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Using specimens from the CIRAD Kourou wood collection to build a database of properties

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Photo 1.
The 445 samples used to measure the modulus and the damping coefficient. The manufacturing of custom-made storage racks limits the risk of error and optimizes handling of the samples.
Photo J. Beauchêne.

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RÉSUMÉ

Création d'une base de données sur les propriétés des bois à partir de spécimens de la collection Kourou du Cirad

Un xylarium, comme celui de Kourou en Guyane française, est une collection unique de spécimens de bois rassemblés sur de nombreuses années et représentant une grande diversité interspécifique. Outre l'utilisation classique de telles collections pour l'anatomie systématique, elles peuvent servir à créer une base de données technologique en utilisant des échantillons supplémentaires prélevés sur le même arbre comme spécimens de référence. Des tests physiques, mécaniques et de durabilité ont été réalisés sur des planches de 10 × 60 × 100 mm^3 (L étant la dimension la plus longue, la largeur et l'épaisseur étant les dimensions transversales mais pas toujours parfaitement radiales ou tangentielles) représentant 445 essences ligneuses appartenant à 63 familles présentes en Guyane française. Les densités des bois varient de 250 à 1 300 kg/m^3, avec une moyenne de 786 kg/m^3. Les valeurs des autres propriétés sont également très variables, tout comme le module d'élasticité longitudinal (de 0,6 à 37 GPa), des échantillons très rigides, des lianes et des stipes de palmiers ayant également été testés. Les corrélations entre les différents paramètres mesurés sur les 445 essences testées nous ont permis d'identifier plusieurs relations entre les propriétés du bois, par exemple : les bois clairs sont moins sujets au retrait, mais plus sujets à la pourriture (l'inverse est vrai pour les bois rouges) ; les bois à faible coefficient d'amortissement sont généralement plus foncés, plus rouges, plus denses et plus résistants à la pourriture. Cette base de données ne peut pas être utilisée pour caractériser une essence particulière puisqu'un spécimen seulement est disponible pour chacune, mais elle peut être utilisée pour étudier les relations entre des propriétés et des descripteurs facilement mesurables liés à la structure du bois (densité ou module, par exemple) ou à la chimie du bois (couleur, durabilité…). Enfin, cette base de données fournit les bases pour de futures banques de données plus importantes comprenant beaucoup plus de spécimens de chaque essence, utiles pour rechercher des propriétés particulières au sein de certaines familles ou certains genres, comme une durabilité naturelle élevée malgré une densité du bois plutôt faible, ou un coefficient d'amortissement faible accompagné d'un module spécifique élevé.

Mots-clés : xylarium, propriétés des bois, bois tropicaux, Guyane française.

ABSTRACT

Using specimens from the CIRAD Kourou wood collection to build a database of properties

A Xylarium, like the one in Kourou in French Guiana, is a unique collection of wood specimens gathered over many years that represents high interspecific diversity. In addition to the standard use of such collections for systematic anatomy, a technological database can be created using supplementary specimens taken from the same tree as the reference specimens. Physical, mechanical and durability tests were performed on wood planks measuring 10 × 60 × 100 mm^3 (L is the longest direction, width and thickness are not always perfectly radial or tangential, just transverse) representing 445 woody species belonging to 63 families found in French Guiana. Wood densities ranged from 250 to 1,300 kg/m^3, with an average of 786 kg/m^3. The other properties also covered a wide range of values, as did the longitudinal modulus of elasticity (ranging from 0.6 to 37 GPa), as samples from lianas, palm stipes and very stiff woods were also tested. The correlations between the different parameters measured on the 445 species tested allowed us to identify some relationships between wood properties, e.g.: (i) light colored woods are less prone to shrinkage, but more prone to rot (the opposite is true for red woods); (ii) woods with a low damping coefficient are generally darker, redder, denser, and more resistant to rot. This database cannot be used to characterize a particular species as only one specimen is available for each species, but it can be used to study the relationships between properties and easily measured descriptors related to wood structure (e.g. density, modulus) or wood chemistry (e.g. color, durability). Finally, this database provides the foundation for future bigger databases including many more specimens of each species that will be useful to search for particular properties in certain families or genera, for example, high natural durability despite rather low wood density, or low damping along with a high specific modulus.

Keywords: wood collection, wood proprieties, tropical wood, French Guiana

RESUMEN

Utilización de ejemplares de la colección de madera del CIRAD Kourou para constituir una base de datos sobre las propiedades de la madera

El Xylarium de Kourou en Guayana Francesa es una colección única de muestras de madera reunidas a lo largo de muchos años, que representa una gran diversidad de especies. Además del uso estándar de estas colecciones para la anatomía sistemática, se puede crear una base de datos tecnológica utilizando muestras adicionales tomadas del mismo árbol como muestras de referencia. Se realizaron pruebas físicas, mecánicas y de durabilidad en tablones de 10 × 60 × 100 mm^3 (L es la dimensión más larga, la anchura y el grosor son las dimensiones transversales, aunque no siempre perfectamente radiales o tangenciales). Estos tablones provienen de 445 especies leñosas pertenecientes a 63 familias encontradas en la Guayana Francesa. Las densidades de la madera oscilaron entre 250 y 1 300 kg/m^3, con una media de 786 kg/m^3. Los valores de las demás propiedades también variaron mucho, al igual que el módulo de elasticidad longitudinal (de 0,6 a 37 GPa), ya que también se probaron muestras muy rígidas, lianas y estipes de palmeras. A partir de las correlaciones entre los diferentes parámetros medidos en las 445 especies analizadas, identificamos diferentes relaciones entre las propiedades de la madera, por ejemplo: (i) las maderas de color claro son menos propensas a la contracción, pero más propensas a la putrefacción (lo contrario es cierto para las maderas rojas); (ii) las maderas con un bajo coeficiente de amortiguación son generalmente más oscuras, más rojas, más densas y más resistentes a la putrefacción. Esta base de datos no puede utilizarse para caracterizar una especie concreta, ya que sólo se dispone de un ejemplar para cada especie, pero puede utilizarse para estudiar las relaciones entre las propiedades y los descriptores fácilmente medibles relacionados con la estructura de la madera (por ejemplo, densidad y módulo) o la química de la madera (por ejemplo, color y durabilidad). Por último, esta base de datos proporciona fundamentos para futuras bases de datos más amplias que incluyan muchos más ejemplares de cada especie, lo que será útil para buscar propiedades particulares en ciertas familias o géneros, como una alta durabilidad natural a pesar de una densidad de la madera más bien baja, o una baja amortiguación junto con un alto módulo específico.

Palabras clave: colección de madera, propiedades de la madera, madera tropical, Guayana Francesa.

Introduction

The CIRAD wood collection named 'Xylarium', in Kourou, French Guiana, consists of an anatomical reference collection with a CTFT (*Centre technique forestier tropical*, Technical Centre for Tropical Forests, the former name of CIRAD's forestry activities) identifier for each different tree. It is an extension of the main CIRAD wood collection kept in Montpellier, France (Langbour *et al.*, 2019). The Kourou Xylarium is devoted to local species, with links to the Cayenne (another town, Prefecture of French Guiana) herbarium[1]. A collection of duplicate specimens taken from the same tree (i.e. with the same CTFT ID) was added to be used for other studies including destructive tests. This duplicate collection comprises 4,285 duplicates from 1,449 trees (references or accessions) belonging to 505 species, 240 genera, and 75 families. It was collected between 1977 and 2005. We selected the best shaped wooden plates to sample 445 species.

A long-term testing procedure was undertaken throughout the 20th century on many tropical species (around one thousand of the eight thousand referenced in the CIRAD wood collection). Among them, some Guianese species have already been tested: the chemical composition of 47 species was tested (Gérard *et al.*, 2019), fungal rot resitance against different fungi in 71 species was tested, and the physical and mechanical properties of 124 species were tested (to be published). Measuring 445 species represents enormous progress even though it only represents one fourth of the list of 1,600 Guianese tree taxa (Molino *et al.*, 2009).

Xylarium wood collections are also long-term records of biological activity and tree function, particular weather conditions, or catastrophic events that occurred in the past (Beeckman, 2003). Xylarium collections are used as reference tools for species identification of woody plants, or dendrochronology from annual increments and more recently, for their biochemical or isotopic memory (Cornish *et al.*, 2013). However, apart from wood density (Maniatis *et al.*, 2011; Langbour *et al.*, 2019), which is sometimes available in these collections, they have only very recently been used to collect other technological data (Deklerck *et al.*, 2019, 2020). As the use of duplicates to take measurements with the aim of creating a large database of wood properties is being promoted as a future use for wood collections (Langbour *et al.*, 2019), we tested the opportunity using the Kourou Xylarium duplicates.

Material

A total of 445 duplicate specimens originating from 445 species (one specimen per species), 213 genera and 63 families were tested. The samples were air dried wood specimens measuring 130 × 10 × 60 mm^3 (L is the longest direction, width and thickness are not always perfectly radial or tangential, just transverse). All the samples had been stored in the collection cabinet for more than 10 years. Mean stabilized moisture content was 11.3%. Only specimens of heartwood were used. First, each specimen was sanded on one side to measure fresh color. However, the color revealed by sanding is not necessarily the color of fresh wood, as some specimens underwent slow in-depth oxidation of secondary metabolites during storage.

Next, the specimen was cut into pieces for different uses (figure 1): 130 × 2 × 10 mm^3 for mechanical tests, 100 × 5 × 10 mm^3 for decay tests, 30 × 5 × 10 mm^3 for shrinkage tests, 20 × 10 × 10 mm^3 to measure moisture content and further chemical analysis.

Figure 1.
Specimens cut from a single anatomical plate.
MC: 20 × 10 × 10 mm^3 specimen for the measurement of moisture content. Ch: 20 × 10 × 10 mm^3 specimen destined for different chemical measurements (not made in the present study). S: 30 × 5 × 10 mm^3 specimen to measure shrinkage.
D: 100 × 5 × 10 mm^3 specimen to measure natural durability.
VT: 130 × 2 × 10 mm^3 specimen for vibratory tests.

Methods

Measurement of color

Measurements were taken at three different representative locations on the surface of the specimen (the orientation was generally slab board or alternate quarter) using a Minolta colorimeter (Spectrophotometer 2500d). The illuminant D65 and the 10° standard observer were used as measurement standards. The surface area observed was 59 mm^2 (small opening of 8.7 mm) and the specular reflection setting was excluded. Reflectance data were collected at 10 nm intervals over the visible spectrum (from 400 to 700 nm). The data are expressed in the CIE L*a*b* color space (Nishino *et al.*, 1998) defined by the

[1] https://herbier-guyane.ird.fr

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International Commission on Illumination (CIE). The colorimetric parameters correspond to:
- L*: clarity, black = 0 and white = 100;
- a*: red (positive) and green (negative) components;
- b*: yellow (positive) and blue (negative) components.

The hue angle $H = atan(b^*/a^*)$ was also calculated.

Density and volumetric shrinkage

The three samples (20 × 5 × 9 mm^3) were used for each reference. The sample was a rectangular parallelepiped whose three perpendicular dimensions were measured with a comparator (precision: 1 µm) of Mitutoyo brand, which made it possible to calculate the volume (V). The mass (M) was measured with a Sartorius precision balance (precision: 0.0002 mg):
- corresponding to the standard conditions in the cabinet (dry wood close to 12% moisture content, M_{12} and V_{12});
- fully saturated (M_s and V_s);
- in the anhydrous state, after reaching equilibrium in an oven heated at 103 °C (M_a and V_a).

Different values can be calculated for wood density:
- dry density $D_{12} = M_{12}/V_{12}$;
- anhydrous density $D_a = M_a/V_a$;
- saturated density ; $D_s = M_s/V_s$;
- basic density $BD = M_a/V_s$;
- conversion factor (Vieilledent *et al.*, 2018) for basic density from air dry density: $CF = BD/D_{12}$.

Total volumetric shrinkage (VS) is calculated using the formula: $VS = (V_s - V_a)/V_s$.

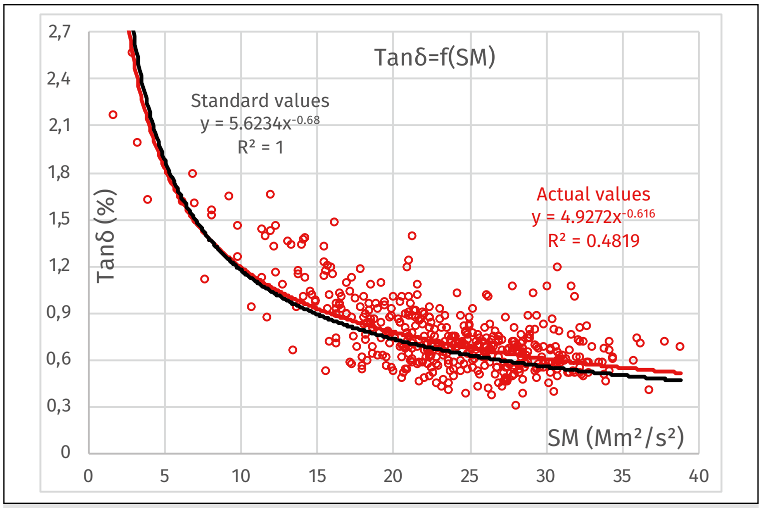

Figure 2.
Relationship between damping and specific modulus. Red circles, actual value: experimental results for both damping coefficient and specific modulus. Black curve, standard value: damping coefficient values calculated from experimental specific modulus.

Mechanical measurements

The three samples (120 × 2 × 9 mm^3) were used for each reference. A vibratory test was used with non-contact forced vibrations of free-free beams placed on elastic supports positioned at the two nodes of the first mode (Brémaud *et al.*, 2012). Dimensions (m), mass (kg), resonant frequency (Hz) and damping coefficient (tanδ)[2] at the resonant frequency were measured in this test. Using mass and dimension, the density (kg/m^3) of the specimen (ρ) was calculated as mass/volume ratio. The specific modulus (SM in m^2/s^2) was calculated using Bernouilli's equation (Brémaud *et al.*, 2012). SM is both the square value of sound speed in the longitudinal direction in the wood and the ratio of the longitudinal modulus of elasticity (E) to the density: $SM = E/\rho$. The modulus of elasticity was calculated using the formula: $E = \rho * SM$.

There is a strong physical relationship between specific modulus (SM) and damping coefficient (tanδ) of mean standard wood (the wood is presumed to be free of extractives) (Brémaud *et al.*, 2012, 2013) due to the microstructure of the cell wall (mainly micro-fibril angle): $\tan\delta = 10^A * SM^B$, where A = 1.23 and B = 0.68.

If the damping coefficient differs from the standard value ($\tan\delta_S$) calculated from the specific modulus value, there is a relative deviation from standard damping ($DS\delta = (\tan\delta - \tan\delta_S)/\tan\delta$), mainly due to the chemical composition of the cell wall (Brémaud *et al.*, 2012, 2013). This deviation was calculated for all the specimens.

Decay resistance

The test protocol for measuring the natural durability of wood is based on the European standard XP CEN / TS 15083-2 and the American standard AWPA E14-07 (Van Acker *et al.*, 2003; Amusant *et al.*, 2014). The test protocol consists in estimating the lifetime of thin specimens in contact with a forest floor, in our case, collected from the Paracou experimental forest in French Guiana (Gourlet-Fleury *et al.*, 2004). Five samples (R × T × L = 10 × 5 × 90 mm^3) were taken from each anatomical plate, representing one repetition per month over the five-month experiment. Each specimen was first dried for 48 hours at 103 °C, then weighed and planted vertically in the soil with 80% of its length immersed in the wet soil. These specimens were interspersed with standard *Virola michelii* reference test specimens evenly distributed in the bins. Each month, one specimen per individual, as well as a control specimen, were taken, dried at 103 °C for 48 hours, and weighed giving the mass loss (ML) of each test piece. The ML of a species at month 6 was estimated from the median value of the slope adjusted over the first 5 months.

[2] The damping coefficient (or loss factor, tanδ) is determined, in the time domain, through the logarithmic decrement ($\lambda = \pi * \tan\delta$) of amplitudes, after stoppingexcitation, which is fixed at resonant frequency Fr.

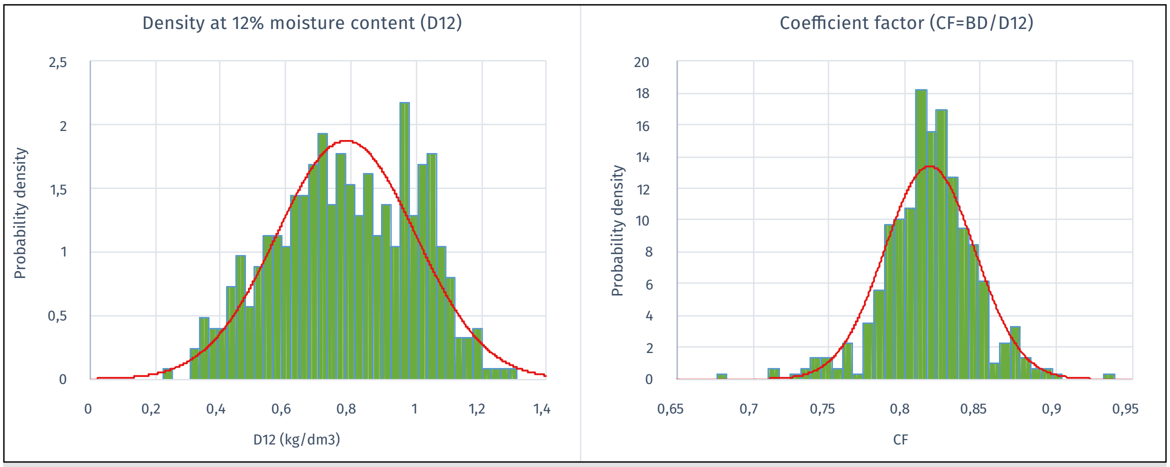

Figure 3.
Histograms of density and coefficient factor. The red curve represents the best fitting normal distribution of the values (for a better readability the units of D12 are expressed in kg/m³).

Data base and statistical methods

Basic statistical analyses were performed using XLSTAT software. The data description table includes the number of specimens, 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 were already available in the dataset (Beauchêne *et al.*, 2021). A box plot is also included for each parameter. The box plot shows the quartiles (the band inside the box is the median). The whiskers in the box plot represent the lowest data item still within the 1.5 IQR (inter quartile range) of the lower quartile, and the highest data item still within the 1.5 IQR of the upper quartile.

For the histograms, the amplitude of each parameter was chosen to provide a clear description of the data. The normality of the distribution was checked using a Shapiro-Wilk test. Pearson type correlation analysis was used for normal distribution, and Spearman's tests for non-normal distribution.

Results

Distribution of the values

Figure 2 shows that the best fitting relationship between damping coefficient (tanδ) and specific modulus (SM) is very close to the standard curve. The tanδ values are distributed on the two sides of the standard curve, as already shown in another study (Brémaud *et al.*, 2012).

At 12% moisture content, there was a wide range of densities (250-1,300 kg/m³) typical of tropical woods (Langbour *et al.*, 2019). There was a small shift towards high density values that could be due to the selection of specimens used in the present study, but the mean density value (786 kg/m³) of the 1,694 specimens from French Guiana is almost identical to the mean density value of the Cirad wood collection as a whole (784 kg/m³). In contrast, the range of coefficient factors (Basic Density/Density at 12% moisture content) was very narrow (figure 3), basic density and density at 12% moisture content were proportional, with a very high coefficient of determination (R^2 = 0.98). The mean CF (0.816) was very close to the CF in the data base containing physical data for 872 species (0.828, in Vieilledent *et al.*, 2018). The statistical tests proved that none of these distributions were normal, so Spearman's test was used for correlation analysis.

The distributions of the different parameters are shown as box plots in figure 4. It should be noted that there are some very low values for SM (below 5 Mm²/s²) not found in usual wood measurements (severe compression wood can go down to 5 Mm²/s²). These very low values are those of liana wood (Rowe and Speck, 2005; Köhler *et al.*, 2000) and juvenile palm xylem (the mature palm xylem measured in this study had the usual values), making the range of elastic modulus (E) wider than usual. Anyway, except for CF (CV = 4%) there was always a wide range of values for all parameters with CV greater than 25% except for L* (18%) and Hue (13%).

The species shown in figure 5 were chosen as representative of the range of color margins in the color space: dark or light species (*Swartzia leblondii, Solanum leucocarpon*), high or small hue angle (*Peltogyne venosa, Pachira dolichocalyx*), red woods (*Guarea guidonia, Aspidosperma sandwithianum*), orange or dark brown woods (*Chrysophyllum pomiferum, Vouacapoua americana*). As reported by Nishino *et al.* (1998), all the color values are positioned in only one quadrant in the a*b* plane (the red/yellow) quadrant (figure 5). Black wood (ebony style) like *Swartzia leblondii* had nearly zero values for a* and b*, i.e. very dark grey. Lighter woods all had rather high values for b*, pale yellow, but not pale grey. Red woods had almost the same value for a* (red) and b* (yellow). They appear as red instead of orange because the b* values are often much higher than a* values. Strictly speaking, Purpleheart wood is the only dark red wood, but is perceived as purple, even though the b* value is slightly positive on the yellow axis (b* = 3.2).

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Correlation analysis

The statistical tests proved that none of these distributions were normal, so a Spearman's test was used for correlation analysis (table I).

Many correlation coefficients (R) were significant at the 0.1% level, but due to the large number of data, the lowest significant R was associated with a low (3%) coefficient of determination (R^2).

Considering the color parameters, L* and hue were very strongly correlated so considering L* alone seems to be efficient (similar but better correlation coefficients with other parameters for L*). The correlations between L* and b* were strong and positive but negative between L* and a*. Light colored woods were rather yellow while dark colored woods were rather red. The link between a* and b* was rather weak and b* was not significantly correlated with any other parameters (except L*). Rather strong links were observed between L* or a* (but with opposite signs) and density, volumetric shrinkage, and mass loss. Light colored woods were less dense, less prone to shrinkage but more prone to rot (the reverse was found for red woods).

Density and specific modulus can be considered as independent parameters. SM was only strongly linked with modulus of elasticity (positive), damping coefficient (negative) and shrinkage (positive). Density (both BD and D12) was strongly linked with all parameters except b*, SM and CF. Dense woods had a lower damping coefficient or mass loss but higher modulus or shrinkage. It is interesting to note that specific modulus and density, which are independent, had almost equally strong links with the same sign as modulus of elasticity, damping coefficient and shrinkage.

Deviation from the standard damping coefficient (DSδ) was quite closely linked with color (L* and a*), density, and mass loss. Woods with a lower damping coefficient than the standard were darker, redder, denser and more resistant to rot.

Nearly 50% of the coefficients of variation (CF = BD/D12) were due to variations in volumetric shrinkage. The latter is a useful parameter that can easily be measured at the same time as basic density if a more precise CF is needed.

Discussion

Using a single wooden plate provided an initial overview but is not sufficient for the characterization of species, for which more duplicates sampled from different trees and from different positions in the tree are needed. Nevertheless, measuring different parameters and properties on the same material in a wide range of species is extremely useful to study the relationships between structural and chemical parameters and wood properties. It is also useful to screen for particular properties required for a specific use. For example, high natural durability represented by low mass loss values due to fungal degradation are good indicators of the presence of protective compounds such as antifungals, insecticides, or antioxidants (Amusant *et al.*, 2014).

There are two successive levels of wood structure with specific mechanical behavior (i) the anatomical level, where wood is a cellular material, like honeycomb, (ii) the cell wall level, which is a fiber composite (Thibaut *et al.*, 2001).

Cellular materials like honeycombs display extremely high anisotropy between in plane and out of plane directions (Gibson and Ashby, 1997) and properties consequently need to be defined with reference to the direction of the test. The key parameter for physical and mechanical properties is the volume proportion (α) of solid matter included in the cell wall. Wood mass depends on this proportion according to the relation $M = \alpha * V * \rho_m$ where V is the global volume of the material, and ρ_m is the density of cell wall matter (around 1,500 kg/m³). The wood density value: $\rho = M/V = \alpha^* \rho_m$ is directly proportional to α, so wood density is a key descriptor for wood as a cellular material.

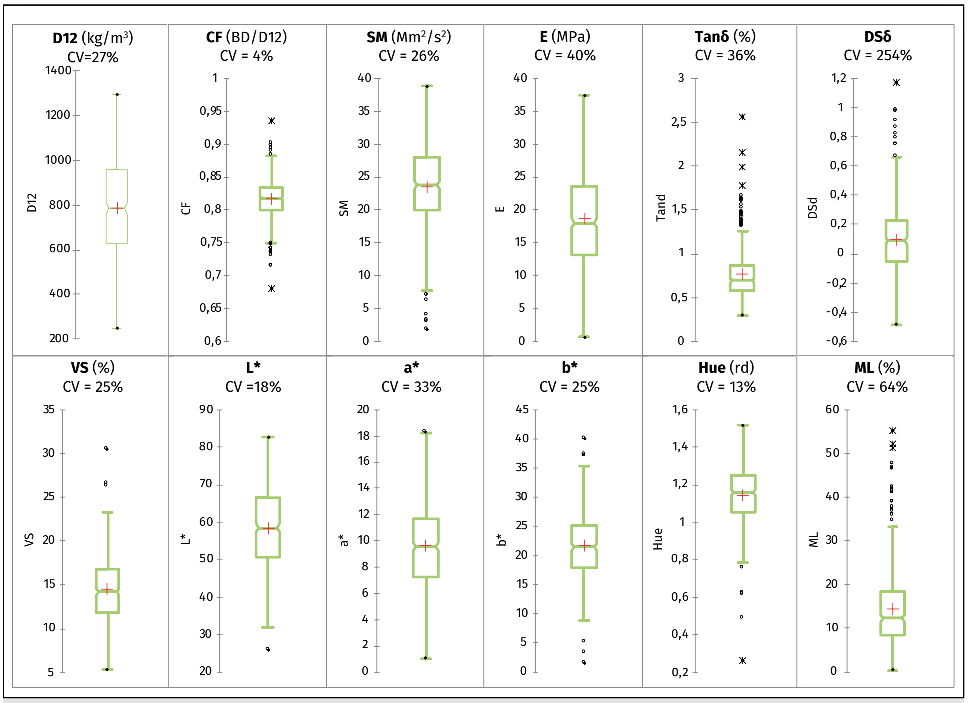

Figure 4.
Distribution (Tukey box plots) of the properties measured in 445 species. Box plot quartiles (the band inside the box is the median). Whiskers plot the lowest datum still within 1.5 IQR (inter quartile range) of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile. Black dots are outliers. L*: clarity coefficient; a*: red/green coefficient; b*: yellow/blue coefficient; Hue angle: angle of the color projection in the a*/b* plane; BD: basic density (kg/dm3); D12: density at level 12% moisture content; CF: conversion factor between density at 12% moisture content and basic density; VS: volumetric shrinkage (%); SM: specific modulus (Mm²/s²); E: longitudinal modulus of elasticity (GPa); tanδ: damping coefficient (%); DSδ: relative deviation from standard damping; ML: mass loss in the soil bed test (%).

Table I.
Spearman's correlation coefficients. Characters in bold: significant correlation at the 0.1% level with R^2 > 5%. Characters in italics: significant correlation at the 0.1% level with R^2 < 5%. L*: clarity coefficient; a*: red/green coefficient; b*: yellow/blue coefficient; Hue angle: angle of the color projection in the a*/b* plane; BD: basic density (kg/dm3); D12: density at level 12% moisture content; CF: conversion factor between density at 12% moisture content and basic density; VS: volumetric shrinkage (%); SM: specific modulus (Mm^2/s^2); E: longitudinal modulus of elasticity (GPa); tanδ: damping coefficient (%); DSδ: relative deviation from standard damping; ML: mass loss in the soil bed test (%).

Variables	L*	a*	b*	Hue	BD	D12	CF	VS	SM	E	Tanδ	DSδ	ML
L*	**1**	**–0.514**	**0.480**	**0.814**	**–0.593**	**–0.578**	–0.017	**–0.266**	*0.115*	**–0.341**	*0.208*	**0.320**	**0.526**
a*	**–0.514**	**1**	*0.175*	**–0.726**	**0.452**	**0.437**	0.002	**0.255**	–0.035	**0.284**	*–0.197*	**–0.266**	**–0.417**
b*	**0.480**	*0.175*	**1**	**0.484**	*–0.134*	*–0.134*	0.016	–0.042	0.050	–0.054	–0.011	0.012	0.040
Hue	**0.814**	**–0.726**	**0.484**	**1**	**–0.515**	**–0.501**	–0.018	**–0.255**	0.077	**–0.304**	*0.176*	**0.254**	**0.434**
BD	**–0.593**	**0.452**	*–0.134*	**–0.515**	**1**	**0.992**	*–0.169*	**0.542**	*0.129*	**0.760**	**–0.379**	**–0.293**	**–0.644**
D12	**–0.578**	**0.437**	*–0.134*	**–0.501**	**0.992**	**1**	**–0.272**	**0.604**	*0.155*	**0.781**	**–0.359**	**–0.257**	**–0.604**
CF	–0.017	0.002	0.016	–0.018	*–0.169*	**–0.272**	**1**	**–0.678**	**–0.256**	**–0.351**	–0.066	**–0.219**	*–0.192*
VS	**–0.266**	**0.255**	–0.042	**–0.255**	**0.542**	**0.604**	**–0.678**	**1**	**0.445**	**0.668**	**–0.234**	0.024	*–0.187*
SM	*0.115*	–0.035	0.050	0.077	*0.129*	*0.155*	**–0.256**	**0.445**	**1**	**0.689**	**–0.563**	0.048	–0.070
E	**–0.341**	**0.284**	–0.054	**–0.304**	**0.760**	**0.781**	**–0.351**	**0.668**	**0.689**	**1**	**–0.587**	*–0.156*	**–0.468**
Tanδ	*0.208*	*–0.197*	–0.011	*0.176*	**–0.379**	**–0.359**	–0.066	**–0.234**	**–0.563**	**–0.587**	**1**	**0.735**	**0.397**
DSδ	**0.320**	**–0.266**	0.012	**0.254**	**–0.293**	**–0.257**	**–0.219**	0.024	0.048	*–0.156*	**0.735**	**1**	**0.373**
ML	**0.526**	**–0.417**	0.040	**0.434**	**–0.644**	**–0.604**	*–0.192*	*–0.187*	–0.070	**–0.468**	**0.397**	**0.373**	**1**

In contrast to most man-made honeycombs, wood cell walls are not isotropic, homogeneous material. Like other complex fiber composite materials, the cell wall has two main components: crystalline nano-cellulose fibers (NCF) with a very high modulus of elasticity (MOE) embedded in a more or less homogeneous matrix with a much lower MOE (Déjardin *et al.*, 2010; Gibson, 2012). The properties of the material comprising the cell wall depend on the proportion and orientation of NCF on the one hand (Donaldson, 2008), and on the chemical composition of the matrix on the other. Most of the mass in the secondary wall (which is responsible for nearly all wood properties) is concentrated in the S_2 layer, usually with small NCF angles (5° to 25°) relative to the main cell direction, while the S_1 layer is much thinner with high NCF angles (70° to 80°) relative to the main cell direction. Because the S2 layer is responsible for a very large proportion of properties in the cell direction, the cell wall material is termed S_2 and the S_2 NCF angle is termed micro-fibril angle (MFA) as if it were the only active angle of the fiber

Figure 5.
Examples of the wide range of colors of the species tested.

composite. In fact, the S_1 layer can play a significant role in transverse properties like shrinkage, if its proportion of mass is not too low, as is the case in thin walled fibers.

Variation in cellulose content between species is rather low with a coefficient of variation (CV) of only 10% whereas the CV for density is around 30% (Gérard *et al.*, 2019), and the density of the cell wall is nearly constant, so MFA is the key factor for the longitudinal MOE (E_m) of the matter forming the wood cells (Cave, 1969). Like wood density, wood MOE (E) is proportional to cell wall MOE (E_m) through the relation $E = \alpha * E_m$

Thus, whatever the density, $E/\rho = E_m/\rho_m$ and $E_m = \rho_m * E/\rho$. Cell wall density (ρ_m) is constant, so the cell wall MOE, a key property of the material, is always proportional to the specific modulus (SM = E/ρ) and the SM is a simple key parameter of the mechanical behavior of the cell wall, like density (ρ) is a key parameter of the behavior of honeycomb, and these parameters should be independent, as was the case in the present study. MOE is the product SM * ρ, so by construction, wood MOE is fully described by density and SM, and here, SM variations explained nearly as much variation in MOE as density (R^2 = 48% and 58% respectively).

For volumetric shrinkage, the situation is similar, variations in Density and SM explain most variations in shrinkage (R^2 = 30% and 20% respectively). However, the relationship between shrinkage and density is not simple. Making holes in metal does not change its dilatation factor following a change in temperature. As the direct expression of the proportion of solid matter, wood density is closely linked to the ratio of cell wall thickness to fiber diameter. Fiber diameter is determined by lignification of the primary wall, whereas cell wall thickness is mainly linked to the secondary wall where the S_2 layer is generally far thicker than the S_1 layer (Déjardin *et al.*, 2010; Borrega *et al.*, 2015). Crystalline fiber reinforcement is longitudinal in S_2 whereas it is transversal in S_1. Shrinkage in S2 is linked to MFA, which is very low in the longitudinal direction but increases with the MFA value, which is high in transverse directions but decreases with an increase in the MFA. Due to its lack of thickness and fiber orientation, S1 has no influence on longitudinal shrinkage but may reduce transverse shrinkage if S2 is not too thick. Consequently, low density means transverse shrinkage will be low (and volumetric shrinkage will also automatically be low) because the S1 layer represents a higher proportion in the secondary wall. Models of the MOE of wood mechanical behavior (Yamamoto and Kojima, 2002; Qing and Mishnaevsky, 2009), and of shrinkage (Yamamoto *et al.*, 2001) show the causal relationship between these properties and structural parameters as α (proportion of matter in the cellular solid) and MFA (anisotropy of the fiber composite material). But only half the variations are linked to these two structural parameters. The chemical composition of the cell wall matrix would thus also be expected to have a major influence.

As predicted by models (Brémaud *et al.*, 2010, 2013), vibration damping was linked to MFA like SM, and the correlation between tanδ and SM was significant at the 0.1% level and was rather high (R^2 = 30%) and tends to explain only one third of damping variations. Here again, matrix chemistry would be expected to play an important role.

The two basic chemical components of the matrix are (i) the main wall polymers such as hemicelluloses and lignin, (ii) extraneous components such as extractives and minerals. Extractives and lignin are known to be linked to color (Baar *et al.*, 2014; Gierlinger *et al.*, 2004; Mayer *et al.*, 2006), shrinkage (Bossu *et al.*, 2016; Leonardon *et al.*, 2010; Royer *et al.*, 2010), mass loss (Rodrigues *et al.*, 2012; Sundararaj *et al.*, 2015) and relative deviation from standard damping (Minato *et al.*, 2010; Brémaud *et al.*, 2011, 2013) in a rather complex causal way (each molecule in the extraction cocktail can have a positive or negative influence on these properties). This common influence could explain the significant correlations between all these properties.

Mass loss was rather closely correlated with whiteness L* (R^2 = 27%) and reddish color a* (R^2 = 18%). This means that darker or redder woods tend to be more resistant to rot (Amusant *et al.*, 2004; Moya and Berrocal, 2010). To understand this correlation, we need to identify which molecules are involved in darker or redder colors and to test them against fungi.

Strictly speaking, there is no clear causal connection between properties like color or mass loss and density. Drilling small holes in a material does not change its color and the small diameter of fungal hyphae enable them to penetrate denser woods. Moreover, some very dense white woods (mostly sapwoods) have been shown to be highly sensitive to rot. However, the presence of reserve material in the heartwood that has not been fully mobilized may make the wood more attractive to the fungus (Magel *et al.*, 2000; Niamké *et al.*, 2010). In the present study, very significant correlations (at the 0.1% level) were found between density and color parameters L* and a* (R^2 = 34% and 21%, respectively) as well as mass loss (R^2 = 42%). Such correlations have also been observed in other studies (Nishino *et al.*, 2000) and tropical woods are often considered to be dense, dark (or red) and resistant to fungi. In the CIRAD wood collection (Langbour *et al.*, 2019), the mean density of tropical American woods (750 kg/m^3) is higher than that of temperate woods (660 kg/m^3), but their density range is wider: 240 to 1,320 kg/m^3 for temperate woods (in all regions of the Northern Hemisphere where the climate includes periods of frost) and 100 to 1,340 kg/m^3 for tropical American woods.

It is highly probable that as yet unidentified parameters have a strong influence on both extractives and on the difference in density between species, in other words, long living trees growing in hazardous conditions in terms of wood predators (fungi, termites or *Cerambycidae*) should have both high densities for hydraulic or mechanical reasons (Hacke *et al.*, 2001), and efficient extractives for wood durability (Kraft *et al.*, 2010; Aubry-Kientz *et al.*, 2013). The extractives give the wood a dark reddish color. Thus, the observed strong correlations may be the consequence of adaptive evolution rather than of the direct influence of density on color or durability.

Conclusion

A data base of basic wood properties like density, color, MOE and acoustic damping, rot resistance, could be built using duplicate specimens taken from the CIRAD Xylarium wood collection in Kourou. Using the same process for the main CIRAD Xylarium in Montpellier would allow an enormous increase in data on different wood properties of many species in the world, without the need for additional sampling in the world's forests.

All the measurements were made on the same specimen, making it easy to correlate properties within a species. This opens the way for the prediction of unknown properties of a given species from easy to measure descriptors related to wood structure (density, grain angle, sound of speed) or wood chemistry (color, near infrared spectrometry).

In the present study, samples were cut individually in order to study the chemical composition of each specimen, particularly the extractives. This involves a tremendous amount of work with dedicated high flow techniques, which was not possible in the present study. Nevertheless, such studies are important for the future, both to build data bases of species chemical signatures (species identification) and to increase the number of descriptions of active molecules present in tree heartwood.

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Data access conditions
The data are freely available and have been uploaded to the CIRAD dataverse https://doi.org/10.18167/DVN1/R4G7BC

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