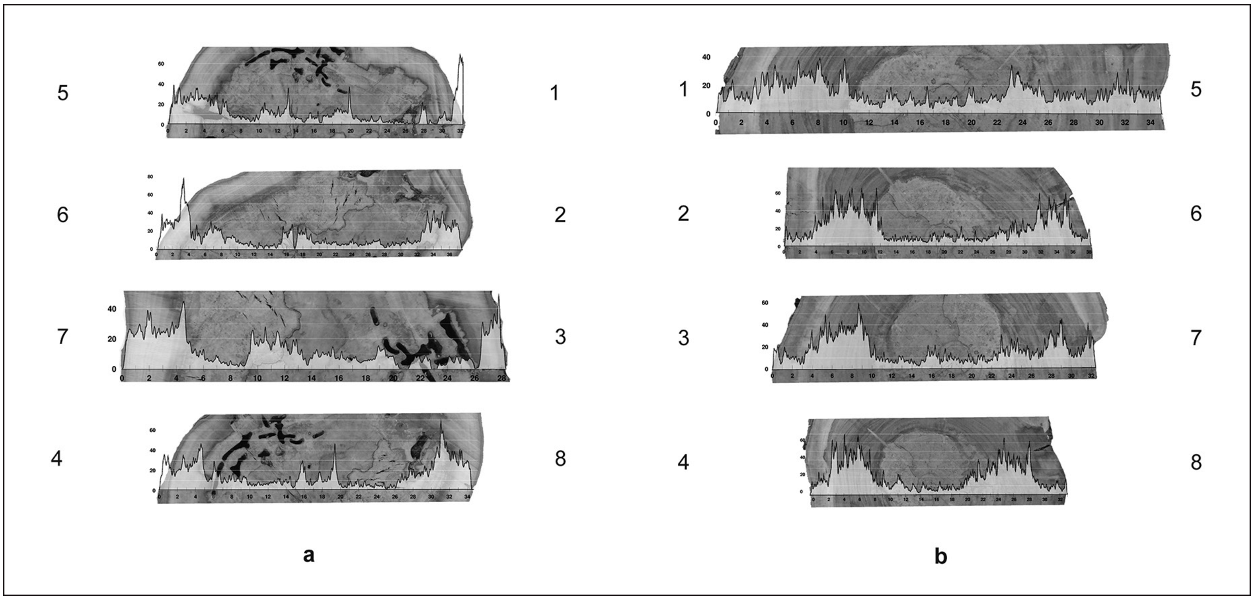

Figure 8. Superposition of the amplitude graph of drilling resistance to the photographic image obtained from the disc, in the position of the needle passage of the resistograph. Species: a) *Platanus* spp., b) *Caesalpinia pluviosa*.

segment of low amplitudes (Figure 8), according to the behavior indicated by Rinn (1996).

CONCLUSIONS

For all studied species, the amplitude ranged from 0% to 40%, with the 0% sections corresponding to the voids, as expected, which confirms that this tool is potentially adequate for the detection of the location and the approximate size of voids. In the heartwood, the values of the amplitudes were superior and statistically different from those obtained in the sapwood, both with moisture content around 10%~11%. There were also statistical differences between species. The variance analysis showed that the amplitude in deteriorated regions (with or without voids) was always lower, except in the *Coleoptera* attacked wood, whose deterioration was not captured by the equipment. In some discs, amplitude-increase peaks observed on the drilling resistance graph were probably associated with compartmentalization zones promoted in the tree tissue to protect themselves from the advancement of the deteriorated zone. This behavior, also observed by other researchers, can affect the inspection interpretation by hiding deterioration, for example.

The impact of feed rate, rotational speed, and density correlation on the obtained results is critical and must be considered in further research. Curves of the same piece of wood drilled with a different feed rate and rotational speed can differ strongly, making it difficult to clearly interpret the meaning of the result. In the same way, analysis of correlation between the device profiles and real local wood density along the drilling path is necessary in order to clarify analyst interpretation and reliable evaluation of the profiles in terms of wood condition by this device.

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Résumé. Le test de résistance au perçage a été abondamment utilisé lors de l'inspection des arbres et de leur structure depuis son introduction en Allemagne en 1988. Une forte corrélation avec la densité du bois permet une interprétation proportionnellement claire et une évaluation fiable des profils en termes de condition du bois. Sans une telle corrélation, la signification des profils n'est pas évidente. Pour cette étude, les chercheurs ont comparé les profils de résistance obtenus avec une perceuse non-étalonnée avec des images de la surface de sections percées de tiges, de manière à découvrir comment les déficiences du bois sont révélées. Pour les zones décomposées, les profils chutèrent et les résultats démontrèrent que les phases avancées de décomposition et les vides de taille significative étaient détectés de manière fiable avec cet appareil. Il y avait des différences statistiques entre l'amplitude de perçage parmi les espèces étudiées ainsi, dans le bois de cœur, les valeurs d'amplitude étaient supérieures et statistiquement différentes de celles obtenues dans l'aubier. Toutefois, l'intensité de la baisse des amplitudes ou les changements de profils de cet appareil, ne permettaient pas aux usagers de différencier parmi les différents degrés de détérioration du bois. De manière similaire, ce n'est pas clair si tous les pics de profil élevés étaient occasionnées par une densité supérieure de bois, en tant que zones de compatibilisation ou par des considérations davantage techniques.

Zusammenfassung. Seit seiner ersten Demonstration in Deutschland 1988 wird der Bohrwiderstandstest bei Bauminspektionen und Holzstrukturen weitläufig eingesetzt. Eine hohe Korrelation zur Holzdichte erlaubt korrespondierend eine klare Interpretation und belastbare Evaluation in Bezug auf den Holzzustand. Ohne eine solche Korrelation wäre nicht klar, was das Profil bedeutet. In dieser Studie vergleichen Forscher die Profile eines nicht-kalibrierten Bohrwiderstand- messgerätes mit den Bildern der Oberfläche eines Stammquerschnittes, um herauszufinden, wie sich die Defekte darstellen. In faulen Bereichen sanken die Profile meist ein und die Ergebnisse zeigten, dass fortgeschrittene Stadien von Holzabbau und Höhlungen von signifikanter Größe mit diesem Gerät verlässlich aufgezeigt werden. Es gab statistische Unterschiede zwischen den Bohramplituden der untersuchten Arten und im Kernholz waren die Amplituden deutlicher und statistisch unterschiedlicher als die aus dem Splintholz. Dennoch kann der Nutzer nicht die Tiefe des Loches oder die Veränderungen an den Profilen von diesem Gerät zwischen den verschiedenen Stadien des Holzabbaus abschätzen. Vergleichsweise ist es auch nicht geklärt, ob alle Höhenausschläge des Bohrprofiles durch lokale höhere Bohrwiderstände verursacht werden, als Abschottungszonen oder durch technische Artefakte.

Resumen. La prueba de resistencia a la perforación ha sido ampliamente utilizada en inspecciones y estructuras de árboles desde su primera demostración en Alemania en 1988. Una alta correlación con la densidad de la madera permite una interpretación clara y una evaluación confiable de los perfiles en términos de condición de la madera. Sin tal correlación, no está claro qué significan los perfiles. En este estudio, los investigadores compararon los perfiles de un taladro de resistencia no calibrado con imágenes de las superficies de las secciones transversales del tallo perforado para descubrir cómo se revelan los defectos. En áreas en descomposición, la mayoría de los perfiles se redujeron y los resultados mostraron que las etapas avanzadas de descomposición y vacíos de tamaño significativo pueden detectarse de manera confiable con este dispositivo. Hubo diferencias estadísticas entre la amplitud de perforación entre las especies estudiadas y, en el duramen, los valores de amplitudes fueron superiores y estadísticamente diferentes de los obtenidos en la albura. Sin embargo, la profundidad de la caída, o los cambios en los perfiles de este dispositivo, no permiten a los usuarios diferenciar entre varias etapas de deterioro. De manera similar, no está claro si todos los picos de perfil en aumento están causados por una mayor densidad de madera localmente, como zonas de compatibilización o por artefactos técnicos.