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ARTÍCULO

Natural durability of wood for fifteen *Eucalyptus* and two *Corymbia* species in contact with the soil

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Abstract:
Wood can be highly susceptible to deterioration by xylophagous agents, which compromises its structural integrity and limits its use in applications involving soil contact. Therefore, evaluating the natural durability of wood is essential to determine its most appropriate uses. The present research aimed to evaluate natural durability as a function of exposure time of 15 species of *Eucalyptus* and two species of Corymbia, in order to classify wood for use in contact with soil. Two fence posts and stakes of each species were installed in the Floresta Estadual de Manduri, SP. The fence posts of *Eucalyptus umbra* (broad-leaved white mahogany) and *Corymbia citriodora* (lemon-scented gum) showed the highest natural durability values, whereas *Eucalyptus dunnii* (dunn's gum) and *Eucalyptus grandis* (rose gum) showed the lowest values. Stakes of *Corymbia citriodora* (lemon-scented gum) and *Corymbia maculata* (spotted gum) showed the highest values, whereas *Eucalyptus dunnii* (dunn's gum) and *Eucalyptus grandis* (rose gum), again, showed the lowest values. Overall, fence posts and stakes have good natural durability against exposure up to 7 years; however, after this period, durability decreases considerably. The natural strength of both posts and stakes can be estimated as a function of exposure time with good accuracy. For most species of *Eucalyptus* and *Corymbia*, cuttings and posts had an average life exceeding 11 years under our experimental conditions.

Keywords: Natural wood durability, wood biodegradation, Field decay test, heartwood resistance, wooden fence posts.

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Introduction

Wood is a renewable material whose physico mechanical and anatomical properties make it a versatile and sustainable option for various applications. Compared to other materials like concrete, plastic, steel and aluminum, wood offers several advantages including aesthetic appeal, high mechanical strength relative to its mass, low energy consumption for processing, excellent thermal insulation, and ease of workability (Brashaw and Bergman 2021). Additionally, wood's renewable nature and ability to store carbon make it a critical resource for mitigating global warming (IPCC 2014). However, wood also presents challenges, such as its combustibility, susceptibility to cracking and warping, in certain species, its limited natural durability against deterioration by xylophagous agents like fungi and insects (Vidal *et al*. 2015). While advancements in treatments and preservation techniques have addressed some of these limitations, understanding and improving the natural durability of wood remains crucial for expanding its applications, particularly in environments exposed to biological degradation.

Natural durability refers to the inherent ability of a wood species to resist the action of biological, physical and chemical deterioration agents (Carballeira Lopez and Milano 1986). Under optimal conditions, wood can last for centuries. However, when wood is exposed to fungi, insects, bacteria, and marine borers, the wood must have either natural chemical protection or complementary treatments to ensure greater durability (Arango *et al*. 2021).

Posts, stakes, and fence poles, when used partially buried, are exposed in the region near the ground level to moisture and aeration conditions that favor the development of wood-decaying fungi. For this reason, decay tends to occur mainly in this zone, compromising durability and rendering the piece unusable. However, even wood not in direct contact with soil may deteriorate if its moisture content exceeds 20 % (Lepage 1986, Jankowsky 1990).

Among wood-destroying insects, termites stand out as the most severe agents of deterioration. Subterranean termites, in particular, live in the soil, from where they build galleries that protect them and allow them to reach the wood they feed on. The soil provides the necessary supply of moisture, while the galleries, composed of soil and partially digested wood, create dark and humid conditions ideal for their survival. Due to this way of life, they mainly attack wood with higher moisture content, such as that used in building foundations, utility poles, railroad ties, and fence posts, among others (Lepage 1986, Jankowsky 1990).

Thus, studies on natural wood durability are essential to properly determine best uses, including contact with soil, construction and support structures, or other applications that pose a risk of damage caused by abiotic and biotic factors (Nadai Corassa *et al*. 2013).

The introduction of species from *Eucalyptus* and *Corymbia* in Brazil aimed to preserve native forests and promote the establishment of renewable plantations. *Eucalyptus* has become a strategic alternative for timber production, meeting the demands of various forestry sectors (Ferreira 2015, Silva *et al.* 2022). However, its low natural durability limits its direct use in fence posts, stakes, and utility poles, making preservative treatments necessary. In this context, studying the natural resistance of the wood is essential, as it defines its durability against fungi, insects, and moisture, thereby reducing maintenance costs, supporting sustainable practices, and enhancing the competitiveness of *Eucalyptus* compared to native timber (Silva *et al.* 2022).

Investigations of natural wood durability can involve chemical compound extraction studies, the identification of the active compounds that make certain woods naturally durable, or simple field observation (Gjovik *et al*. 1991). *Eucalyptus* and *Corymbia* woods can be treated with chromated copper arsenate (CCA) against fungal attack in order to increase natural wood durability (Lopes *et al*. 2018). Field trials are a faithful reflection of real conditions that challenge durability in soil contact (Lepage 1986, Willeitner 1984). Several *Eucalyptus* and *Corymbia* species, despite being difficult to treat with preservatives, show significant natural resistance to *Gloeophyllum trabeum* under laboratory conditions (Oliveira 2005).

Therefore, this study evaluates a long-term field trial involving a wide range of *Eucalyptus* and *Corymbia* species. The primary focus is on untreated wood, with the aim of providing practical insights for applications in civil construction and in uses where the wood is in direct contact with the soil.

Thus, this study aimed to determine the natural durability of fence posts and stakes in 17 species of *Eucalyptus* and *Corymbia* installed in a field decay test located in the Floresta Estadual de Manduri, municipality of Manduri, São Paulo, Brazil.

Materials and methods

Wood raw material and sample preparation

Wood samples from 15 species of *Eucalyptus* and two *Corymbia* species were sourced from area from various planting areas (Table 1).

Table 1: Characterization of seventeen species, as well as the age and origin of the wood samples used in the durability test of a field experiment conducted in the Floresta Estadual de Manduri, municipality of Manduri, São Paulo, Brazil.

Species	Basic Density Classification	Tree age	Provenances
Corymbia citriodora	heavy wood[1]	29	Floresta Estadual de Manduri (23°00'S, 49°29'W, elevation 658 m)
Corymbia maculata	heavy wood[1]	29	Floresta Estadual Águas de Santa Bárbara (22°43'S, 49°06'W, elevation 644 m)
Eucalyptus cloeziana	heavy wood[1]	17	Floresta Estadual de Manduri (23°00'S, 49°29'W, elevation 658 m)
Eucalyptus dunnii	medium wood[1]	22	Floresta Estadual Águas de Santa Bárbara (22°43'S, 49°06'W, elevation 644 m)
Eucalyptus grandis	light wood[1]	14	Floresta Estadual Águas de Santa Bárbara (22°43'S, 49°06'W, elevation 644 m)
Eucalyptus microcorys	heavy wood[1]	21	Floresta Estadual de Piraju (23°05'S, 49°22'W, elevation 599 m)
Eucalyptus paniculata	heavy wood[1]	29	Floresta Estadual de Pederneiras (22°27'S, 48°44'W, elevation 500 m)
Eucalyptus pilulares	medium wood[2]	29	Floresta Estadual de Pederneiras (22°27'S, 48°44'W, elevation 500 m)
Eucalyptus propinqua	heavy wood[3]	32	Estação Experimental de Buri (23°43'S, 48°28'W, elevation 600 m)
Eucalyptus punctata	heavy wood[1]	27	Floresta Estadual de Piraju (23°05'S, 49°22'W, elevation 599 m)
Eucalyptus resinifera	heavy wood[1]	27	Estação Experimental de Itirapina (22°15'S, 47°45'W, elevation 740 m)
Eucalyptus robusta	medium wood[1]	29	Floresta Estadual de Angatuba (23°22'S, 48°24'W, elevation 650 m)
Eucalyptus saligna	medium wood[1]	22	Floresta Estadual Águas de Santa Bárbara (22°43'S, 49°06'W, elevation 644 m)
Eucalyptus tereticornis	heavy wood[1]	29	Estação Experimental de Itapetininga (23°42'S, 47°57'W, elevation 500 m)
Eucalyptus umbra	heavy wood[4]	29	Floresta Estadual de Angatuba (23°22'S, 48°24'W, elevation 650 m)
Eucalyptus urophylla (hybrid)	medium wood[1]	34	Floresta Estadual de Manduri (23°00'S, 49°29'W, elevation 658 m)
Eucalyptus urophylla (pure)	medium wood[1]	27	Parque Estadual Alberto Löfgren (23°27'S, 46°37'W, elevation 812 m)

[1]Flores *et al.* 2016 ;[2]Oliveira *et al.* 2005; [3]Mori *et al.* 2003 and [4]Lima *et al.* 2011, where: light wood (BD <500 kg/m^3), medium wood (500 <BD> 650 kg/m^3) and heavy wood (BD >650 kg/m^3).

Experimental setup

These samples were installed in a field at the Floresta Estadual de Manduri (FEM) (Figure 1a), located in Manduri, São Paulo, Brazil (23o00'S, 49o29'W, elevation 658 m) (Gurgel-Garrido *et al.* 1997).

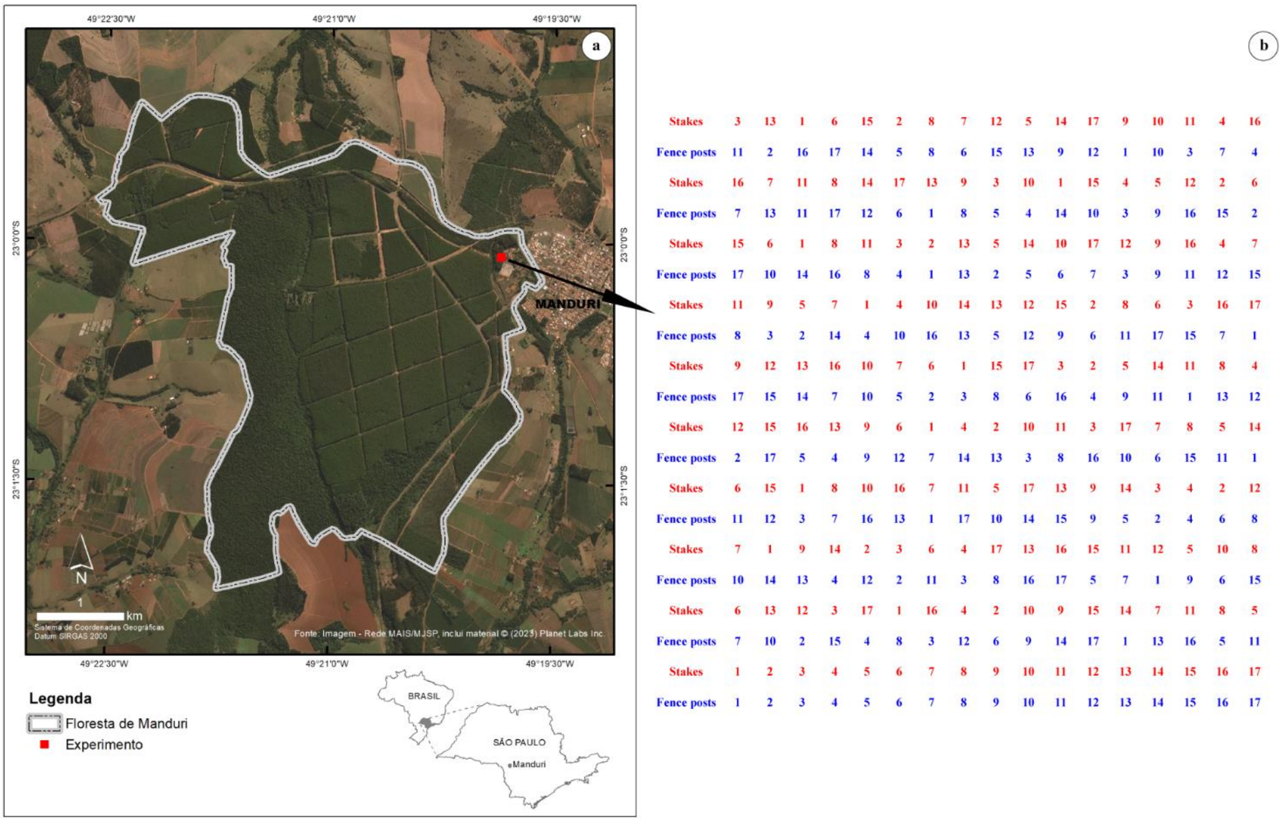

Figure 1: (a) Location of rotting field (red square) with 15 species of *Eucalyptus* and two *Corymbia* species in the Floresta Estadual de Manduri, São Paulo, Brazil. (b) Experimental design showing the location of stakes and fence posts.

The region has a Cfa climate, with an average annual rainfall of 1274 mm, and average annual temperature of 19,9ºC (Alvares *et al.* 2013). The soil is classified as a Red Latosol or Red-Yellow Dystrophic type, with moderate or weak A horizons, medium texture, and smooth wavy relief phases (Rossi and Kanashiro 2022).

Ten heartwood fence posts of each species were sawn to moisture content below 30 % and installed, totaling 170 sawn fence posts (8 cm x 8 cm x 2,2 m). Each fence post was buried vertically to a depth of 0,5 meters. The area was divided into 10 sections, and a fence post of each species was randomly placed in each one. The distance between sections was 1,5 m and between fence posts of each section, the distance was 0,75 m. In the same rotting field, 10 heartwood stakes of each species were sawn to 30 % and installed, totaling 170 stakes (2,5 cm x 5 cm x 50 cm). The stakes were buried vertically up to 50 % of their length. The area was also divided into 10 sections, and, like fence posts, stakes of each species were installed at similar distances (Figure 1b).

The fence posts and stakes were exposed for 11 years. Evaluations were carried out at 3, 4, 5, 6, 7, 9 and 11 years from the date of installation. In each evaluation, each fence post or stake was removed from the soil by lightly pushing at the upper end. If fence posts did not break, it was removed from the ground and assessed. For the degree of decay on a scale from 10 (sound) to destroyed (Table 2). Stakes with no fracture at the end were also removed, and their health status was evaluated according to the degree of deterioration, using an adaptation of the system proposed by ASTM-D1758 (1992) (Table 2).

Table 2: Fence post evaluation system (Martinez 1952). Stake evaluation system adapted from ASTM-D1758 (1992) and Becker (1972).

Index of condition	Degree of deterioration of Fence posts	Degree of deterioration (stakes)
10	Heartwood without attack	Not attacked
9	Heartwood with onset of attack	Surface attacked
7	Heartwood moderately attacked	Moderately attacked
4	Heartwood deeply attacked	Severely attacked
0	Fence post breakage	Stake breakage

The condition index for both fence posts and stakes was used as a parameter to evaluate all species. The lowest value corresponded to least durability (Table 3 and Table 4). The average life (AL) per species was determined when 60 % of the stakes had failed (Table 5).

Data analysis

The data were subjected to polynomial regression analysis ($P < 0,05$) using SAS® software for Windows (SAS Institute Inc. 1999). A grouping analysis of *Eucalyptus* spp. and *Corymbia* spp. was carried out using a cluster dendrogram to classify the species according to their resistance to wood degradation. Statistical analyzes were performed using the R software (R Core Team 2021).

Results and discussion

All samples used in the study were from heartwood and did not receive any type of treatment. The index of condition of natural durability of fence posts and stakes from 17 species tested is presented as a function of exposure time (Table 3 and Table 4). Broad-leaved white mahogany (*Eucalyptus umbra* R.T. Baker) and lemon-scented gum (*Corymbia citriodora* (Hook.) KDHill & LASJohnson) were the most durable woods, presenting the highest total values, whereas dunn's gum (*Eucalyptus dunnii* Doncella) and rose gum (*Eucalyptus grandis* W.Hill ex Maiden) showed the lowest values. Based on the same analysis of stakes, we highlight that lemon-scented gum (*Corymbia citriodora* (Hook.) KDHill & LASJohnson) and spotted gum (*Corymbia maculata* (Hook.) K.D.Hill & L.A.S.Johnson) wood presented the highest total values, whereas dunn's gum (*Eucalyptus dunnii* Doncella) and rose gum (*Eucalyptus grandis* W.Hill ex Maiden) again presented the lowest values. These results suggest that age and type of wood fragment, fence post or stake, affect durability. However, before drawing our conclusions, it should be noted that rose gum (*Eucalyptus grandis* W.Hill ex Maiden) fence posts were made with wood already 14 years old, or half the age of broad-leaved white mahogany (*Eucalyptus umbra* R.T. Baker) and lemon-scented gum (*Corymbia citriodora* (Hook.) KDHill & LASJohnson) fence posts (29 years old), which had the highest durability. Dunn's gum (*Eucalyptus dunnii* Doncella) was 22 years old at the time samples were taken. Thus, these results can be partially explained by the difference in the original age of wood. On the other hand, rose gum (*Eucalyptus grandis* W.Hill ex Maiden) normally has low natural durability to xylophagous agents (Vivian *et al*. 2015). The Index of condition of stakes observed during the first years of the trial (Table 4) were higher than those recorded for two native Brazilian species, *Inga* sp.

and cow wood (*Bagassa guianensis* Aubl.), which exhibited indices below 4,9 (moderate to severe) at 18 months of evaluation (Nadai Corassa *et al.* 2013).

Interestingly, swamp mahogany (*Eucalyptus robusta* Sm.) samples came from 29-year-old trees planted in Angatuba, like those of broad-leaved white mahogany (*Eucalyptus umbra* R.T. Baker), which showed the highest durability for fence posts. Nonetheless, wood from swamp mahogany (*Eucalyptus robusta* Sm.) presented the worst result in durability of fence posts. Thus, even if the age of the tested wood affects durability, it would be secondary factor compared to the effects of extractives, lignin and holocellulose contents. More specifically, resistance to wood deterioration can be attributed to the concentration of phenolic extractives, such as tannins, polyphenols, stilbenes, lignans and flavonoids (Walker 2006). Anatomical features, such as percentage of fibers or cell wall thickness or cell pits through which fungal hyphae can pass (Arango *et al*. 2021) may also imply greater or lesser durability. However, a separate study of all these chemical and anatomical characteristics is necessary to demonstrate with precision their relationship to the results presented here.

The results are consistent with the literature, as there is a direct relationship between wood density and natural resistance, which is crucial for assessing durability, resistance to biological attacks, and suitability for use in construction or posts. Wood density is the main indicator of natural resistance, as denser woods have a higher mass-to-volume ratio, which generally increases resistance to fungi and insect attacks. As shown in Table 4, the woods of broad-leaved white mahogany (*Eucalyptus umbra* R.T. Baker), lemon-scented gum (*Corymbia citriodora* (Hook.) KDHill & LASJohnson), spotted gum (*Corymbia maculata* (Hook.) K.D.Hill & L.A.S.Johnson), grey ironbark (*Eucalyptus paniculata* Sm.), and cloeziana (*Eucalyptus cloeziana* F.Muell.), which exhibited the highest fence post condition indices over time, are characterized by high wood density according to the literature (Flores *et al.* 2016). In addition to wood density, the age of the material must also be considered, as trees older than 15 years have a higher proportion of mature wood relative to juvenile wood.

Carvalho *et al*. (2015), studying the natural durability of four forest species, including samples of swamp mahogany (*Eucalyptus robusta* Sm.) (2 x 2 x 30 cm), suggest that swamp mahogany (*Eucalyptus robusta* Sm.) wood is not influenced by time or environment in terms of its resistance and rigidity and is, therefore, indicated for uses in contact with the ground. The authors report that swamp mahogany (*Eucalyptus robusta* Sm.) wood showed the highest resistance to fungal attack when compared to the other three species, dunn's gum (*Eucalyptus dunnii* Doncella), forest red gum (*Eucalyptus tereticornis* Sm.) and japanese raisin tree (*Hovenia dulcis* Thunb.), further suggesting that this greater resistance to xylophagous organisms can be attributed to the higher concentration of wood extractives. However, compared with the results of the present study, as described above, the wood samples, i.e., fence posts and stakes, were exposed to soil for 11 years. Thus, it is possible to establish a long-term evaluation. The study by Carvalho *et al*. (2015) evaluated samples with a shorter exposure of about two months.

Fence posts of cloeziana (*Eucalyptus cloeziana* F.Muell.), grey gum (*Eucalyptus punctata* DC.) and broad-leaved white mahogany (*Eucalyptus umbra* R.T. Baker) showed no signs of heartwood decay after four years (Table 3). These results could be further explained by apparent density which does not always directly influence natural durability (Carvalho *et al*. 2015). It should be noted that cloeziana (*Eucalyptus cloeziana* F.Muell.) fence posts were made of 17-year-old trees and exhibited behavior very similar to that of the more resistant species (Table 3). This good performance has already been observed in laboratory tests in which 16-year-old cloeziana (*Eucalyptus cloeziana* F.Muell.) wood showed less loss of mass compared to rose gum (*Eucalyptus grandis* W.Hill ex Maiden) at the same age (Vivian *et al*. 2015).

After 11 years of field exposure, stakes of lemon-scented gum (*Corymbia citriodora* (Hook.) KDHill & LASJohnson), grey ironbark (*Eucalyptus paniculata* Sm.), blue gum (*Eucalyptus saligna* Sm.) and, forest red gum (*Eucalyptus tereticornis* Sm.) showed lower values than those reported by Mucci *et al*. (2001) for the same species after 15 years of field exposure at another site. Such differences can be attributed to environmental conditions since the species reacted differently to the exposure time

(Cavalcante 1985). In a study involving *Eucalyptus* and *Corymbia* species, it was found that genetic material had no significant effect on the deterioration index or mass loss, either in treated or untreated wood (Quintilhan *et al.* 2018).

Table 3: Index of condition of fence posts as a function of exposure time in 15 species of *Eucalyptus* and two *Corymbia* species installed in a rotting field located in the Floresta Estadual de Manduri, municipality of Manduri, São Paulo, Brazil.

Species	Index of condition							
	3 years	4 years	5 years	6 years	7 years	9 years	11 years	Total
Corymbia citriodora	9,9	9,9	9,9	9,7	9,3	6,4	3,6	58,7
Corymbia maculata	9,9	9,9	9,6	9,5	7,5	6,4	4,6	57,4
Eucalyptus cloeziana	10	10	9,6	9,6	8,2	6,1	3,5	57
Eucalyptus dunnii	9,2	9,2	8,9	8,7	7	3,4	1,2	47,6
Eucalyptus grandis	9,5	9	8	6,7	3,6	1,2	0	37
Eucalyptus microcorys	9,7	9,6	9,4	9,1	7,5	5,7	2,8	49,8
Eucalyptus paniculata	9,7	9,7	9,7	9,7	8,4	6,4	3,6	57,2
Eucalyptus pilulares	9,9	9,9	9,8	9,7	8,0	5,8	2,4	55,5
Eucalyptus propinqua	9,7	9,7	9,7	9,4	7,7	5,5	2,4	54,1
Eucalyptus punctata	10	10	9,5	9,3	6,9	6,7	3,9	56,3
Eucalyptus resinifera	9,9	9,6	9,2	8,8	6,7	4,8	2,7	51,7
Eucalyptus robusta	7,8	7,8	7,2	7,0	4,2	1,9	0	35,9
Eucalyptus saligna	9,7	9,6	8,9	8,7	6,8	4,0	1,2	48,9
Eucalyptus tereticornis	9,3	9,1	8,7	8,5	7,4	5,1	2	50,1
Eucalyptus umbra	10	10	9,9	9,9	9	7	4	59,8
Eucalyptus urophylla (hybrid)	10	9,9	9,8	9,8	8,4	5,8	2,8	56,5
Eucalyptus urophylla (pure)	9,4	9,4	8,8	8,8	7,4	5,7	2,4	51,9

Fence posts exhibit more resistance to exposure than stakes, as shown in Table 3 and Table 4. This can be explained by the larger size of fence posts in relation to the stakes, contributing to longer resistance time against attack by wood-eating agents. Even when both contain a predominance of heartwood, wooden poles are more resistant to degradation over time than stakes due to their larger volume, lower surface-to-volume ratio, and reduced exposure to soil contact.

To better explain the performance of fence posts and stakes over the exposure time, an analysis of the decay resistance index of condition curve was performed. The best regression model that explained the behavior of the species was the polynomial with a 99 % significance level (Figure 2).

Table 4: Index of condition of stakes as a function of exposure time in 15 species of *Eucalyptus* and two *Corymbia* species installed in a rotting field located in the Floresta Estadual de Manduri, municipality of Manduri, São Paulo, Brazil.

Species	Index of condition							
	3 years	4 years	5 years	6 years	7 years	9 years	11 years	Total
Corymbia citriodora	9	8,8	8,8	8,8	8,8	6,7	4	54,9
Corymbia maculata	9	9	9	9	8,6	6,4	3,2	54,4
Eucalyptus cloeziana	9,3	8,3	8,1	8,1	7,9	5,4	2,8	49,9
Eucalyptus dunnii	7,3	6,4	6,2	5,7	4,9	1,2	0,8	32,5
Eucalyptus grandis	6,8	6,8	5,1	5,1	4,6	2,8	0,4	31,6
Eucalyptus microcorys	8,4	8,2	8	7,7	6,7	3,7	2,4	45,1
Eucalyptus paniculata	9	9	8,8	8,5	8,5	5,7	2,8	52,3
Eucalyptus pilulares	8,4	7,9	7,6	7,6	7,1	4,7	2,8	46,1
Eucalyptus propinqua	8,8	8,5	7,7	7,7	7,7	3,9	2,4	46,7
Eucalyptus punctata	8,6	8,4	7,9	7,9	7,3	5,4	2,8	48,3
Eucalyptus resinifera	8,2	7,4	6,8	6,5	6,5	3,9	2	34,5
Eucalyptus robusta	7,8	7,5	6,3	6,3	5	2,2	0,4	36,1
Eucalyptus saligna	8,8	8,6	8,4	8,4	7,2	4,4	2	47,8
Eucalyptus tereticornis	8,6	8,4	7,9	7,7	6,6	4	2,4	45,6
Eucalyptus umbra	8,8	8,8	8,5	8,5	8,5	6	3,2	52,3
Eucalyptus urophylla (hybrid)	8,5	8,5	8,3	8,3	8,3	6,1	2,8	50,8
Eucalyptus urophylla (pure)	8,0	7,4	7,1	7,1	6,1	2,2	1,6	39,5

In general, after exposure of both fence posts and stakes to soil up to 7 years, the wood still has good resistance for the wood-decaying agents, after which it decreases considerably (Figure 2). An allometric equation showing the behavior curve of each species can be used to estimate the resistance of the fence post and stake over the exposure time with good precision (Figure 2).

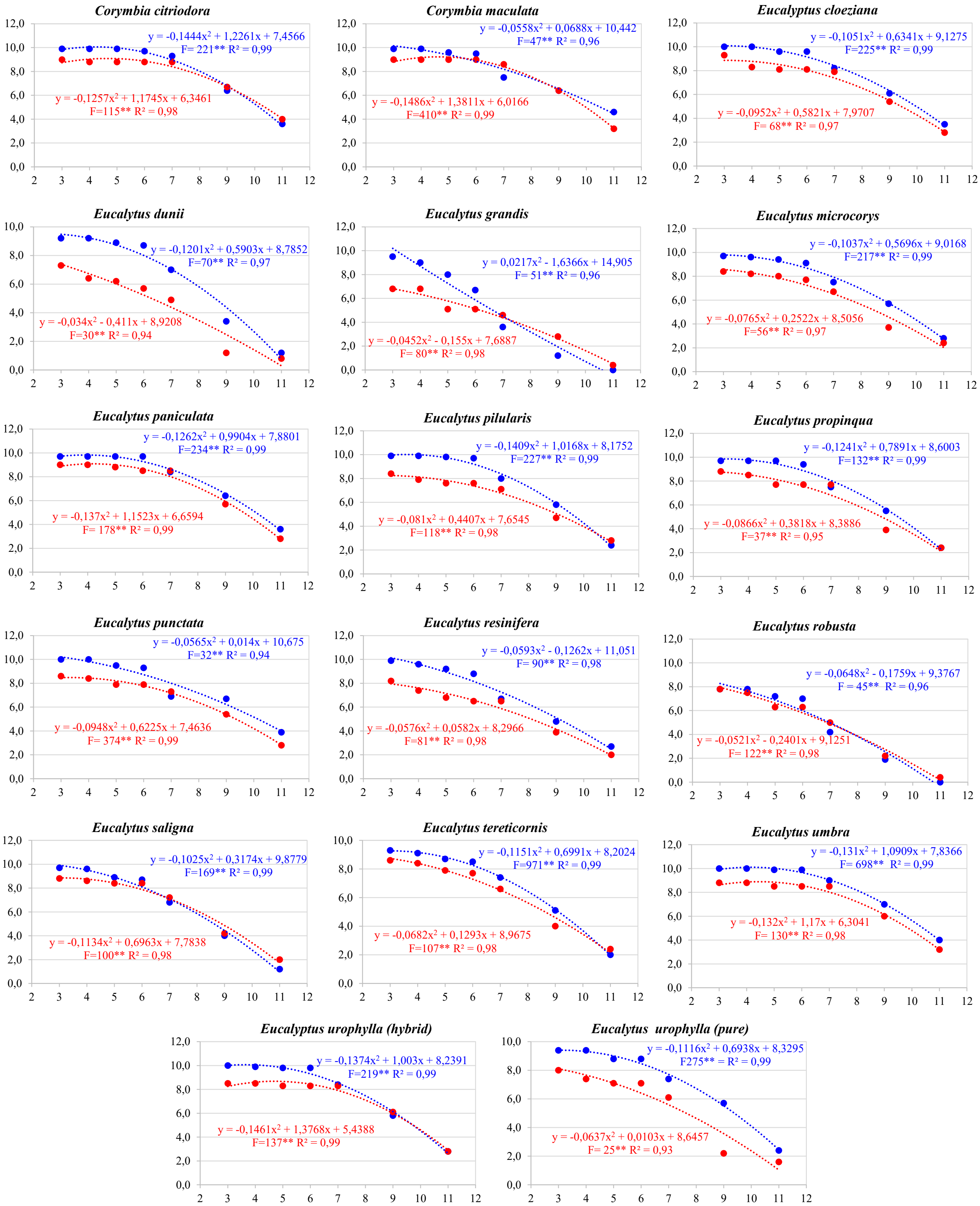

Figure 2: Condition index curves for fence posts (blue) and stakes (red) as a function of exposure time for 15 species of *Eucalyptus* and two *Corymbia* species in a field experiment conducted at the Floresta Estadual de Manduri, municipality of Manduri, São Paulo, Brazil. Condition index (y-axis) and years (x-axis). ** significant at 1 % probability.

The multivariate cluster analysis was carried out to group *Eucalyptus* and *Corymbia* species according to their resistance to wood degradation. The dendrogram, constructed from the degradation index of fence posts and stakes, revealed consistent clustering patterns among the evaluated species (Figure 3). This analysis resulted in the formation of four main groups, reflecting different levels of similarity in degradation behavior.

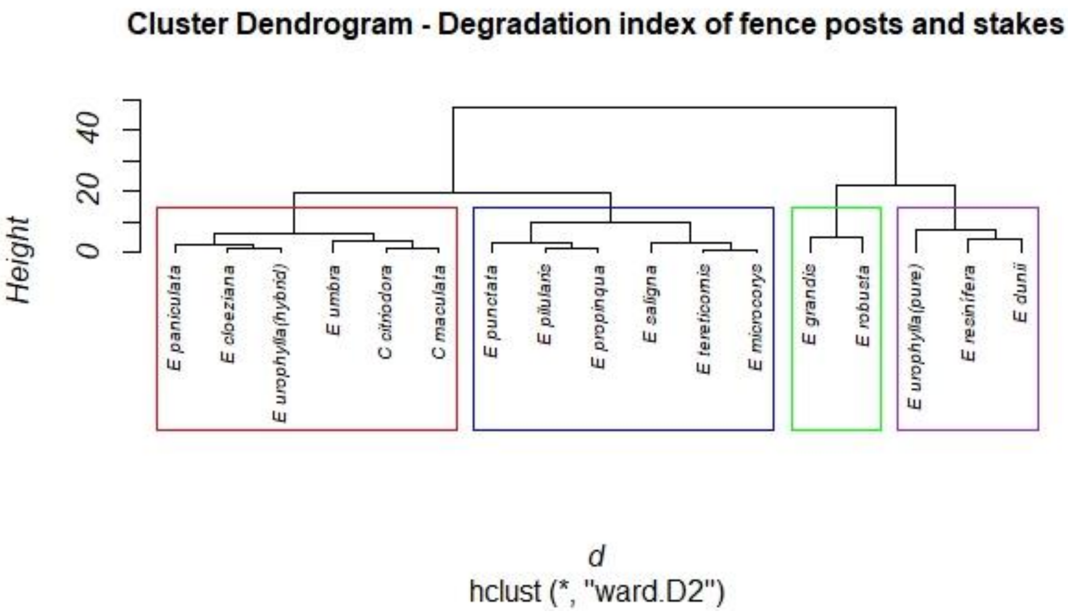

Figure 3: Cluster analysis dendrogram of *Eucalyptus* spp. and *Corymbia* spp.

The first group (red cluster) comprised grey ironbark (*Eucalyptus paniculata* Sm.), cloeziana (*Eucalyptus cloeziana* F.Muell.), upland mahogany (*Eucalyptus urophylla* S.T. Blake)(hybrid), broad-leaved white mahogany (*Eucalyptus umbra* R.T. Baker), lemon-scented gum (*Corymbia citriodora* (Hook.) KDHill & LASJohnson) and spotted gum (*Corymbia maculata* (Hook.) K.D.Hill & L.A.S.Johnson). These species exhibited similar performance, indicating greater proximity in terms of resistance to degradation, and were also characterized by high basic density (Table 1, Table 3 and Table 4). Additionally, grey ironbark (*Eucalyptus paniculata* Sm.) and cloeziana (*Eucalyptus cloeziana* F.Muell.) showed highly durable outer heartwood in natural durability tests under soil contact (Oliveira *et al.* 2005).

The second group (blue cluster) included grey gum (*Eucalyptus punctata* DC.), blackbutt (*Eucalyptus pilularis* Sm.), grey gum (*Eucalyptus propinqua* Deane & Maiden), blue gum (*Eucalyptus saligna* Sm.), forest red gum (*Eucalyptus tereticornis* Sm.), and tallowwood (*Eucalyptus microcorys* F.Muell.). This cluster exhibited intermediate behavior, with post resistance around 50 % and stake resistance around 47 %. Regarding basic density, blackbutt (*Eucalyptus pilularis* Sm.) and blue gum (*Eucalyptus saligna* Sm.) are classified as medium-density species, whereas the others fall into the high-density category (Table 1, Table 3 and Table 4).

The third group (green cluster) gathered rose gum (*Eucalyptus grandis* W.Hill ex Maiden) and swamp mahogany (*Eucalyptus robusta* Sm.), which showed the lowest resistance values for both stakes and posts. Both species are classified as medium-density (Table 1, Table 3 and Table 4).

Finally, the fourth group (purple cluster) consisted of upland mahogany (*Eucalyptus urophylla* S.T. Blake)(pure), red mahogany (*Eucalyptus resinifera* Sm.), and dunn's gum (*Eucalyptus dunnii* Doncella). These species showed intermediate resistance for posts (around 50 %) but low resistance for stakes, with values below 40 % (Table 3 and Table 4).

In general, species clustered at lower levels of the dissimilarity axis exhibited higher similarity in performance against degradation and may be considered equivalent in durability tests. Conversely, those grouped only at higher dendrogram levels displayed greater behavioral divergence, reflecting distinct responses to field degradation.

Overall, *Eucalyptus* and *Corymbia* species show low natural durability, remaining in satisfactory service conditions for only a few years when exposed to direct soil contact (Silva *et al.* 2022, Batista *et al.* 2022). In comparison, their natural durability is generally lower than that of tropical woods (Valle *et al.* 2013). It is important to emphasize, however, that no species is capable of resisting xylophagous agents indefinitely (Valle *et al.* 2013). Within this context, groups of species with higher or lower natural resistance were distinguished. The first group (red cluster), comprising grey ironbark (*Eucalyptus paniculata* Sm.), cloeziana (*Eucalyptus cloeziana* F.Muell.), upland mahogany (*Eucalyptus urophylla* S.T. Blake)(hybrid), broad-leaved white mahogany (*Eucalyptus umbra* R.T.

Baker), lemon-scented gum (*Corymbia citriodora* (Hook.) KDHill & LASJohnson) and spotted gum (*Corymbia maculata* (Hook.) K.D.Hill & L.A.S.Johnson), stood out with the best performance against degradation in both stakes and posts. In contrast, rose gum (*Eucalyptus grandis* W.Hill ex Maiden) and swamp mahogany (*Eucalyptus robusta* Sm.) showed the poorest performance.

The average life of wood for each species (fence posts) is the time necessary for 60 % of fence posts to receive a score of 0 (zero) (Martinez 1952). Thus, the average life values of the 17 species were obtained through field data as shown in Table 5. To theoretically obtain the average life, the "McLean Diagram (theoretical)" was also applied to the data (Table 5). While half-life figures and diagrams are approximate, experience shows that this type of evaluation is an excellent approximation of results (Lepage 1986).

By the criterion adopted in wood classification in terms of durability in the field test, it was observed that values obtained for fence posts and stakes are very similar (Table 5). In most of the evaluated species, the average life of fence posts and stakes was found to be greater than 11 years of exposure time. However, blue gum (*Eucalyptus saligna* Sm.) and dunn's gum (*Eucalyptus dunnii* Doncella) have an average life greater than 9 and less than 11 years, respectively; for swamp mahogany (*Eucalyptus robusta* Sm.), average life was greater than 9 years, and in rose gum (*Eucalyptus grandis* W.Hill ex Maiden), we found average life greater than 7 and greater than 9 years of exposure time (Table 5).

To establish the average life of stakes from 17 species, data was obtained through the values of the tests with stakes based on adaptation of a system recommended by ASTM D1758 (1992). Most wood stakes presented average life greater than 11 years of exposure. An exception to this was dunn's gum (*Eucalyptus dunnii* Doncella) which presents average life greater than 9 years, but less than 11 years. For swamp mahogany (*Eucalyptus robusta* Sm.) and rose gum (*Eucalyptus grandis* W.Hill ex Maiden), the average life was equal to 9 years, and for rose gum (*Eucalyptus grandis* W.Hill ex Maiden), the average life was equal to 9 years, while the average life for upland mahogany (*Eucalyptus urophylla* S.T. Blake)(pure) was equal to 11 years (Table 5).

Table 5: Average life values (data over 11 years) in 15 species of *Eucalyptus* and two *Corymbia* species installed in a field located in the Floresta Estadual de Manduri, municipality of Manduri, São Paulo, Brazil.

Species	Fence posts (average life AF)		Stakes (average life AF)	
	Field	Diagram	Field	Diagram
Corymbia citriodora	AF > 11	AF = 17	AF > 11	AF= 15
Corymbia maculata	AF > 11	AF= 16	AF > 11	AF = 17
Eucalyptus cloeziana	AF > 11	AF = 15	AF > 11	AF = 14
Eucalyptus dunnii	9 < AF < 11	AF = 10	9 < AF < 11	AF = 10
Eucalyptus grandis	7 < AF < 9	AF = 8	AF = 9	AF = 9
Eucalyptus microcorys	AF > 11	AF = 14	AF > 11	AF = 12
Eucalyptus paniculata	AF > 11	AF = 17	AF > 11	AF = 14
Eucalyptus pilulares	AF > 11	AF = 12	AF > 11	AF = 14
Eucalyptus propinqua	AF > 11	AF = 12	AF > 11	AF = 12
Eucalyptus punctata	AF > 11	AF = 17	AF > 11	AF = 14
Eucalyptus resinifera	AF > 11	AF = 12	AF > 11	AF = 12
Eucalyptus robusta	AF > 9	AF = 9	AF = 9	AF = 9
Eucalyptus saligna	9 < AF < 11	AF = 10	AF > 11	AF = 12
Eucalyptus tereticornis	AF > 11	AF = 12	AF > 11	AF = 13
Eucalyptus umbra	AF > 11	AF= 16	AF > 11	AF = 15
Eucalyptus urophylla (hybrid)	AF > 11	AF = 14	AF > 11	AF = 14
Eucalyptus urophylla (pure)	AF > 11	AF = 12	AF = 11	AF = 11

For both fence posts and stakes, we must also consider the age of trees used as samples for the field tests, e.g., rose gum (*Eucalyptus grandis* W.Hill ex Maiden) at 14 years old, half the age of most species used in the tests (Table 1).

As a material of organic origin, wood is highly susceptible to deterioration by xylophagous agents, which can attack cellulose, hemicellulose, and lignin. In view of the perspective presented in this study, the natural durability of wood is a characteristic vital to the determination of its most rational uses (Vivian *et al*. 2020, Arango *et al*. 2021). Therefore, such tests as those carried out in the present paper against xylophagous agents can facilitate the selection of species growing in areas of greater xylophagous aggressiveness, weathering, and permanent humidity in contact with the soil, but also with greater natural resistance to these conditions (Vidal *et al.* 2015). In general, the performance of wood (posts and cuttings) of *Eucalyptus* and *Corymbia* species varied little in relation to wood xylophagous agents, according to environmental conditions, exposure time and the age of wood.

Conclusions

Eucalyptus umbra and *Corymbia citriodora* wood fence posts showed the highest index of condition as a function of exposure time, whereas *Eucalyptus dunnii* and *Eucalytus grandis* showed the lowest index of condition. *Corymbia citriodora* and *Corymbia maculata* stakes showed the highest index of condition as a function of exposure time, and *Eucalytus dunnii* and *Eucalyptus grandis*, again, showed the lowest index of condition. Fence posts are more resistant to deterioration than stakes as a function of exposure time. Both have a natural resistance up to 7 years, but after this period, resistance decreases considerably.

The growth curve based on the allometric equation, as plotted for each species in the present study, was used to estimate the durability of fence posts and stakes over the exposure time with good precision. For most species of *Eucalyptus* and *Corymbia*, fence posts and stakes had an average life of over 11 years under our experimental conditions.

Authorship contributions

R. G. M.: Conceptualization, supervision, data curation, formal analysis, writing – review & editing. J. A. F.: Methodology, investigation, writing – original draft. A. O. L. F. N.: Methodology, investigation, writing – original draft. W. J. F.: Methodology, investigation, writing – original draft. L. A. B.: Methodology, investigation, writing – original draft. M. R.: Data curation, formal analysis, writing – review & editing. I. L. L.: Data curation, formal analysis, writing – review & editing. E. L. L.: Data curation, formal analysis, writing – review & editing.

All authors have seen and approved the submitted version of the manuscript.

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Declaration of interest

The authors declare that there is no conflict of interest associated with this work.

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