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Anatomical and physico-mechanical characteristics of *Cenostigma pluviosum* var. *pelthophoroides* (Fabaceae) wood decayed by *Ganoderma australe* (Basidiomycota, Polyporales)

Características anatômicas e físico-mecânicas da madeira de *Cenostigma pluviosum* var. *pelthophoroides* (Fabaceae) deteriorada por *Ganoderma australe* (Basidiomycota, Polyporales)

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ABSTRACT

Sibipiruna (*Cenostigma pluviosum* var. *pelthophoroides*) trees are common in the São Paulo city urban forest, but they may cause accidents when deteriorated by wood-decaying fungi due to trunk rupture and tree fall. Therefore, this study aimed to evaluate anatomical, physical, and mechanical changes in sibipiruna wood attacked by *Ganoderma australe*. Adult trees with basidiomata of this fungus and at imminent fall risk were macro and microscopically analyzed to investigate wood biodeterioration and resistance mechanisms (compartmentalization). Physical and mechanical tests (specific gravity, mechanism of resistance and static bending) were performed. In sibipiruna trees, degradation was observed in the heartwood, being more intense in the region near the pith and more extensive at the stem base, from where basidiomata were collected. Fungal attack was characterized as white pocket rot, i.e. non-selective to cell wall components, causing erosion of the S2

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layer from the cell lumen. Decaying wood was also attacked by xylophagous insects, like the subterranean termite *Coptotermes gestroi* and wood-boring beetles. Wood compartmentalization was characterized by accumulation of extractives. White rot caused significant reductions in specific gravity, modulus of rupture and modulus of elasticity, which justify the rupture of trees when subjected to external forces, such as strong winds.

Keywords — Mechanical properties; simultaneous rot; white rot; wood decay fungi.

RESUMO

Árvores da espécie sibipiruna (*Cenostigma pluviosum* var. *pelthophoroides*) são muito comuns na arborização urbana da cidade de São Paulo, mas podem causar acidentes quando deterioradas por fungos decompositores de madeira, devido à ruptura do tronco, resultando na queda dessas árvores. Portanto, este trabalho teve como objetivo avaliar mudanças anatômicas, físicas e mecânicas na madeira da sibipiruna atacada por *Ganoderma australe*. Árvores adultas com a presença de basidiomas desse fungo e em iminente risco de queda foram analisados macro e microscopicamente para investigar a biodeterioração e os mecanismos de resistência da árvore (compartimentalização). Foram efetuados ensaios físicos e mecânicos (massa específica, resistência e módulo de elasticidade à flexão estática). Na árvore de sibipiruna, a degradação ocorreu no cerne, sendo mais intenso próximo à medula e mais extensiva no colo da árvore, onde os basidiomas foram coletados. O ataque do fungo foi identificado como podridão branca em bolsas, i.e. não-seletivo aos componentes da parede celular, causando a erosão da camada S2 do lumen celular. A madeira degradada também foi atacada por insetos xilófagos, como o cupim subterrâneo *Coptotermes gestroi* e besouros de madeira. A compartimentalização da madeira foi caracterizada pelo acúmulo de extrativos. Podridão branca causou significativa redução na massa específica e no módulo de elasticidade, o que justifica a ruptura das árvores quando sujeitas às forças externas, tais como fortes ventos.

Palavras-chave — Fungos decompositores de madeira; podridão branca; podridão simultânea; propriedades mecânicas.

INTRODUCTION

Wood decay is the biological process by which cellulose and lignin, the two most abundant organic compounds on Earth, are converted to carbon dioxide and water with a release of energy to maintain forest processes (Shortle & Dudzik, 2012). All of the decay fungi, to some degree, recycle lignocellulosic and mineral nutrients back into the ecosystem. In addition, their decay activities soften the woody tissues, making them more amenable to bird and small mammal habitation and use by arthropods, nematodes, and other invertebrates as well as other fungi (Huhndorf *et al.*, 2004; Ryvarden, 2004).

However, the attack of urban trees by fungi is a problem related to the safety of city inhabitants, as the deterioration of stem, branches or roots may result in mechanical failures (Schwarze, 2007).

One of the items evaluated during tree inspection (or Visual Tree Analysis) is the presence of decaying fungi on the roots or stem. These fungi degrade wood cells and may cause three types of decay: white rot, brown rot and soft rot. White rot is caused by basidiomycetes that degrade cellulose, hemicellulose and lignin; it can be simultaneous when fungi degrade all those three components, or selective delignfication, when lignin is degraded earlier and cellulose is relatively unaltered in which case the wood exhibits a whitish aspect due to the absence of lignin (Ryvarden, 2004; Schwarze, 2007). Brown rot is caused mainly by basidiomycetes and certain ascomycetes that degrade wood carbohydrates (cellulose and hemicellulose). Soft rot is produced by ascomycetes that can slowly degrade not only those carbohydrates but also lignin, yet usually causing no extensive damage to the wood of living trees (Obst *et al.*, 1994; Schwarze, 2007; Brazolin, 2009; Downer & Perry, 2019).

Species of *Ganoderma* (Polyporales, Basidiomycota) cause white rot (Blanchette, 1984; Luna *et al*., 2004; Terho, 2009; Rojas *et al.*, 2018) and when they infect urban trees, they promote root and stem deterioration (Loyd *et al.*, 2017, 2018).

On the other hand, during an attack, trees initiate a compartmentalization process to defend themselves from pathogen spread (Rayner & Boddy, 1988; Loyd *et al.*; 2018). This active process begins with the formation of a chemical reaction zone, through the production of toxic substances by sapwood parenchymatous cells and a physical barrier (growth layer) originated by the cambium, which isolates the injured tissues (Shigo, 1984; Seitz, 1996; Shortle & Dudzik, 2012).

So far, the biodeterioration process caused by *Ganoderma* spp. in the wood of sibipiruna species remain unknown. Thus, the evaluation of the colonization and deterioration processes may contribute to better understand the degree of damage and the consequent risk in urban trees failures. In that sense, we aimed to: a) evaluate the macro and microscopic patterns of deterioration caused by the fungus *Ganoderma australe* (Fr.) Pat., b) verify the mechanism of resistance of the sibipiruna tree to the biodeterioration process and c) characterize the physical (specific gravity) and mechanical properties (static bending) of the sound and fungal-decayed wood.

MATERIAL AND METHODS

Tree samples

The sibipiruna [*Cenostigma pluviosum* var. *pelthophoroides* (Benth.) Gagnon & G.P. Lewis] Fabaceae, is one of the species recommended for urban forestation in São Paulo city and corresponds to 11.84% of the trees registered in the municipality (SVMA, 2015). *Ganoderma* is among the most common wood-rotting species of basidiomycetes occurring on standing trees in São Paulo city. For this study, three specimens of sibipiruna with basidiomata of *G. australe* attacking the stems, resulting in high degree of biodeterioration, justified the removal of these trees because of the fall risk, with possible stem rupture. These evaluations were based on phytosanitary status of the trees, like fissures, cracks and degree of stem decomposition. During tree removal, serial disks were obtained from the tree base to BHD (Breast Height Diameter) for the analysis of macro and microscopic characteristics of sound and deteriorated woods as well as their physical and mechanical properties. Basidiomata were also collected to confirm the fungus identification.

The identification was based on macro- and microscopic characters of the basidiomata (Ryvarden, 2004; Gugliotta *et al.*, 2011; Torres-Torres *et al.*, 2012). The vouchers were deposited in the Herbarium SP. Cultures were obtained from fresh basidiomata, grown in Potato Dextrose Agar (PDA) and deposited in the "Coleção de Culturas de Algas, Cianobactérias e Fungos (CCIBt)" of the Instituto de Pesquisas Ambientais, São Paulo, Brazil (CCIBt 4166/SP466477; CCIBt 4175/SP466495 and CCIBt 4178/SP466501).

Analysis of sound and deteriorated woods

The anatomical structure of sound and deteriorated woods of sibipiruna and its mechanism of resistance against this xylophagous organism were characterized through macro and microscopic examination. For macroscopic analysis, the transverse surfaces of wood samples were polished in a sanding machine for better visualization of the heartwood and sapwood regions, the site and extension of fungal attack, the presence of termites and wood-boring insects, the type of deterioration and the occurrence of resistance mechanisms. These analyses were conducted using a 10 x magnifying glass and a stereoscopic microscope. For microscopic analysis, sections varying from 16 to 20 μm thick were obtained with a sliding microtome (2000 R, Leica) and observed under a light microscope DM 4000B, Leica) attached to a camera (DFC310 FX, Leica). The sections were obtained following the method developed by Barbosa *et al.* (2010). Safranin and picro-aniline were used to stain, respectively, the secondary xylem and the fungal hyphae and spores.

Physical and mechanical properties of sound and deteriorated woods

The specific gravity and bending strength were determined using wood samples (4 mm x 4 mm x 75 mm) acclimatized under controlled temperature and humidity (20 ± 3 °C and 65 ± 5%, respectively), until 12% of moisture content. The specific gravity (kg m^{-3}) determination was based on the ASTM D2395 standard (ASTM, 2014). Their volumes were obtained by the directly measuring of their dimensions (length, width, and height) with a caliper (0.01 mm precision). Each sample was evaluated for its resistance (modulus of rupture) and rigidity (modulus of elasticity) in static bending parallel to fibers, with a radially applied force, following the NBR 7190 standard (ABNT, 1997). In the static scheme, the specimens were assayed in a universal machine (model K500SMP, Kratos).

A force was applied to their center (Fig. 1) and the deflection and force were simultaneously recorded for determination of the maximum value of modulus of

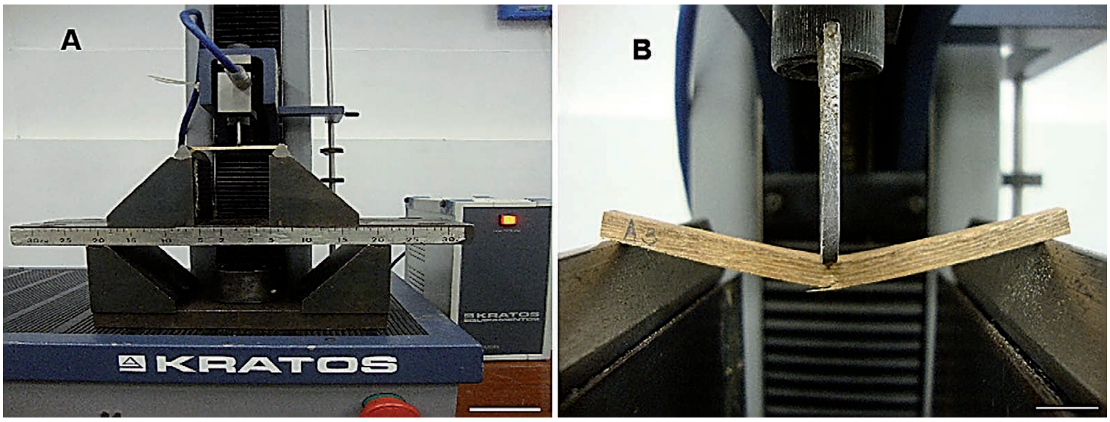

Fig. 1. A) Static bending tests on the sibipiruna wood in a universal machine. B) Specimens ruptured during the testing (scale A = 10 cm, scale B = 1 cm).

Fig. 1. A) Ensaios de flexão estática do lenho de sibipiruna em máquina universal. B) Corpo de prova rompido durante o ensaio (escala A = 10 cm, escala B = 1 cm).

rupture (MPa) and the modulus of elasticity (MPa). The failure model (fracture) of deteriorated samples was evaluated following Bodig and Jayne method (Bodig & Jayne, 1992), as illustrated in Fig. 2. Kruskall-Wallis' analysis of variance was used in the analyses of physical and mechanical properties of sound and deteriorated sibipiruna woods and Mann-Whitney's test was applied to compare treatment means at the 5% significance level.

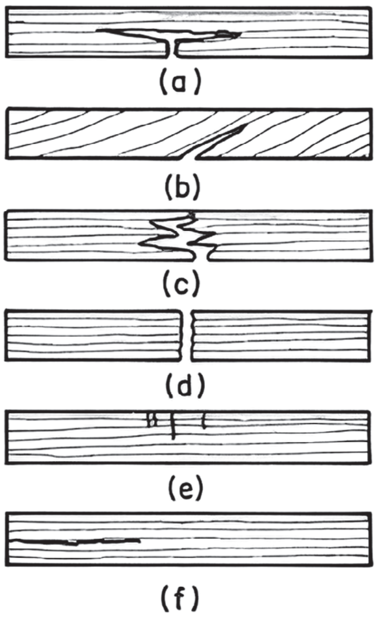

Fig. 2. Failure model in static bending. A) Simple tension. B) Cross-grain tension. C) Splitering tension. D) Brash tension. E) Compression. F) Horizontal shear. Source: Bodig & Jayne (1992, p. 305).

Fig. 2. Modelo de falha à flexão estática: A) Tração simples. B) Grã inclinada. C) Lascamento. D) Tração abrupta. E) Compressão. F) Cisalhamento horizontal. Fonte: Bodig & Jayne (1992, p. 305).

RESULTS AND DISCUSSION

Ganoderma australe caused a simultaneous white rot in the sibipiruna wood. *Ganoderma* species are known for such type of wood decay, as they possess an enzymatic system capable of degrading plant cell wall constituents, being cellulose, hemicellulose, and lignin (Rayner & Boddy, 1988; Eaton & Hale, 1993; Tomazello-Filho *et al.*, 2008; Brazolin, 2009).

Macro and microscopic analysis of sound and decayed woods

Macroscopically the sound wood of sibipiruna showed a dark heartwood due to the deposition of extractives and a light-cream-colored sapwood (Fig. 3A). The analysis of tree disks at different trunk heights showed that fungal attack was more intense at the stem base, where basidiomata are usually formed, and decreased with the increase of stem height (Fig.3B, 3C). In the tree number 2, the deterioration extended to the root system, further compromising its structural stability (Fig. 3D). White-rotted wood was lighter in color and softer than healthy one. Degradation by the white rot fungus was observed in the heartwood, more intensely in the region near the pith or juvenile wood, progressing towards the mature wood (Fig. 3E, 3F). In the less-affected heartwood region (mature wood), a white pocket rot pattern was observed, i.e., small decayed areas (in pockets forms but with no differentiation of selective delignification) interspersed with sound tissue (Fig. 3G). Such fungal colonization strategy has been denominated by Rayner & Boddy (1988) as “heartwood rot”. The difference in the natural durability of tree wood in the radial direction can be explained, among other factors, by the gradual conversion of extractives into less toxic compounds as the tree gets older (Oliveira *et al.*, 1986). A mycelial mass was observed in the pith region (Fig. 3H) as well as in inner cracks of the wood, evidencing an intense fungal growth. Heartwood decay do not affect tree vigor, as it occurs on physiologically inactive wood (heartwood).

Colonization by *G. australe* in the sibipiruna wood occurred predominantly through vessels and cells of the radial and axial parenchyma (Fig. 4A, 4B). The same was observed in *Fagus orientalis* wood (Bari *et al.*, 2015b), i.e. the accumulation of white-rot fungus hyphae in vessels and the penetration of the neighboring fibers to degrade them completely. The pattern of wood decay observed in sibipiruna trees is characterized here as simultaneous white rot (Fig. 4C, 4D), i.e., non-selective degradation of all cell wall components (lignin, cellulose, and hemicellulose).

Degradation of such components occurred in the proximities of the hyphae located in the cell lumen, from the S3 layer of the cell wall, resulting in erosion of the S2 layer of fibers. This pattern of decay was also observed by many authors in different woods (Brazolin, 2009; Bari *et al.*, 2015a, 2015c; Karim *et al.*, 2016). Deterioration of the sibipiruna wood occurred markedly in fibers (Fig. 5A, 5B) which ultimately led to xylem rupture. At advanced stages of decay (Fig. 5C, 5D), almost complete degradation of fiber cell wall was observed, leaving only the middle lamella undamaged, whereas the parenchyma and vessels walls also remained intact. The selective attack of some cells by white-rot fungi was also observed in other woods

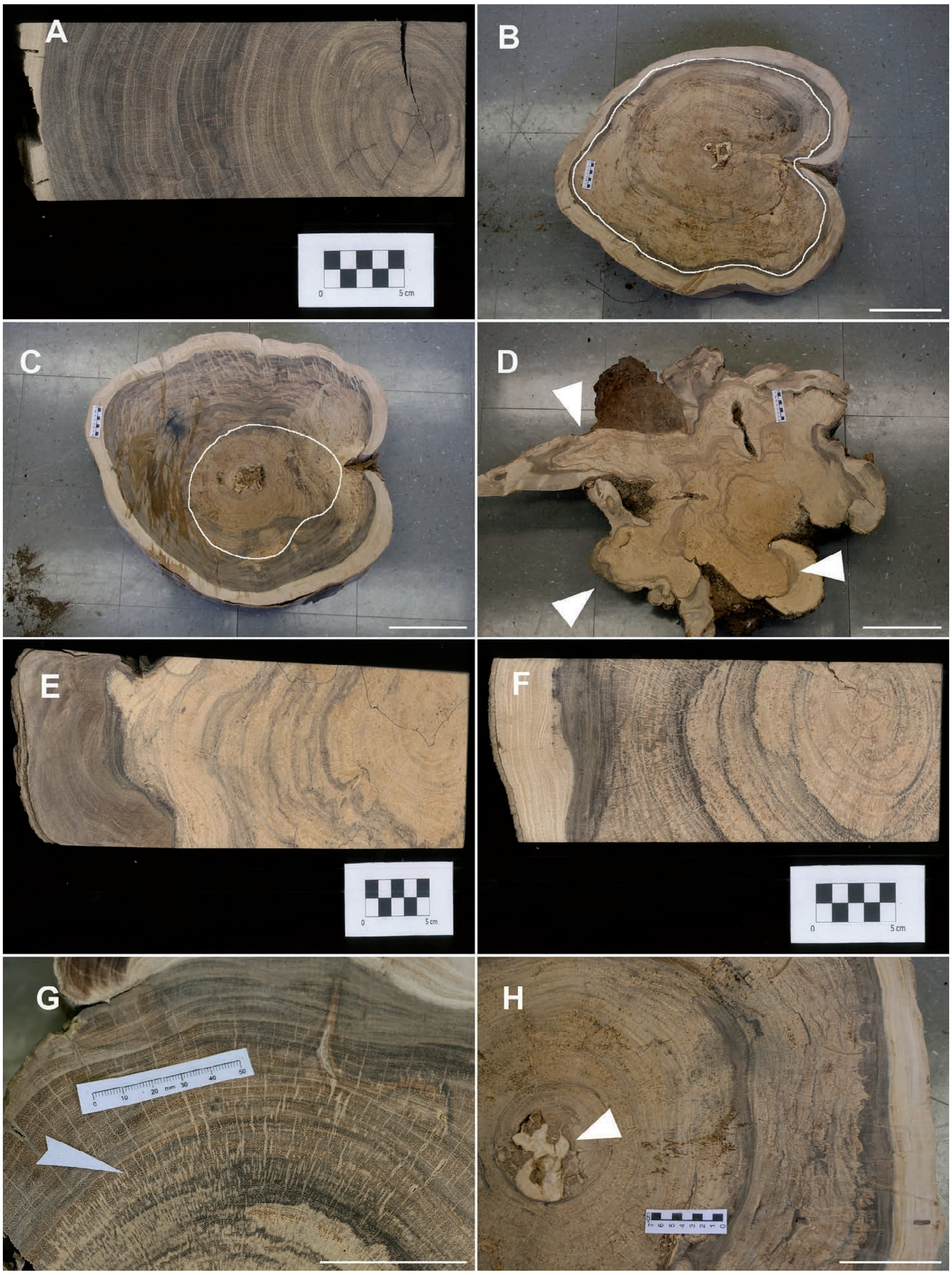

Fig. 3. Macroscopic characterization of the sibipiruna wood deteriorated by *Ganoderma australe*. A) Heartwood and sapwood of the sound wood on tree 1. B) Larger extension of the white rot (dashed line) at the stem base. C) Lower extension of the white rot at Breast Heigth Diameter (BHD) on tree 1. D) Intense decay of roots (arrows), as seen on the lower surface of a disk from tree 2. E) White rot in the heartwood of tree 2. F) White rot in the heartwood of tree 3, with a higher intensity on the region near the pith (juvenile wood). G) White rot in pockets (arrow) on the mature wood of tree 2. H) Mycelial mass in the pith region (arrow) of tree 2 (scale B-D = 20 cm, G = 5 cm, H = 10 cm).

Fig. 3. Caracterização macroscópica do lenho de sibipiruna deteriorado por *Ganoderma australe*. A) Cerne e alburno do lenho sadio da árvore 1. B) Maior extensão de podridão branca (linha tracejada) no colo. C) Menor extensão de podridão branca na altura do Diâmetro à altura do peito (DAP) da árvore 1. D) Apodrecimento intenso da raiz (setas), visto na face inferior do disco da árvore 2. E) Podridão branca no cerne da árvore 2. F) Podridão branca no cerne da árvore 3, com maior intensidade na região próxima à medula (Lenho juvenil). G) Podridão branca em bolsas (seta) no lenho adulto da árvore 2. H) Massa micelial na região da medula (seta) da árvore 2 (escala B-D = 20 cm, G = 5 cm, H = 10 cm).

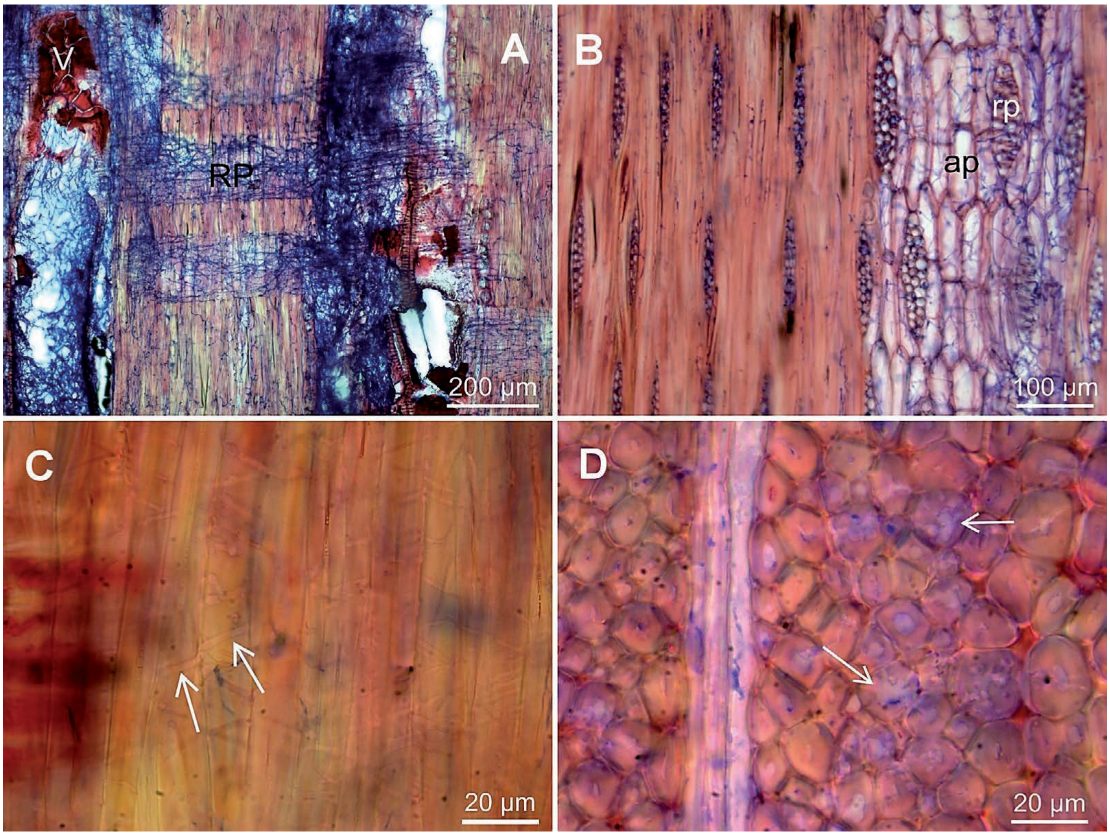

Fig. 4. Microscopic characterization of the sibipiruna wood deteriorated by *Ganoderma australe*. A) Radial longitudinal section. B) Tangential longitudinal section. Hyphae (in blue) intensely colonizing vessels and cells of the radial and axial parenchyma. C) Tangential longitudinal section. D) Transverse section. Erosion (arrows) of the cell wall of fibers, which is characteristic of the simultaneous white rot. Abbreviations: ap: axial parenchyma; rp: radial parenchyma; V: vessels.

Fig. 4. Caracterização microscópica do lenho de sibipiruna deteriorado por *Ganoderma australe*. A) Secção longitudinal radial. B) Secção longitudinal tangencial. Hifas (em azul) colonizando intensamente os vasos e células dos parênquimas radial e axial. C) Secção longitudinal tangencial. D) Secção transversal. Erosão (setas) na parede celular das fibras de sibipiruna, característica de podridão branca simultânea. Abreviaturas: ap: parênquima axial; rp: parênquima radial; V: vasos.

(Anagnost,1998; Tomazello-Filho *et al.*, 2008; Brazolin, 2009) and can be explained by the variation in lignin composition among different cell types. For instance, the vessels walls contain high concentrations of guaiacyl lignin, while the walls of fibers contain high concentrations of syringyl lignin; the walls of radial and axial parenchyma cells, on the other hand, are formed by a combination of guaiacyl and syringyl-type lignin (Schwarze, 2007). Therefore, the higher resistance of the walls of vessels and parenchyma cells could be associated with a higher amount of guaiacyl-type lignin (Schwarze, 2007).

Concerning the compartmentalization of the fungal attack in the sibipiruna wood, it was evidenced by the development of thin, dark, irregular lines resulting from the formation of a pseudosclerotium, a structure, with dense hyphal strands, in the lumen of fibers, vessels, and axial and radial parenchyma cells (Fig. 6A, 6B), that prevents other fungi accessing the wood within it. Such lines are characteristic of the white rot fungi (Rayner & Boddy, 1988; Brazolin, 2009).

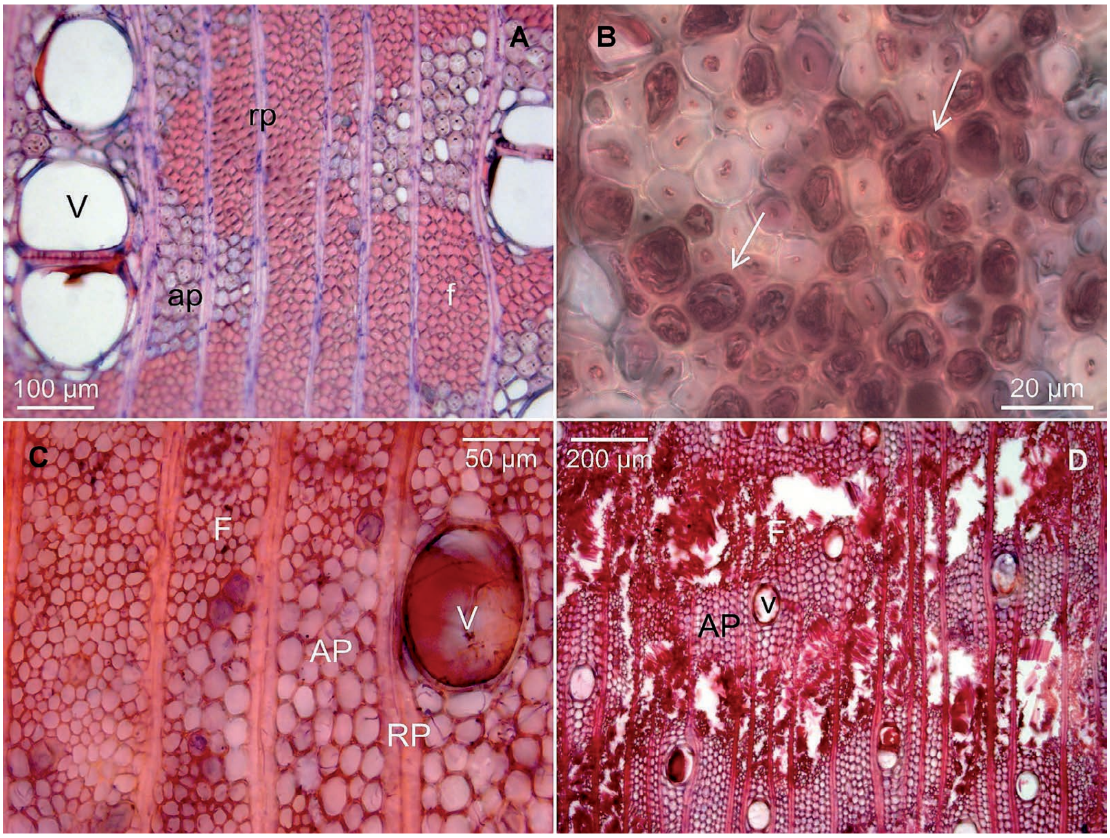

Fig. 5. Microscopic characterization of the sibipuruna wood deteriorated by *Ganoderma australe*. A) Transverse section of sound wood. B-D) Transverse section of wood at advanced deterioration stage, with degradation of fibers cell walls, yet with intact middle lamellae and not attacked cells of the radial and axial parenchyma. Abbreviations: ap: axial parenchyma; f: fibers; rp: radial parenchyma; V: vessels.

Fig. 5. Caracterização microscópica do lenho de sibipiruna deteriorado por *Ganoderma australe*. A) Secção transversal do lenho sadio. B-D) Secção transversal do lenho em estágio avançado de deterioração, com degradação das paredes celulares das fibras, mas ainda com as lamelas médias intactas e as células dos parênquimas radial e axial não atacadas. Abreviaturas: ap: parênquima axial; f: fibras; rp: parênquima radial; V: vasos.

The occurrence of the subterranean termite *Coptotermes gestroi* (Wasmann) and of wood-boring beetles (Order Coleoptera) was observed in the decayed wood of trees number 3 (Fig. 6C) and number 1 (Fig. 6D), respectively. According to Brazolin (2011), there is a frequent association between xylophagous insects and decayed woods infected by *Ganoderma* spp. Brazolin *et al.* (2010) found a similar association between *Coptotermes gestroi* and wood-boring beetles in decayed wood of *Tipuana tipu*, another tree species utilized for urban forestation in São Paulo city. The partial digestion of wood by fungi promotes the interaction with the mentioned insects, due to the difficult to digest cellulose and lignin by termites and the capacity of fungi to detoxify repellent or toxic substances in the wood (Sands, 1969; Grassé, 1962). In sibipiruna wood decayed by *G. australe*, reaction zones (Fig. 6E) or lines (Fig. 6F) were observed as a mechanism of resistance in response to the deterioration process promoted by the fungi, termites and wood-boring insects. The microscopic analysis revealed an accumulation of extractives in the lumen of xylem cells such as vessels,

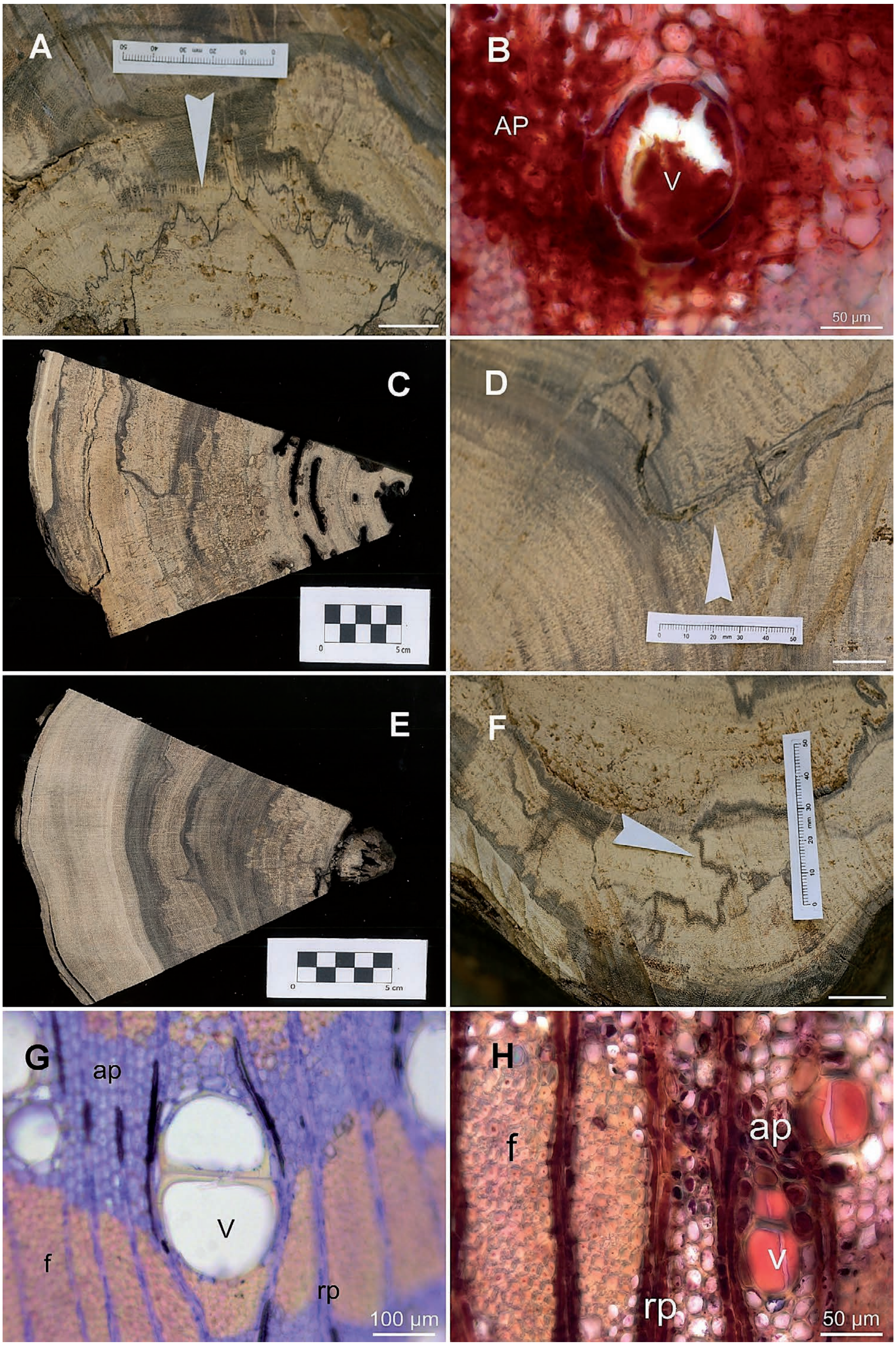

Fig. 6. Macro and microscopic characterization of the sibipuruna wood deteriorated by *Ganoderma australe*. A) Fungal compartmentalization line on tree 3. B) Histological transverse section of the pseudosclerotial plate in the lumen of axial parenchyma and vessel cells. C) Galleries of *Coptotermes gestroi* in the intensely decayed heartwood of tree 3. D) Gallery of a wood-boring beetle in the decayed heartwood of tree 1. E) Wood compartmentalization, with formation of zones of reaction due to accumulation of extractives. F) Wood compartmentalization with formation of or lines (arrrow) of reaction due to accumulation of extractives. G) Transverse section of a wood without accumulation of extractives. H) Transverse section of a wood with accumulation of extractives in the lumen of

vessels, fibers, and cells of the radial and axial parenchyma. Abbreviations: ap: axial parenchyma; f: fibers; rp: radial parenchyma; v: vessels (scale A, D, F = 2 cm).

Fig. 6. Caracterização macro e microscópica do lenho de sibipiruna deteriorado por *Ganoderma australe*. A) Linha de compartimentalização do fungo na árvore 3. B) Secção transversal histológica da placa pseudoesclerotial no lume das células do parênquimas axial e vasos. C) Galerias (setas) de *Coptotermes gestroi* no cerne intensamente decomposto da árvore 3. D) Galeria (seta) de broca de madeira no cerne apodrecido da árvore 1. E) Compartimentalização da árvore (setas) formando zonas. F) Compartimentalização da árvore com formação de linhas (seta) de reação, devido ao acúmulo de extrativos. G) Secção transversal do lenho sem extrativos. H) Secção transversal do lenho com acúmulo de extrativos no lume dos vasos, fibras e células dos parênquimas radial e axial. Abreviaturas: ap: parênquima axial; f: fibras; rp: parênquima radial; v: vasos (escala A, D, F = 2 cm).

fibers, and radial and axial parenchyma (Fig. 6G, 6H). This mechanism is known as compartmentalization and it is characterized by the accumulation of extractives that are usually not produced by the tree in the sound heartwood (Hillis, 1962; Manion & Zabel, 1979; Shigo, 1984; Shigo, 1979; Brazolin, 2009).

Physical and mechanical properties of sound and deteriorated wood by *Ganoderma australe*

Based on macro and microscopic analyses, four zones from sound to deteriorated wood by *Ganoderma australe* were defined in the sampled trees: sound sapwood (SS) – light-cream-colored wood with no sign of fungal attack (Fig. 3A); heartwood with accumulation of extractives (EX) – dark-brown- or black-colored sound heartwood of irregular shape and size, delimitating sound wood from decayed one (Fig. 6E); heartwood with white pocket rot (WPR) – small decayed regions interspersed with sound areas (no selective delignification) (Fig. 3G); and heartwood with intense simultaneous white rot (IWR) – whitish wood showing a spongy aspect and perceptible by touch (Fig. 3E). The wood patterns showed significant differences in their specific gravity (Table 1). It was observed the highest mean values in the heartwood with accumulation of extractives (EX) and decreasing values in wood regions with white rot (WPR and IWR). The results of mechanical assays revealed high variability

Table 1. Physico-mechanical properties of sibipiruna wood patterns: sound and deteriorated wood by Ganoderma australe. SS – sound sapwood; EX – heartwood with accumulation of extractives; WPR – heartwood with white pocket rot; IWR – heartwood with intense white rot. C.V. – coefficient of variation.

Tabela 1. Propriedades físico-mecânicas do lenho de sibipiruna: lenho sadio e deteriorado por Ganoderma australe. SS – alburno sadio; EX – cerne com acúmulo de extrativo; WBB – cerne com podridão branca em bolsas; IWR – cerne com podridão branca intensa. C.V. – coeficiente de variação.

Wood pattern	Specimens number	Specific gravity (kg m^{-3}) (C.V.)	Modulus of rupture (MPa) (C.V.)	Modulus of elasticity (MPa) (C.V.)
SS	50	867 ± 61 (7)	118 ± 26^a (22)	9780 ± 1874^a (19)
EX	29	920 ± 61 (6)	131 ± 27^a (21)	11750 ± 2235 (19)
WPR	32	712 ± 99 (8)	78 ± 38 (48)	8582 ± 3239^a (38)
IWR	43	595 ± 93 (15)	33 ± 16 (48)	5536 ± 2492 (45)

Mann-Whitney's test – means followed by the same letter do not differ statistically ($p < 0.05$).
Teste de Mann-Whitney – valores seguidos de mesma letra não diferem estatisticamente ($p < 0,05$).

Fig. 7. Failure model in the static bending tests samples from the sibipuruna wood decayed by *Ganoderma australe*, ruptured by simple tension (scale = 1 cm).

Fig. 7. Modelo de falha no ensaio de flexão estática dos corpos de prova do lenho de sibipiruna deteriorada por *Ganoderma australe*, rompidos por tração simples (escala = 1 cm).

(coefficient of variation – C.V.) in the modulus of rupture and modulus of elasticity of decayed heartwood (WPR and IWR), which can be explained by the difficulty to obtain homogenous wood samples, as the decayed regions were irregular, with a variation in size along the stem. In relation to sound sapwood (SS), modulus of rupture (resistance) values decreased significantly with the increasing degree of deterioration, reaching values of 34% and 72% in regions with WPR and IWR, respectively.

The modulus of elasticity (rigidity) did not differ in the WPR zone from the one in the SS zone, as such wood property is related to the amount of effective (sound) wood mass, thus representing the average of the evaluated specimens. Although the values were similar ($p = 0.103$), the decrease in modulus of rupture was significant, as wood rupture depends only on the most fragile point of the wood samples. While a given tree with such decay pattern may still keep its wood rigidity, it nonetheless should be considered susceptible to fractures caused by external forces, such as winds. In wood zones with the IWR, a significant reduction in rigidity (43%) was observed in relation to the SS. A decrease in values of specific gravity, modulus of rupture and modulus of elasticity of wood of several tree species infected by xylophagous fungi has also been observed (Manion & Zabel, 1979; Zabel & Morrell, 1992; Eaton & Hale, 1993; Tomazello-Filho *et al.*, 2008; Brazolin, 2009, 2011). Accumulation of extractives in the lumen of cells in the EX zone led to an increase in specific gravity and consequently in the modulus of elasticity, in comparison with the SS. In the case of the modulus of rupture, despite being similar to SS ($p = 0.06638$), it suggests a tendency to increase in mechanical resistance, as observed in tipuana trees (*Tipuana tipu*) decayed by *Ganoderma* sp. (Brazolin, 2009). Thus, we found evidence of an increase in mechanical properties in sibipiruna wood in response of the fungi deterioration. The analysis of the failure model in the static bending assay showed that samples were ruptured by simple tension (Fig. 7). Microscopically, this rupture can be explained by the formation of fiber erosion channels and by complete cell wall depletion at advance stages, after which only the middle lamella remains among fibers, vessels, and cells of the axial and radial parenchyma, which provides higher susceptibility to rupture. Thus, a tree whose stem is inclined or subjected to strong winds and has basidiomata of *G. australe* on its tensioned side (and consequently presents simultaneous white rot in the inner wood) can be considered dangerous due to imminent fall risk.

In sibipiruna (*Cenostigma pluviosum* var. *pelthophoroides*) trees, the fungus *Ganoderma australe* developed in juvenile and mature heartwoods, causing simultaneous white rot, leading to advanced stages of deterioration. Although the presence of *Ganoderma* fruiting bodies on living trees does not always indicate imminent tree failure or death (Loyd et al., 2017), the decay caused by *Ganoderma australe* significantly affected the wood specific gravity and consequently its mechanical resistance and rigidity, thus becoming the trees susceptible to rupture and fall.

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CONFLICT OF INTEREST

Authors declare there is no conflict of interest in publishing the article.

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