Survey on the natural resistance to decay of five hundred tropical wood species

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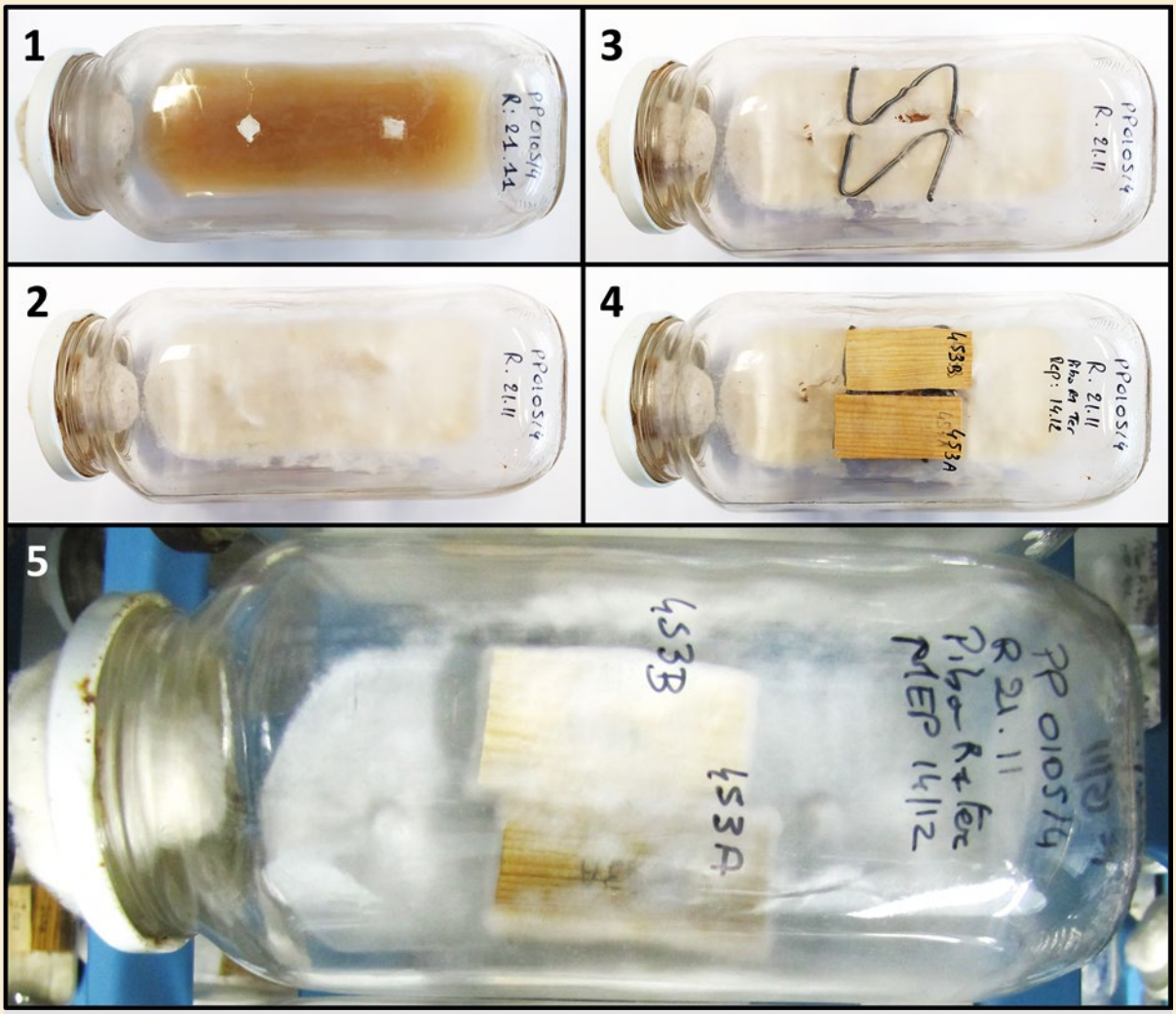

Photos 1.
Agar test in French squared glass bottles. (1) Yellow agar bed is inoculated with two white pieces of desired fungi from stock culture. (2) Mycelium has covered the whole agar bed. (3) Two Z-shaped sterilized metal supports are placed upon the mycelium bed. (4) Two wood blocks are placed upon the metal supports. (5) French squared glass bottle with perforated metal cap closed by a wad of cotton wool. Mycelium covers the two wood blocks.
Photos K. Candelier.

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RESEARCH / RESISTANCE TO DECAY OF TROPICAL WOOD SPECIES

RÉSUMÉ

Enquête sur la résistance naturelle aux champignons lignivores de cinq cents essences de bois tropicaux

La durabilité naturelle des essences de bois contre la pourriture redevient un sujet d'actualité avec d'une part l'essor des utilisations du bois en tant que matériau naturel, et d'autre part le débat sur l'utilisation de fongicides synthétiques. Au milieu du 20e siècle, de nombreuses études expérimentales ont été réalisées en Europe et en Amérique du Nord, en utilisant différents protocoles standardisés. Plus de cinq cents essences de bois tropicaux - 9842 échantillons au total - ont été testées en France entre 1955 et 1990. Il semble utile de permettre un accès libre à l'ensemble des données issues de ces tests afin d'approfondir les connaissances sur la durabilité naturelle d'un large éventail d'essences de bois. La majorité (68 %) des tests a utilisé deux protocoles légèrement différents, où seules les dimensions des échantillons de bois testés ont changé. Environ la moitié des essences ont été testées dans le cadre de l'un des deux protocoles, et l'autre moitié par le second. Par ailleurs, certaines essences ont été testées avec les deux protocoles. Les dimensions des blocs, la souche fongique utilisée et le type de bois (aubier ou duramen) donnent tous des résultats significativement différents, mais la perte de masse moyenne due aux 4 principales souches fongiques est un bon indicateur de la résistance du bois à la pourriture. Globalement, la perte de masse de l'aubier selon chacun des protocoles est plus élevée de 45 % que celle du duramen de la même essence. Il existe une corrélation positive significative entre la résistance à la pourriture de l'aubier et la résistance du duramen, mais la diminution du duramen vers l'aubier est plus importante pour les essences de bois durables que pour les non durables. La résistance à la pourriture du duramen varie fortement entre les arbres d'une même essence, à l'exception de celles classées « très durables » et « non durables ». Cela ouvre la perspective d'une classification de la résistance naturelle à la pourriture pour de nombreux types de bois utiles, mais souvent considérés comme « modérément » résistants parce qu'ils comprennent une petite proportion d'essences peu résistantes. Chacun des deux protocoles d'essais comprenaient plus d'une centaine d'essences pour lesquelles la densité et la composition chimique étaient disponibles. La densité, la teneur en lignine et la teneur en matières extractibles ont une influence similaire et très significative sur la résistance du bois à la pourriture (R^2 d'environ 0,25).

Mots-clés : composition chimique, densité, champignons, durabilité naturelle, collection de bois, essences tropicales.

ABSTRACT

Survey on the natural resistance to decay of five hundred tropical wood species

The natural durability of wood species against rot has again become a matter of interest for the uses of wood as a natural material, while the use of synthetic fungicides is being debated. In the mid-20th century, many experimental studies were performed in Europe and North America, using different standardised protocols. More than five hundred tropical wood species were tested in France between 1955 and 1990, with a total of 9,842 wood samples tested. It would seem useful to allow free access to all the data from these tests in the interests of a more comprehensive study of the natural durability of a wide range of wood species. The great majority (68%) of all these tests used two slightly different protocols with only a change in woodblock test dimensions. Roughly half of the species were tested under one of the two protocols, and the other half under the second. In addition, certain species were tested with both protocols. The dimensions of the test blocks, the fungal strain used, and the wood type (sapwood or heartwood) all give significantly different results, but the mean mass loss due to the 4 main fungal strains is a good predictor of the wood resistance to rot. Overall, mass loss for sapwood with each protocol is 45% higher than for heartwood of the same species. There is a significant positive correlation between the rot resistance of the sapwood and the heartwood, but the decrease from heartwood to sapwood is greater in durable wood species than in non-durable ones. Heartwood rot resistance was observed to be highly variable between trees of the same species, except in those classified as "very durable" and "non-durable". This opens up possibilities for a classification of natural rot resistance for numerous useful types of timber that are often regarded as only moderately resistant because they include a small proportion of species with poor resistance. Each protocol group included over one hundred species for which density and chemical composition data were available. Density, lignin content, and extractive content have a similar and very significant influence on the rot resistance of the wood (R^2 around 0.25).

Keywords: chemical composition, density, fungi, natural durability, wood collection, tropical wood species.

RESUMEN

Revisión de la resistencia natural a la descomposición fúngica de quinientas especies madereras tropicales

La durabilidad natural de las especies madereras ante la pudrición se ha convertido de nuevo en un tema de interés para la utilización de la madera como material natural, mientras se está debatiendo el uso de fungicidas sintéticos. A mediados del siglo XX se realizaron muchos estudios experimentales en Europa y América del Norte, mediante diferentes protocolos estandarizados. Se hicieron ensayos en Francia con más de quinientas especies madereras tropicales entre 1955 y 1990, en un total de 9842 muestras de madera. Parece útil permitir un acceso libre a todos los datos de estas pruebas para un estudio más completo de la durabilidad natural de una amplia gama de especies de madera. La gran mayoría (68 %) de estas pruebas utilizaban dos protocolos ligeramente distintos, con una diferencia únicamente en las dimensiones de los bloques utilizados para los ensayos. Aproximadamente la mitad de las especies se ensayaron bajo por uno de los dos protocolos, y la otra mitad por el segundo. Además, algunas especies se analizaron con ambos protocolos. Las dimensiones de los bloques de ensayo, la cadena fúngica utilizada y el tipo de madera (albura o duramen) proporcionan resultados significativamente diferentes, pero la pérdida de masa media debida a las cuatro cadenas fúngicas principales es una buena predicción para la resistencia de la madera a la pudrición. En general, la pérdida de masa en la albura con cada protocolo es el 45 % más elevada que para el duramen de la misma especie. Hay una correlación positiva significativa entre la resistencia a la pudrición de la albura y del duramen, pero el decrecimiento del duramen a la albura es mayor en las especies madereras duraderas que en las no duraderas. Se observó que la resistencia del duramen a la pudrición era altamente variable entre árboles de la misma especie, excepto en los que se califican como «muy duraderos» y «no duraderos». Esto abre posibilidades de una clasificación de la resistencia natural a la pudrición para numerosos tipos de madera útiles que se consideran a menudo solo como moderadamente resistentes porque incluyen una pequeña proporción de especies con baja resistencia. Cada protocolo se aplicó a un centenar de especies para las cuales estaban disponibles los datos de densidad y composición química. Densidad, contenido en lignina y contenido en materias extractibles tienen una influencia similar y muy significativa en la resistencia a la pudrición de la madera (R^2 aproximadamente del 0,25).

Palabras clave: composición química, densidad, hongos, durabilidad natural, colección de madera, especies de madera tropical.

Introduction

Wood represents a source of nutriments for microorganisms like fungi, and decay is a common natural way of wood degradation in forest conditions or whenever moisture content keeps high in a piece of timber (Fougerousse 1960). This is also true inside tree living parts such as the trunk or branches (Taylor et al. 2002) and each species has developed ways to limit fungal attacks so that decay of dead wood in a forest can take from a few months to many years depending on the species, tree or part of the tree (Déon et al. 1980), and climatic conditions, of course.

This natural resistance to decay (NRD) is different from conferred resistance using chemical treatments by fungicides (Fougerousse 1966) or any other wood modification processes (Gérardin 2016), but the way to test it is just the same, and standard tests for treated woods are used to quantify NRD.

The knowledge of NRD, as well as natural resistance to insects or marine borers, is key for structural design as well as mechanical resistance to external stresses (Sundararaj et al. 2015). There is much evidence of species' choices based on their NRD for long-lasting buildings in all civilizations (Scheffer and Morrell 1998).

The fast advances in chemistry during the last century provided a wide range of biocides, including efficient fungicides to protect wood pieces against decay (Fougerousse 1961). For some time, NRDs seemed less important than treatability in rich, industrialised countries. But today, pesticides are less and less accepted, and treating timbers massively takes away the advantage of environmentally friendly wood (Infodal 2013). Therefore, there is a renewed interest in the natural durability of tree species (Willeitner and Peek 1997), both in the developed northern countries and in the southern ones, where many tropical species present a good resistance against biodegradation.

Besides, as NRD is considered to be strongly influenced by the different fractions of the secondary metabolites (also called extractives) (Déon et al. 1980), durable wood species can also be a valuable source of active chemical compounds for treating fungal disease, both for plants and humans (Royer et al. 2012).

Ultimately, there is a large amount of literature about NRD, including some reviews with lists of species (Bavendamm 1960, Scheffer and Morrell 1998, Akhter et al. 2003, Sundararaj et al. 2015). But, as described by Willeitner and Peek (1997), there are many discrepancies between sources, and they even consider that "this data is of only limited value, because often no details are given on the test protocol and parameters, and no general classification system has been used to achieve comparable statements".

One of the major problems comes from the choice to publish NRD classification results instead of experimental data on well-defined laboratory or field tests. Wood durability classification depends on the author, timber use, as well as on the tree, or the position in the tree. In addition, the variation in NRD also depends on the fungus (age or health and virulence of strains for laboratory tests) or the presence and competition between fungi in the field. Thus, there can be large variability for the same species, and there is no way to understand the reasons for such divergences.

During 35 years (1953 to 1989), CIRAD [previously *Centre Technique Forestier Tropical* (CTFT, in French) until 1985] wood preservation laboratory achieved 10,400 natural decay tests, measuring mass loss for standard wood specimens against standard fungal strains, in standard laboratory conditions. All the basic information about these tests, which included maximum, minimum, and mean mass loss values for 10 specimens of the same provenance, was put in digital form in a data file. In total, 580 species were tested under different conditions: specimen dimensions, fungal exposure durations, type of wood (sapwood or heartwood), and fungal strains (6 different strains accounting for 90% of the tests, 4 various strains accounting for 75% of the tests).

There were two main test periods: before 1965 and after 1975, the main difference being the specimen dimension (figure 1 and figure 2). Between 1965 and 1974, there was an active business about the French standard for testing wood decay concerning the efficiency of treatments on treated wood decay (Afnor 1973, Afnor 1994). Since 1974, the experimental conditions (specimen dimension, duration of fungal exposure, fungal strain) have been kept constant. Between 1953 and 1965, another standard was used with a much smaller size of wood samples, but with the same duration and mainly the same fungal strain. There are approximately the same number of species (around 250) for each of the standards.

This article aims to share all these data and discuss the relationships between fungal natural durability and the density, chemical composition, species, and portion (sapwood or heartwood) of the wood.

All test results by botanical species are available in the Excel file accessible in the dataverse referenced at the end of this article.

Materials & Methods

Agar test using the French standard for testing wood decay

Wood blocks are stored in a climate chamber (20 ± 2 °C, 65 ± 5%) to share a common equilibrium moisture content (12% as a mean). For each fungal test, there is a test block and an assumedly very similar water content control block. All wood blocks are weighed at the beginning. Test blocks are sterilised (temperature or best Gamma-ray irradiation) before the decay test.

All tests are performed as follows: malt-agar is diluted in water and used as a support and initial food for fungi growth. It is deposited in French squared glass bottles

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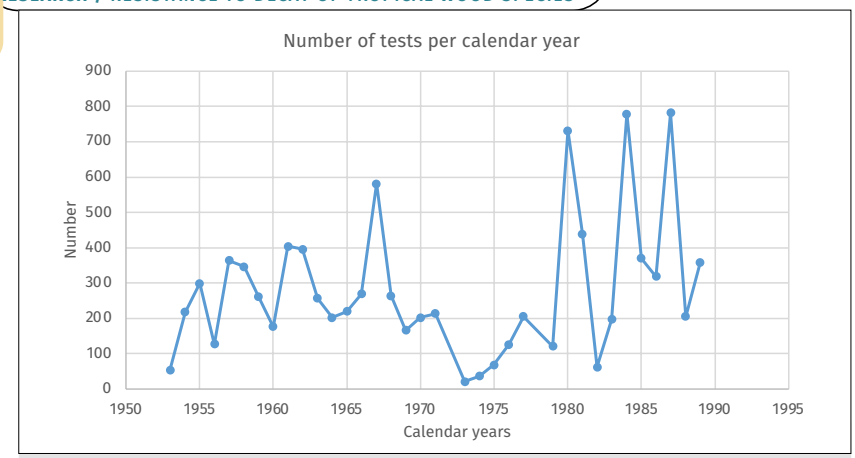

Figure 1.
History of the decay resistance tests carried out between 1953 and 1989. The fluctuation of the number of tests was dependent on the research and development projects and activities of the laboratory of wood durability.

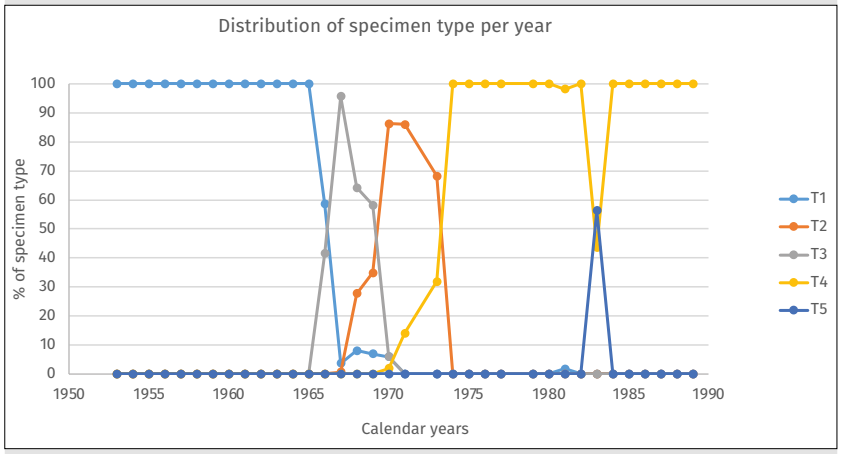

Figure 2.
Distribution in % of specimen type per calendar year.

with perforated metal caps closed by a wad of cotton wool and inoculated from stock cultures of the desired fungi (photo 1-1). Two weeks are needed in closed, dark rooms with even temperature and air humidity conditions (22 ± 2 °C and 70 ± 5% RH) for the fungi to cover the whole culture medium surface (photos 1-2). Z-shaped sterilised metal supports are placed upon the mycelium bed (photos 1-3) and sterilised wood blocks are placed upon the metal supports (photos 1-4) where they will be exposed to the mycelium during the test period (photos 1-5). The total test duration in the darkroom is usually 16 weeks (11% of the tests were carried out during 12 weeks).

Moisture control blocks are used to estimate the mean equilibrium moisture content (MC_s, in %) for the species in the standard condition (20 ± 2 °C, 65 ± 5% RH). If M_0 is the mass of the test block at the equilibrium moisture content, its theoretical initial anhydrous mass (M_i, in g) should be:

$$M_i = \frac{M_0}{(1+MC_s)}$$

At the end of the 16 weeks of fungal exposure, samples were carefully cleaned of the mycelium remains on their surfaces and they were weighed at the final mass (M_f, in g). Then, all the samples were oven dried at 103 ± 2 °C until mass stabilisation in order to record their anhydrous mass (M_a, in g), allowing calculation of the final moisture content (MC_f, in %) of the wood samples (which should be over 25%), and the relative mass loss (ML, in %) due to the fungal attack that occurred during the test:

$$MC_f = \frac{(M_f - M_a)}{M_a}$$

$$ML = \frac{(M_i - M_a)}{M_a}$$

The same whole procedure is done at the same time with reference wood blocks of a not-durable species (scots pine sapwood or beech, usually), used as virulence control samples to check the efficiency of the tested fungi. For pine and beech virulence control samples, the required minimum median values of mass loss are 30% for brown rots and 20% for white rots.

Sample dimensions and wood zones

Most specimens came from trees with a reference in the CIRAD collection (Langbour et al. 2019) and were delivered by the carpenter's workshop to the wood preservation laboratory. Ten neighbouring specimens were used for each of the 9,842 tests. Five different geometries, all rectangular parallelepiped (T1 to T5) were used (table I). T1 type is the mini wood-block test used by Bravery (1978) and later by Deklerck et al. (2019).

Block type T1 was massively used between 1953 and 1965, while it was type T4 after 1975. Together, T1 and T4 types account for 84% of all the tests, and globally, 90% of all tests had a 16-week duration. Testing with a 12-week duration concerns massively T3 block type, while it represents only 1% for T1 and T4 types. Accordingly, the study of duration influence is not possible on these data. All results analysed in the paper are limited to 16-week durations on both T1 and T4 block types.

Heartwood (HW) and sapwood (SW) portions respectively represent 89% and 11% of all the tests. The two zones are analysed separately.

Fungal strains

A total of 28 fungal strains (FS) were used, but six of them accounted for 86% of the tests (table II).

The four fungal strains F1, F2, F4, and F6 together account for 77% of all tests, and they are very often used all

four together. Analyses are done only for these four strains. In adding T1 + T4 block types tested against the 4 fungal strains (F1 + F2 + F4 + F6), this accounts for 68% of all the tests (6,677 tests). Those are the basis of further analysis.

Table I.
Description of the different specimen geometries.

Type	Number	Length	Width	Height	Volume	Surface	Sur/Vol	ML	16 weeks
T1	3,559	30	10	5	1,500	1,000	0.67	22.60	99.8%
T2	507	50	14	5	3,500	2,040	0.58	20.93	95.5%
T3	943	50	14	14	9,800	3,192	0.33	19.21	1.1%
T4	4,722	50	25	15	18,750	4,750	0.25	18.10	98.7%
T5	111	50	17	17	14,450	3,978	0.28	22.39	100.0%

Length (in the longitudinal axis), Width and Height in mm, V olume in mm^3.
Surface: sum of the 6 face's areas in mm^2.
Sur/Vol: ratio between surface and volume in mm^{-1}.
ML: mean mass loss on all specimens from the same type (%).
16 weeks: proportion of tests during 16 weeks (the other tests duration is 12 weeks).

Description of the database

The available data coming from the tests previously described and used for this present survey are divided into three data sheets and two comment sheets (Candelier et al. 2023). All these sheets are detailed below.

Decay test sheet

This gathers the results from the 9,842 tests in CTFT reference numerical order (472 tests have no N° CTFT) with the 14 following columns: Species, Country (the provenance of the tree), N° CTFT, Vernacular name, Year (of the test), Spec. type (dimension of the specimen tested), Duration (duration of the test), Nb FS (number of fungal strain used), FS (fungal strain used), Zone (heartwood or sapwood), Nb Spec. (number of specimens tested against the fungal strain), mean ML (mean mass loss), min ML (minimum mass loss), max ML (maximum mass loss).

Decay + Chemistry T1 HW sheet

This second sheet gathers the results for 182 species. It was built from the decay test sheet for the mass loss, using only heartwood specimen type T1 against the four standard fungal strains (F1, F2, F4, F6) and from the chemical data sheet (Gérard et al. 2019) for the chemical composition and density of the species common to both sheets. There are 15 columns: Family, Genus, Species, mean ML (mean value of mass losses for the 4 fungal strains), D*ML (product of the two values: density and mean mass loss for the species), mean Nb (mean number of trees tested against the 4 fungal strains), Nb trees (number of trees in the chemical test), AB ext (% extractive content in alcohol-benzene solution), W ext (% extractive content in hot water), Ash (% mineral content), Silica (% silica content), Tot (total result of chemical analyses in %), Lig rel (relative lignin content in %), Pento rel (relative pentosan content in %), Cell rel (relative cellulose content in %).

For lignin, pentosane, and cellulose content, relative means that the proportion is based on the extracted mass instead of the initial dry mass, to avoid low values due to very high levels of extractives that are not representative of the basic lignocellulosic matter.

Decay + Chemistry T4 HW sheet

This sheet gathers the results for 100 wood species. It was built just like the precedent sheet but using only heartwood specimen type T4.

Species T1 sheet

This sheet gathers the results for 219 species. It was built from the decay test sheet for the mass loss, using only heartwood specimen type T1 against the four standard fungal strains (F1, F2, F4, F6).

There are 18 columns: The first column concerns the Species T1 (all species for specimen type T1). Then, one block composed of the 4 following was done for each standard fungal strain (F_i = F_1, F_2, F_4 or F_6): Nb Fi (number of tests for fungal strain Fi), Mean (mean mass loss value for Fi), Min (minimum mass loss value for Fi), Max (maximum mass loss value for Fi). Finally, the last column is G mean (global mean mass loss for the 4 fungal strains F1, F2, F4 and F6).

Species T4 sheet

This sheet gathers the results for 151 species. It was built just like the precedent sheet, but using only heartwood specimen type T4.

Database and statistical methods

All the informative data and metadata about the collection have been recorded in digital files since 1980 (Gérard and Narboni 1996). In the open data file associated with this survey, the botanical names have been updated and mean density values have been added at the species level.

Table II.
Fungal strain (FS) used.

FS	Species	Type	Nb	%	ML
F1	*Pycnoporus sanguineus*	White rot	1,400	14.2	14.86
F2	*Lentinus squarrosulus*	White rot	1,849	18.8	21.08
F3	*Coriolopsis polysona*	White rot	825	8.4	22.80
F4	*Antrodia* sp.	Brown rot	2,169	22.0	26.90
F5	*Coniophora puteana*	Brown rot	506	5.1	7.40
F6	*Coriolus versicolor**	White rot	2,181	22.2	19.90
Total			**8,930**	**84.9**	**19.00**

Nb: total number of tests for the strain.
ML: mean mass loss for the strain (%).
* *Coriolus versicolor* is now known by its accepted scientific name *Trametes versicolor*.

Basic statistical analyses were performed using the XLSTAT 2020.5.1 software. The data description table includes the number of present and missing data, minimum, maximum, 1st quartile, median, 3rd quartile, and mean (with its standard deviation) values for each parameter, as well as the coefficient of variation (CV), skew (Pearson) and kurtosis (Pearson) of the distribution. A box plot is also given for each parameter. The box plot shows the quartiles (the band inside the box is the median). Whiskers plot the lowest data item still within the 1.5 IQR (interquartile range) of the lower quartile, and the highest data item is still within the 1.5 IQR of the upper quartile.

Table III.
Mean global results for standard tests.

Category	Total		F1	F2	F4	F6
16W T4 HW	Nb test	3,461	610	747	1,047	1,057
	Nb species		173	228	249	249
	ML	17.59	11.45	13.25	25.72	16.14
16W T4 SW	Nb test	685	109	161	217	198
	Nb species		68	87	106	107
	ML	25.47	21.57	20.43	32.23	24.31
16W T1 HW	Nb test	2,364	597	622	561	584
	Nb species		260	267	252	248
	ML	24.11	16.72	28.87	26.34	24.44
16W T1 SW	Nb test	167	43	44	43	37
	Nb species		24	25	24	22
	ML	34.62	25.10	38.43	36.53	38.93
T1/T4 HW	ML	1.37	1.46	2.18	1.02	1.51
T1/T4 SW	ML	1.36	1.16	1.88	1.13	1.60
SW/HW T1	ML	1.44	1.50	1.33	1.39	1.59
SW/HW T4	ML	1.45	1.88	1.54	1.25	1.51

FS: fungal strain (F1, F2, F4, F6) see Table 2.
Nb tests: total number of tests in the category.
Nb species: total number of species tested in the category.
mean ML: mean mass loss for the tests in the category (%).
16W T1 HW: test duration 16 weeks, with T1 specimen type (see Table 1), on heartwood.
16W T1 SW: test duration 16 weeks, with T1 specimen type, on sapwood.
16W T4 HW: test duration 16 weeks, with T4 specimen type (see Table 1), on heartwood.
16W T4 SW: test duration 16 weeks, with T4 specimen type, on sapwood.
T1/T4 HW: ratio between specimen type T1 and T4 mass loss for heartwood, general mean (first column), mean for a given fungal strain in the other columns.
T1/T4 SW: ratio between specimen type T1 and T4 mass loss for sapwood, general mean (first column), mean for a given fungal strain in the other columns.
SW/HW T1: ratio between specimen type sapwood and heartwood mass loss for specimen type T1, general mean (first column), mean for a given fungal strain in the other columns.
SW/HW T4: ratio between specimen type sapwood and heartwood mass loss for specimen type T4, general mean (first column), mean for a given fungal strain in the other columns.

For the histogram presentation, the amplitude was chosen for each parameter to have a clear description of the data. The normality of the distribution was verified by Shapiro-Wilk tests. A Pearson-type correlation analysis was used for a normal distribution and a Spearman-type correlation analysis for a non-normal distribution.

Results and discussions

Influence of testing conditions

Two sample sizes (T1 and T4), two types of wood (HW and SW), and four fungal strains (F1, F2, F4, and F6) are considered for this survey. All of these parameters are presented in table III. The number and nature of the wood species tested under a given set of conditions are very different (few species are tested with both specimen dimensions). Moreover, there are sometimes rather large variations among species for the same set of conditions, and the number of trees per species and set of conditions is very low (most often only one tree).

The values in the Total column or heartwood (HW) lines are more reliable for comparisons. There are very significant differences between fungal strains, specimen dimension, and type of wood. At a mean, the mass loss for the smallest dimension (T1) is around 40% higher than for the T4 dimension. Sapwood loses around 45% more mass than heartwood.

Variability of results

Each test was performed on 10 specimens with the same position in the tree, and the mean, minimum, and

Table IV.
Mean global results for standard tests.

Species	Nb tree	Mean ML (%)	CV tree (%)
Tectona grandis T4 SW	11	19.25	22.7
Tectona grandis T4 HW	11	6.67	46.6
Tectona grandis T1 SW	17	10.07	71.4
Aucoumea klaineana T1 HW	15	42.98	16.5
Triplochiton scleroxylon T1 HW	12	36.36	16.9
Cedrela odorata T4 HW	8	12.56	59.8
Shorea polysperma T4 FS4 HW	5	26.62	26.0
Shorea palosapis T4 FS4 HW	7	24.25	26.2
Shorea negrosensis T4 FS4 HW	6	30.45	8.3

Tx SW: mean values for Tx specimen type in sapwood.
Tx HW: mean values for Tx specimen type in heartwood.
T4 FS4 HW: mean values for T4 specimen type in heartwood tested with fungal strain FS4.
Nb tree: number of trees within the species.
Mean ML: mean value of the mean mass loss for all the tests in each tree.
CV tree: coefficient of variations of mean values.

maximum values of the mass loss for these 10 samples are given in the open data file (Candelier et al. 2023). The result is that the mean difference between maximum and minimum values amounts to 68% of the mean value, which means that there is a rather strong variability within decay tests themselves. This is the reason for testing 10 different specimens from the same position for each test.

There are 34 trees (same CTFT ID) where more than 5 different positions were tested inside the same tree using the same testing conditions: T4 specimen, FS4 fungal strain. The variability of mass loss values is measured by the standard deviation (figure 3). It appears that within-tree standard deviation values are much greater for trees with mass loss in the central range (mean ML between 15% and 30%). In comparison, there are few variations (small standard deviation for high mass loss) for the less durable (ML > 35%) and the most durable (ML < 5%) species.

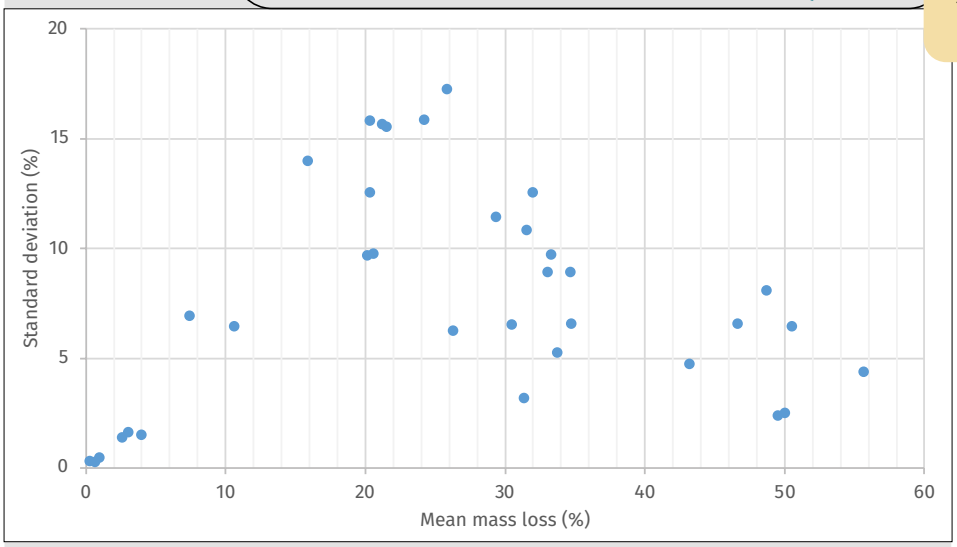

Figure 3.
Variability of mass loss within 34 trees having at least 5 tests. All specimens are T4 type and fungal strain FS4 is always used. In the vertical axis: standard deviation for the mass loss values within a tree. In the horizontal axis: mean mass loss for all tests in a tree.

For nine species, there are at least five different trees that were tested (table IV). For the less durable species (ML above 30%), variations between trees are rather low (CV below 20%), but they are quite high (CV near or above 50%) for the durable woods (ML below 15%).

This was described in the literature as the occurrence of far fewer durable trees within a durable species such as *Dycorinia guianensis*, *Tectona grandis*, or *Quercus petrea* (Guilley et al. 2004, Amusant et al. 2004, Moya and Berrogal 2010). Often, those trees are a minority and are characterised by low levels of extractives for this given species (Guilley et al. 2004). If these species are chosen for high-durability uses, it might be advisable to set up a sorting system based on a chemical test, such as near-infrared spectroscopy (Zahri et al. 2008), as is the case for mechanical sorting for structural use.

Difference between sapwood and heartwood

For the specimen dimension T4 (which is the standard now), there are 106 species with results against two different fungal strains, both on sapwood and heartwood. There are always very significant differences (at 0.1% level) between the 2 wood portions. Moreover, there is a very significant positive correlation between heartwood and sapwood mass losses (figure 4).

Table V gathers the results by class of global mean mass loss for the heartwood of the species. It appears in table V that globally, sapwood resistance to decay is higher for species with durable heartwood than for non-durable wood species, but the difference between sapwood and heartwood resistance is naturally much higher for species with durable heartwood.

Species influence

To have enough tests using the 4 most frequent fungal strains, it was decided to carry out two separate analyses on small specimens (T1 type) and big specimens (T4 type)

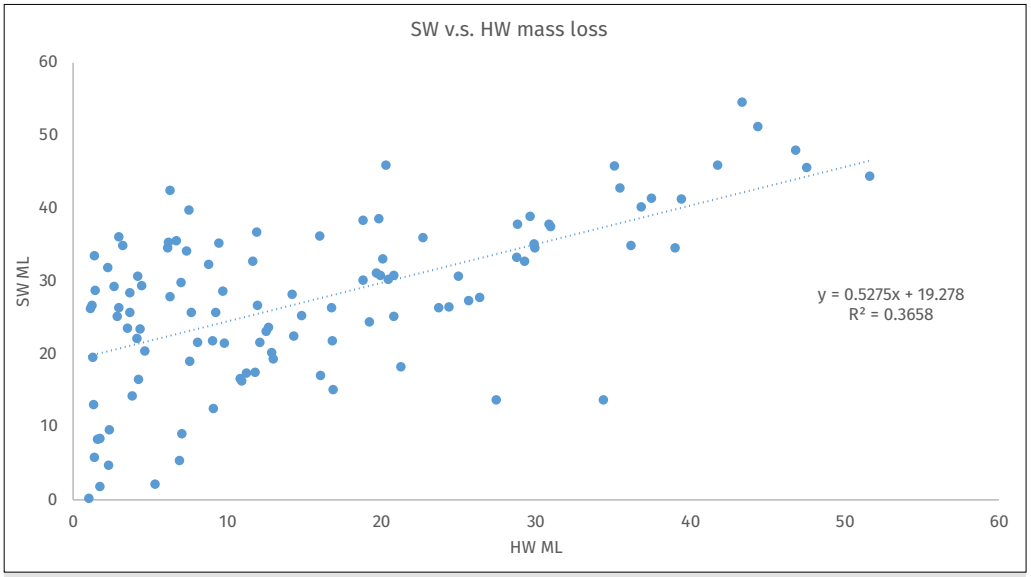

Figure 4.
Relationship between mean sapwood and heartwood mass loss for 106 species. In the vertical axis: SW ML represents the mean mass loss for sapwood against fungal strains F4 and F6. In the horizontal axis: HW ML represents the mean mass loss for sapwood against fungal strains F4 and F6.

and to use the species sharing the 4 fungal strains in each category: 219 species for type 1 specimens and 151 species for type 4 specimens. The global mean (G mean) value of the mass loss was calculated for each wood species as the mean value for the mass losses against the 4 fungal strains.

The distributions of values are very large (with coefficients of variation of 66% and 92% for T1 and T4, respectively) and not normal (figure 5, figure 6 and table VI).

With both T1 and T4 specimen types, the G mean has a very high correlation (using the Spearman correlation test) with the mean value of Mass loss from each fungal strain (tables VI and VII). In this sense, the G mean value could be used as a proxy to estimate the wood decay resistance according to the species.

Table V.
Comparison between mean mass loss (ML, in %) from heartwood and sapwood for 106 species.

HW Mean	Nb	F4 HW mean ML	F6 HW mean ML	HW mean ML	F4 SW mean ML	F6 SW mean ML	SW mean ML	SW-HW F4	SW-HW F6	SW-HW Mean
< 5	28	2.07	3.16	2.62	23.81	17.81	20.81	21.74	14.64	18.19
[5 ; 10[	20	8.08	7.20	7.64	28.56	22.97	25.77	20.48	15.77	18.12
[10 ; 15[	14	16.16	8.33	12.25	25.39	20.78	23.08	9.23	12.44	10.84
[15 ; 20[	11	23.75	12.32	18.04	34.85	21.55	28.20	11.10	9.22	10.16
[20 ; 25[	9	25.43	17.69	21.56	34.29	26.25	30.27	8.86	8.56	8.71
[25 ; 30[	9	33.86	22.90	23.38	33.89	28.67	31.28	0.03	5.76	2.90
> 30	15	47.81	31.02	39.42	47.75	34.78	41.26	-0.06	3.76	1.85

HW mean: class of global mean heartwood values.
Nb: number of common species in the class.
F4 HW: tests of the species heartwood against fungal strain 4.
F6 HW: tests of the species heartwood against fungal strain 6.
F4 SW: tests of the species sapwood against fungal strain 4.
F6 SW: tests of the species sapwood against fungal strain 6.
HW: mean of the tests against F4 and F6 for heartwood (global mean).
SW: mean of the tests against F4 and F6 for sapwood (global mean).
SW-HW: difference of mean mass loss between sapwood and heartwood.
F4, F6: test against fungal strain F4 and F6 respectively.
Mean ML: mean mass loss for the tests in the category (%).

Table VI.
Coefficient of correlation for mass loss between fungal strains for T1 specimens.

Spec. T1	Mean F1	Mean F2	Mean F4	Mean F6	G Mean
Mean F1	**1**	**0.649**	**0.608**	**0.764**	**0.810**
Mean F2	**0.649**	**1**	**0.713**	**0.735**	**0.906**
Mean F4	**0.608**	**0.713**	**1**	**0.671**	**0.872**
Mean F6	**0.764**	**0.735**	**0.971**	**1**	**0.879**
G Mean	**0.810**	**0.906**	**0.872**	**0.879**	**1**

Spec. T1: species tested with specimen type T1
Mean Fi: mean value of mass loss for the species using fungal strain Fi
G mean: global mean value for the 4 fungal strains for the species
Bold characters: significant value at level 0.1%

Links with species' chemical composition

By examining the data on the chemical composition of wood (Gérard et al. 2019) for the same species (and usually the same trees), it was possible to find 182 species tested with type T1 specimens and 100 species tested with type T4 specimens. These two samplings allowed a reasonable statistical analysis to be carried out on the correlations between natural decay resistance and the chemical composition of wood.

The description of the data (tables VIII and IX) shows that the sampling of species covers a wide range of density and chemical composition. Moreover, the variability (CV) is very high for fungal mass loss, similar to the variability of extractive content but much higher than the variability in density or cell wall polymer proportion.

A very significant negative correlation between mass loss, density, AB extract, and relative lignin content (table X and XI) is always observed. When total mass loss (D*ML) is used instead of relative mass loss (mean ML), the correlation is weaker with density (though still highly significant), but remains very similar for AB extract or lignin content.

Density, extractives, and lignin are always described as the main factors explaining wood resistance to decay (Sundararaj 2015, Scheffer and Morrell 1998, Fougerousse 1960, Deklerck et al. 2019, Stirling et al. 2017). The role of density is often discussed, as there are many counter-examples (Akhter et al. 2003, Fougerousse 1960). According to Willeitner and Peek (1997), "If test results are based on mass loss as a percent of the initial weight this will be favourable for high-density timber, as demonstrated in a small test". Moreover, according to Willeitner (1984), "the same absolute mass loss of maybe 6 g will be 50% for a specimen of 12 g mass and only 30% in case of an 18 g specimen". For this reason, the value D*ML was used because it is proportional to absolute mass loss while ML is a relative mass loss (note that this is still a Spearman correlation test). The results highlight that the correlation with density is lower for D*ML, but it is still very significant (tables X and XI), showing that this argument is not sufficient. On the contrary, the level of correlation is the same between both extractives

(AB extract) and lignin content and both ML and D*ML. All these results show that it is difficult to find a direct causality between high density and high resistance to decay when looking at the action of fungi on wood, while there are reasons for inhibiting the effect of extractives and lignin on fungal activity. There is probably a synergetic effect of both high-density and highly efficient extractives in tropical woods that confers on the wood a good natural durability against wood-destroying fungi (Scheffer and Morrell 1998).

Key findings

The great number of decay tests performed in the same conditions for at least two different specimen dimensions and four fungal stains confirms the findings from Willeitner and Peek (1997). There is a very large variability in resistance to decay, and results are strongly dependent on specimen type and fungal strain (besides test duration).

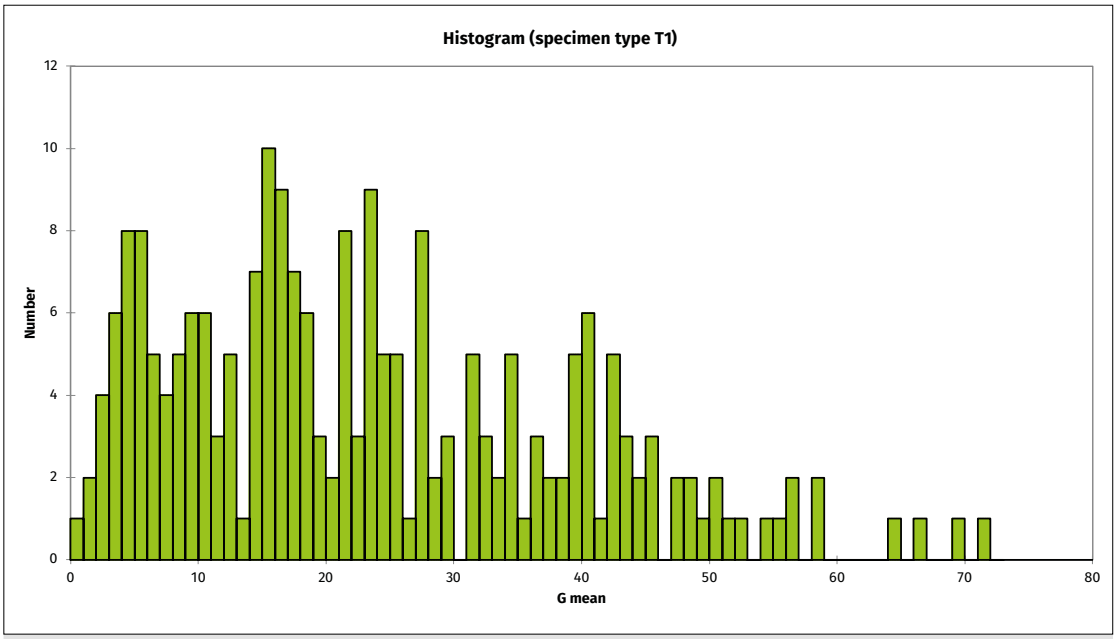

Figure 5.
Distribution of mean mass loss per species for T1 specimens.

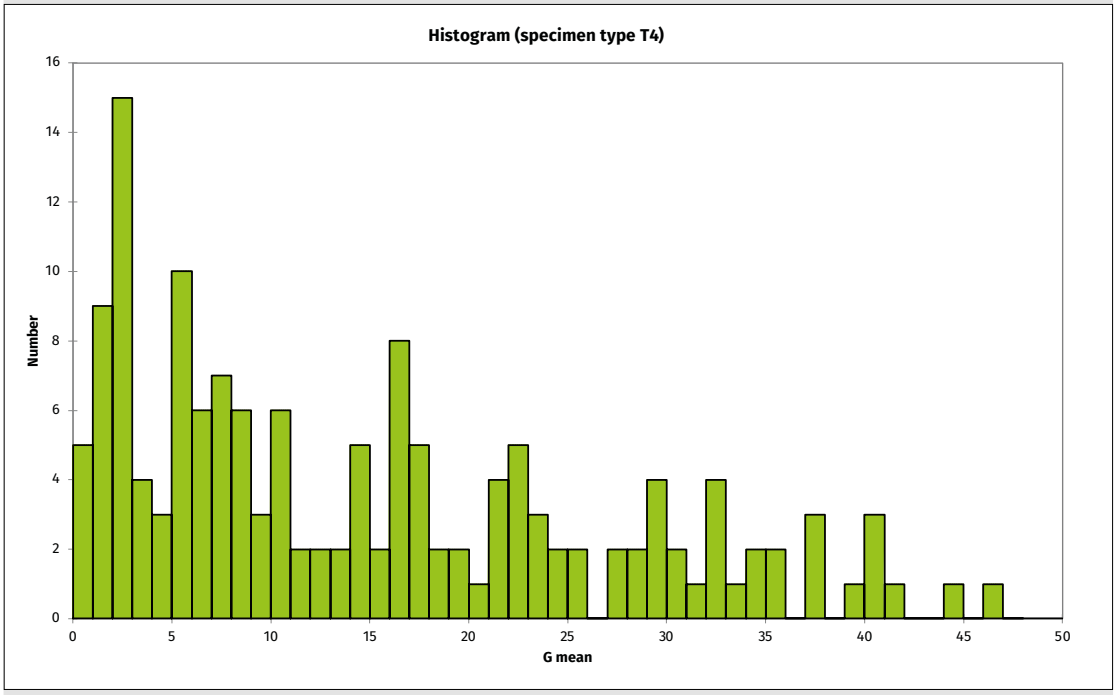

Figure 6.
Distribution of mean mass loss per species for T4 specimens.

The two specimen dimensions used are very different in volume and ratio surface/volume (table I), and this should explain the higher relative mass loss values (+40%) for the smaller specimen compared to those of bigger sample sizes, both experiencing the same fungal exposure duration (Bravery 1978).

Table VII.
Coefficient of correlation for mass loss between fungal strains for T4 specimens.

Spec. T1	Mean F1	Mean F2	Mean F4	Mean F6	G Mean
Mean F1	**1**	**0.892**	**0.764**	**0.871**	**0.901**
Mean F2	**0.892**	**1**	**0.753**	**0.870**	**0.942**
Mean F4	**0.764**	**0.753**	**1**	**0.812**	**0.882**
Mean F6	**0.871**	**0.870**	**0.812**	**1**	**0.929**
G Mean	**0.901**	**0.942**	**0.882**	**0.929**	**1**

Spec. T4: species tested with specimen type T4.
Mean Fi: mean value of mass loss for the species using fungal strain Fi.
G mean: global mean value for the 4 fungal strains for the species.
Bold characters: significant value at level 0.1%.

Using the mean mass loss for 4 different fungal strains allows for a more robust description of each wood species. When looking at the ranking of species by mean mass loss for each specimen dimension (T1 and T4), the result is similar to the results from the scientific literature (Scheffer and Morrell 1998) concerning durable versus non-durable wood species.

There were enough species combining sapwood and heartwood specimens with the same set of conditions to have a look at the differences between sapwood and heartwood. For the same wood species, heartwood is more resistant to decay (+45%) than sapwood. In addition, sapwood durability is globally higher for a wood species with a durable heartwood compared to sapwood from a wood species with a low durable heartwood. The difference in fungal resistance between heartwood and sapwood for a species is also higher for highly resistant heartwood. There is a very large diversity of situations in the durable wood species, sometimes sapwood is fairly resistant, and sometimes it has a very low resistance towards fungi.

In this collection of data, lignin content seems to be as influential as extractives, but only specific extractives prove to be very efficient against fungal decay (Neya et al. 2004). The problem with the value of extractive content from this open data file is that their chemical compositions are not known. In this sense, some of these wood species could contain extractives with anti-fungal and/or insecticide activities, and some wood species could be resistant to insects but not to fungi (Fougerousse 1960).

The publication in open source (Candelier et al. 2023) of these old data is an opportunity to enhance the knowledge of wood species concerning their decay resistance, by collecting other numerical data to perform some meta-analysis with better statistical robustness. Ranking of the species (either in T1 or T4 block types) by the mean value of mass loss for the four main fungal strains, together with their basic chemical compositions, can be used for further investigations on the lignin proportion of monomers on one side and the chemical description of extractives (and maybe some mineral compounds) on the other side to better understand the decay resistance of wood, together with the discovery of active molecules towards fungi metabolism.

Table VIII.
Description of data for specimen type T1 (182 species).

T1 (182 species)	Min	Max	Mean	CV (%)
Mean ML	0.0	71.9	23.4	65.8
D * ML	0.0	409	146	55.4
D	252	1,26	703	27.0
AB ext	0.60	21.20	4.84	78.6
W ext	0.20	12.13	3.00	60.7
Ash	0.10	4.53	0.97	71.8
Tot	87	101	96	2.2
Lig rel	22.8	43.4	32.7	12.0
Pento rel	6.3	26.9	17.2	18.7
Cell rel	38.1	55.0	45.7	6.9

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.

Table IX.
Description of data for specimen type T4 (100 species).

T4 (100 species)	Min	Max	Mean	CV (%)
Mean ML	0.3	46.9	15.6	77.5
D * ML	2	291	99	70.6
D	240	1210	716	28.4
AB ext	0.20	20.06	5.09	69.5
W ext	0.90	8.50	2.94	48.9
Ash	0.02	3.16	0.92	75.5
Tot	90.7	101.5	96.6	2.2
Lig rel	19.1	45.8	32.4	14.3
Pento rel	6.0	25.2	16.4	20.6
Cell rel	36.3	59.9	47.5	9.4

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.

Table X.
Correlation table for mass loss, chemical composition for T1 (182 species).

T1 (182 species)	Mean ML	D * ML	D	AB ext	W ext	Ash	Tot	Lig rel	Pento rel	Cell rel
Mean ML	**1**	**0.913**	**-0.631**	**-0.477**	-0.210	0.143	**-0.334**	**-0.502**	0.189	0.235
D * ML	**0.913**	**1**	**-0.316**	**-0.525**	-0.218	0.125	**-0.309**	**-0.458**	0.178	0.201
D	**-0.631**	**-0.316**	**1**	0.081	0.058	-0.133	0.170	0.338	-0.160	-0.184
AB ext	**-0.477**	**-0.525**	0.081	**1**	0.226	-0.111	**0.257**	0.172	0.134	-0.175
W ext	-0.210	-0.218	0.058	0.226	**1**	0.239	0.199	0.077	0.160	-0.127
Ash	0.143	0.125	-0.133	-0.111	0.239	**1**	0.079	-0.053	0.196	-0.063
Tot	**-0.334**	**0.309**	0.170	**0.257**	0.199	0.079	**1**	0.541	-0.005	0.003
Lig rel	**-0.502**	**-0.458**	**0.338**	0.172	0.077	-0.053	**0.541**	**1**	**-0.423**	**-0.443**
Pento rel	0.189	0.178	-0.160	0.134	0.160	0.196	-0.005	**-0.423**	**1**	**-0.372**
Cell rel	0.235	0.201	-0.184	-0.175	-0.127	-0.063	0.003	**-0.443**	**-0.372**	**1**

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: Product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.
Bold characters: significant value at level 0.1%.

Table XI.
Correlation table for mass loss, chemical composition for T4 (100 species).

T4 (100 species)	Mean ML	D * ML	D	AB ext	W ext	Ash	Tot	Lig rel	Pento rel	Cell rel
Mean ML	**1**	**0.947**	**-0.574**	**-0.493**	0.101	**0.479**	-0.203	**-0.343**	0.245	0.122
D * ML	**0.947**	**1**	-0.324	**-0.481**	0.157	**0.449**	-0.265	-0.325	0.295	0.029
D	**-0.574**	-0.324	**1**	0.273	0.061	-0.313	-0.125	0.148	0.049	-0.301
AB ext	**-0.493**	**-0.481**	0.273	**1**	-0.018	-0.171	0.273	0.240	0.078	-0.214
W ext	0.101	0.157	0.061	-0.018	**1**	0.161	0.011	-0.055	0.292	-0.202
Ash	**0.479**	**0.449**	-0.313	-0.171	0.161	**1**	-0.196	-0.262	**0.341**	-0.083
Tot	-0.203	-0.265	-0.125	0.273	0.011	-0.196	**1**	0.309	-0.200	0.260
Lig rel	**-0.343**	-0.325	0.148	0.240	-0.055	-0.262	0.309	**1**	**-0.462**	**-0.535**
Pento rel	0.245	0.295	0.049	0.078	0.292	**0.341**	-0.200	**-0.462**	**1**	-0.319
Cell rel	0.122	0.029	-0.301	-0.214	-0.202	-0.083	0.260	**-0.535**	-0.319	**1**

Mean ML: mean value of mass losses for the 4 fungal strains (%).
D*ML: Product of the two values: density and mean mass loss for the species.
D: density for the species, in kg/m3.
AB ext: % extractive content in alcohol-benzene solution.
W ext: % extractive content in hot water.
Ash: % mineral content.
Silica: % silica content.
Tot: total result of chemical analyses in %.
Lig rel: relative lignin content in %.
Pento rel: relative pentosan content in %.
Cell rel: relative cellulose content in %.
Bold characters: significant value at level 0.1%..

Conclusion

A database of decay resistance related to density, chemical composition, and zones (heartwood and sapwood) of wood has been built from 9,842 tests carried out on 500 tropical wood species in CIRAD, since 1953. All these tests were not carried out with the same protocol nor under identical conditions. Five different sample sizes, six fungal strains, and heartwood and sapwood fractions have been explored, giving significantly different results. However, most of the tests used the same fungal exposure duration (i.e., 16 weeks), and the mean mass loss due to the four main fungal strains is a good predictor of the wood decay resistance. In addition, the results confirm that there is probably a synergetic effect of both high-density and highly efficient extractives in tropical woods that confers on the wood a good natural durability against wood-destroying fungi. The publication of these old data in open source is an opportunity to enhance the knowledge of wood species concerning their decay resistance, by collecting other numerical data to perform some meta-analysis with better statistical performance. However, it's important to point out that the results coming from this database concern only 4 strains of wood-destroying fungi, which, even if carefully selected, do not fully reflect the great fungal diversity of natural conditions, which often bring surprises when it comes to natural durability.

In general, standards tend to rank wood's natural durability in order of worst-case performance. However, very poor tests are often the exception in databases, and better classification using high-throughput tools such as those proposed (NIRS) could enable better optimisation/pricing of natural durability, which is by far one of the most important in the current use of wood.

In the same way, additional chemical composition analyses of extractive compounds could be very interesting to be input within these data sheets, to better understand the decay resistance of wood together with the discovery of active molecules towards fungi metabolism. Finally, such analyses could also allow the identification of some interesting wood species for their resistance towards insects.

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Access to data:
Data are freely available and have been uploaded to the CIRAD dataverse:
Candelier K., Thévenon M. F., Gérard J., Thibaut B., 2023. CIRAD wood resistance to decay database. CIRAD Dataverse. https://doi.org/10.18167/DVN1/ZAHGCF

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