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Anatomy and mechanical properties of woods used in electric guitars

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ABSTRACT

Many endangered tropical hardwoods are commonly used in electric guitars. In order to find alternative woods, the current electric guitar woods need to be studied and classified as most research in this field has focused on acoustic instruments. Classification was done based on luthier literature, woods used in commercially available electric guitars, commercially available tonewoods and by interviewing Finnish luthiers. Here, the electric guitar woods are divided into three distinct classes based on how they are used in the guitar: low-density wood used in the body only (alder, poplar, basswood, ash), medium-density wood used in the body and neck (maple and mahogany), and high-density wood used in the fretboard only (rosewood and ebony). Together, these three classes span a wide range of anatomical and mechanical properties, but each class itself is limited to a relatively narrow parameter space. Statistically significant differences between these classes and the average hardwoods exist in the wood anatomy (size and organization of vessels, fibres, rays and axial parenchyma), in the mechanical properties (density, elastic modulus, Janka hardness, etc.) and in the average price per volume. In order to find substitute woods for a certain guitar wood class, density and elastic modulus can already be used to rule out most wood species. Based on principal component analysis of the elastomechanical and anatomical properties of commercially available hardwoods, few species are similar to the low- and high-density class woods. However, for all of the three electric guitar wood classes, non-endangered wood species are already commercially available from tonewood retailers that match the class characteristics presented here.

Keywords: Tropical hardwoods, electric guitar, tonewoods, CITES, principal component analysis, wood anatomy.

Note: Supplementary data can be accessed in the online edition of this journal via http://booksandjournals.brillonline.com/content/journals/

INTRODUCTION

Many of the wood species typically used in electric guitars are either vulnerable or endangered, such as mahogany (*Swietenia macrophylla*, vulnerable; *Swietenia mahagoni*, endangered), African mahogany (*Khaya ivorensis*, vulnerable), rosewood (*Dalbergia latifolia*, vulnerable) and ebony (*Diospyros crassiflora*, endangered) (IUCN 2017). The

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use of these typical tropical hardwoods in instrument making has also other, ethical challenges, including illegal logging (Johnson & Laestadius 2011; Martinez-Reyes 2015). Moreover, several of the tropical hardwoods used are CITES-listed resulting in limitations on international trade. Therefore, there is a clear need for the electric guitar industry to move into more environmentally sustainable wood species. One method of finding alternative woods is to find wood species that are similar to the current woods in their mechanical and anatomical properties and then try them out in actual instruments.

Although the sound of an electric guitar is formed digitally by pick-ups and further processed electronically by amplifiers, the source of the sound is the mechanical vibration of the strings. The strings are connected to the guitar body, neck and fretboard by bridge saddles, nuts and frets and the wood components affect the tonal qualities of an electric guitar (Hunter 2006; Lospennato 2015). The choice of an electric guitar body material can affect the balance, brightness, sustain, precision and warmth of the sound (Koch 2001; Hunter 2006) whereas the neck material can affect the attack as well as the warmth and brightness (Koch 2001; Hunter 2006). The choice of an electric guitar fretboard material has been connected to the precision, attack and balance of the instrument (Paté *et al.* 2015). There is still, however, very little scientific research on the effect of wood material on the sound quality of an electric guitar.

The woods used in acoustic guitars (Sproßmann *et al.* 2017) and, even more so in violins, have been studied more actively (Schwarze *et al.* 2008; Carlier *et al.* 2014; Bennett 2016). Recently, some specific wood species have been studied for electric guitars and bass (Paté *et al.* 2013, 2015; Zauer *et al.* 2016) and for acoustic guitars (Hamdan *et al.* 2016; Ncube & Masilinga 2017). There are also studies that classify wood species based on their use in different parts of acoustic string instruments or their acoustical properties (Yoshikawa 2007; Yoshikawa & Waltham 2014; Sproßmann *et al.* 2017) but similar research is lacking focusing on electric guitars. A recent article (Neyses & Sandberg 2015) studies wood used in electric guitars but does not classify woods of different parts of an electric guitar.

One of the reasons this research is sparse is that there is a limited amount of quantitative information on many of the key electric guitar wood species. For example, the TRY Plant trait database (Kattge *et al.* 2011) lists quantitative information on plant anatomy, but is missing several important electric guitar woods (of those listed later in this article). Similarly the work of Brémaud *et al.* (2012) that focuses on acoustic properties of wood, is missing several of these guitar woods. Also the Wood Handbook (Forest Products Laboratory - USDA 2010), which lists wood properties in several prospective categories in terms of electric guitar woods, is lacking the key electric guitar wood species.

Important acoustical properties of wood, the speed of sound ($c = \sqrt{E/\rho}$), the characteristic impedance ($z = c\rho$) and the sound radiation coefficient ($R = c/\rho$) are related to the elastic modulus (E) and to the density of wood (ρ) (Wegst 2006), suggesting these two would be key parameters for assessing guitar woods. Mechanical properties and the density of wood are also important due to non-acoustical properties of the guitar, such as the instrument weight and balance, surface hardness, and material stiffness and durability (Hunter 2006; Lospennato 2015). The elastomechanical properties of commercial hardwoods are available from the Wood Database (Meier 2015, 2017). More directly related to the acoustical properties only, the internal friction (or damping coefficient) of wood is also an important parameter for describing the vibrational properties of wood (Yoshikawa 2007; Brémaud 2012). While this acoustic property is not available for all guitar woods, anatomical properties are available in the InsideWood database (Wheeler 2011; InsideWood 2017) and therefore should also be considered.

This study focuses on normal wood with regular grain pattern. In electric guitar making, wood of extraordinary nature is also used; non-standard grain pattern may even be desired (Lospennato 2015) and woods are classified by how they are figured: wavy, flamed, bird's eye, etc. The grain pattern is also connected to the nanoscale structure, as was shown recently for wavy sycamore maple (*Acer pseudoplatanus*) (Alkadri *et al.* 2017). A special visual appearance on the guitar body can also be achieved by adding a thin veneer top of suitable grain pattern (Koch 2001). As the visual part of these guitar tops is likely more important than their mechanical properties when selecting one, guitar tops are not covered in this article. Woods of non-standard densities may also be preferred by luthiers, such as swamp ash. Characterisation of the mechanical properties and anatomy of actual wood pieces selected by luthiers merits further study as it cannot be covered by the statistical approach taken in this study.

One alternative to finding wood species with ideal properties is to modify the properties of local hardwoods. Acoustic properties of wood have been seen to change due to natural aging (Noguchi *et al.* 2012), hydrothermal treatment (Endo *et al.* 2016; Obataya 2017), impregnation with wood extractives (Minato *et al.* 2010), chemical treatment (Yano & Minato 1992), and fungi (Schwarze *et al.* 2008). Using these methods many more wood species may be processed to be more suitable for the use in electric guitars. However, the wide-scale manufacture of electric guitars calls for reliable wood availability in large quantities (Koch 2001) and tradition and customer needs have also worked to effectively limit the number of woods mostly used in electric guitars to quite a few species (Koch 2001), which will be the focus of this article.

The effect of the wood material on the sound quality of solid-body electric guitars is discussed in Paté *et al.* (2013, 2015) and will not be addressed here. This work will also not study how the different parts of an electric guitar affect the sound quality. This article studies the elastomechanical and anatomical properties of known electric guitar woods, that is the woods used in modern electric guitars, using a purely statistical approach. The article aims firstly to list the wood species used in different parts of a solid-body electric guitar (body, neck and fretboard), secondly to classify them, and thirdly to study what are the particular anatomical and mechanical properties of woods within this classification. Finally, potential replacements are suggested for endangered wood species commonly used in electric guitars.

MATERIALS AND METHODS

Information on what wood is used in solid body electric guitars was gathered from four sources: 1) major online retailers of musical instruments, 2) online tonewood retailers, 3) luthier literature and 4) by interviewing Finnish luthiers. For each online electric

Table 1. The correlation values (r^2) of selected elastomechanical properties and the most correlated anatomical property (upper half). Asterisks (lower half) indicate significance for p-values 0.05, 0.01 and 0.001, for 1 to 3 asterisks, respectively. Based on 125 commercial hardwood species.

	SEM	MOR	EM	Dens.	JH	CS	FT
Specific elastic modulus (SEM)		0.05	0.37	-0.21	-0.20	0.07	-0.10
Modulus of rupture (MOR)			0.89	0.90	0.87	0.93	0.68
Elastic modulus (EM)	***	***		0.81	0.76	0.89	0.65
Density	*	***	***		0.96	0.89	0.76
Janka hardness (JH)	*	***	***	***		0.86	0.72
Crushing strength (CS)		***	***	***	***		0.70
Thickness of fibre walls (FT)		***	***	***	***	***	

guitar retailer (n = 5, listed in Table S1, supplementary) and each guitar part (body, neck and fretboard) a percentage was calculated for each wood. The retailers list the woods by common names, such as maple and ebony. The average and the standard deviation of these percentages are shown in Table 2 and are referred to here as *retail popularity*. Information on different guitar part woods were available for 1,200 to 1,300 guitars, on average, per retailer. Information on what tonewoods (woods used for musical instruments; here: electric guitars) are widely available were collected from online tonewood retailers (n = 12, listed in Table S2, supplementary) and is referred to as *tonewood availability* here (Table 2). Information on what wood is suitable for electric guitar making was also collected from popular guitar-building books (Koch 2001; Hunter 2006; Lospennato 2015). Additionally, the personal preferences of Finnish luthiers (n = 18) were polled using an in-person, anonymous questionnaire on February 10, 2018 during the Tonefest event in Helsinki, Finland and are shown in Table 2. Additional information on the questionnaire is provided in supplementary Table S3 and the questionnaire is available in the online supplementary materials.

This study focuses on electric guitars with separate body, neck and fretboard woods. When the neck is made of a suitable wood, such as hard maple, separate fretboards are sometimes not used. As different woods may be used in electric basses (Koch 2001), semi-acoustic guitars, heavymetal guitars and guitars with more than 6 strings, those were left out and focus was on traditional, Stratocaster/Telecaster style instruments.

Data on anatomical and elastomechanical properties for this article are collected from two main sources: the InsideWood database (InsideWood 2004-onwards; Wheeler 2011) and The Wood Database (Meier 2015, 2017). These databases cover a wide variety of commercially available wood species, including those typically used in electric guitars (Table 2). For the InsideWood database, only woods of commercial importance (IAWA Hardwood code #192, (IAWA Committee 1989)) were selected, taking out shrubs (#190) and vines/lianas (#191), leaving a total of 1,123 entries. The Wood Database entries were chosen by selecting hardwoods that were listed as commercial woods in the database, giving out 188 entries. In both of these databases one entry may include more than one wood species, if the wood species are similar. For simplification, the entries are referred to as species in the following text.

Table 2. Significant wood species used in electric guitars. Retail popularity signifies the portion of electric guitars with that wood species for select major online retailers (n = 5, listed in Table S1, supplementary), retail availability signifies the portion of online tonewood retailers (n = 12, Table S2, supplementary) that have the specific wood species for sale. Finnish luthiers' opinions (n = 18, survey information on Table S3, supplementary) on what are the best wood species to be used in electric guitars. Only wood species mentioned by at least 4 of the luthiers are listed.

	Common name	Typical species	Retail popularity (mean ± standard deviation, %)	Tonewood availability (%)	Finnish luthiers (%)
Class		**Body wood**			
2	Mahogany [a c]	*Swietenia macrophylla* † *Khaya ivorensis* †	42 ± 7	83	56
1	Alder [a b c]	*Alnus glutinosa*, *A. rubra*	22 ± 8	75	100
1	Basswood [a b c]	*Tilia americana*, *T. europaea*	14 ± 5	25	19
2	Maple [a b]	*Acer pseudoplatanus*, *A. macrophyllum*, *A. platanoides*	6 ± 7	50	6
1	Ash* [a b c]	*Fraxinus americana* ‡, *F. pennsylvanica* ‡	6 ± 3	75	63
1	Poplar** [a b c]	*Liriodendron tulipifera*, *Populus alba*	5 ± 3	25	25
–	Birch	*Betula* spp.	0	8	38
Class		**Neck wood**			
2	Maple [a b]	*Acer saccharum*, *A. pseudoplatanus*, *A. macrophyllum*	67 ± 8	100	94
2	Mahogany [a b c]	*Swietenia macrophylla* †, *Khaya ivorensis* †	30 ± 7	67	47
1	Alder [a b c]	*Alnus* spp.	0	0	35
–	Birch	*Betula* spp.	0	0	29
Class		**Fretboard wood**			
3	Rosewood [a b c]	*Dalbergia latifolia* †, *D. baronii* †	66 ± 8	75	80
2	Maple [a]	*Acer saccharum*	19 ± 4	67	87
3	Ebony [a b c]	*Diospyros crassiflora* ‡, *D. celebica* †	11 ± 4	58	60
–	Birch	*Betula* spp.	0	0	60
–	Elm	*Ulmus* spp.	0	0	20

† *Vulnerable*, ‡ *Endangered / Critically endangered* (IUCN Red List (IUCN 2017)).
* Often referred to as swamp ash; a lower-density wood used mainly in building guitars (Koch 2001).
** Including yellow poplar, *Liriodendron tulipifera*.
Listed as a common wood for the corresponding guitar part in [a] (Hunter 2006), [b] (Koch 2001), [c] (Lospennato 2015).

Based on the woods listed in Table 2, woods were classified into three categories: 1) low-density body-only wood, 2) medium-density body and neck wood and 3) high-density fretboard-only wood. The classification is based on how the woods are used in the electric guitar, but the classification correlates strongly with density as listed. The properties of woods from these classes were also compared to the average values of all commercially important hardwoods (as categoriszed respectively in the InsideWood database and the Wood Database).

The InsideWood database features information on several anatomical features in a semi-quantitative form, where consecutive feature numbers correspond to one categorised anatomical feature, based on the IAWA List of microscopic features for hardwood identification (IAWA Committee 1989). If the anatomical feature included a range of values, the lower limit of that range was chosen as the quantification. For features where the range did not have an explicit lower limit, the lower limit was taken to be halfway between the upper limit and zero. For example, the IAWA hardwood codes #52–54 correspond to mean vessel elements lengths of ≤ 350 μm, 350–800 μm, and ≥ 800 μm, and were mapped to values of 175 μm, 350 μm, and 800 μm, respectively. The mapping is shown in full in Table 4. Average values were calculated based on the quantified values both for different wood classes and for all commercial hardwoods. As the mapping was chosen based on the lower value of the limits, the actual average values calculated here should be considered as lower limits as well.

Principal component analysis (PCA) was done with R (3.4.3) for the elastomechanical and anatomical properties of hardwoods. The same software was used to calculate weighed averages and weighed t-tests. The weights were calculated using the retail popularity values in Table 2. To further assess a weight for each wood species, rather than a group of species or a genus, the *tonewood availability* of individual wood species with the same common name (such as maple or mahogany) was taken into account, using the species-specific information available from tonewood retailers. The species-specific weighing coefficients in the PCA for individual wood species are listed in supplementary Tables S4 & S5.

RESULTS

Many of the mechanical properties of the commercial hardwoods analysed are highly correlated with its density ρ (Table 1). Janka hardness has a strong correlation with density, although this correlation is not fully linear (Fig. 1). Modulus of rupture (MOR) and crushing strength (CS) have a strong correlation with density, whereas the elastic modulus (E) is the least strongly correlated with these other mechanical properties. Specific elastic modulus (E/ρ) has no correlation with Janka hardness, modulus of rupture or crushing strength (Table 1 and Supplementary Fig. 1). Out of this set of six mechanical properties, the least correlated ones are Janka hardness, elastic modulus and specific elastic modulus. Many class 1 and class 3 woods are outside the linear correlation range when the elastic modulus is compared to the other mechanical properties that have strong linear correlation with the elastic modulus. Class 3 woods, for example, have lower elastic moduli than their densities would suggest based on a linear model and the opposite is true for class 1 woods. Class 2 woods are on the linear range.

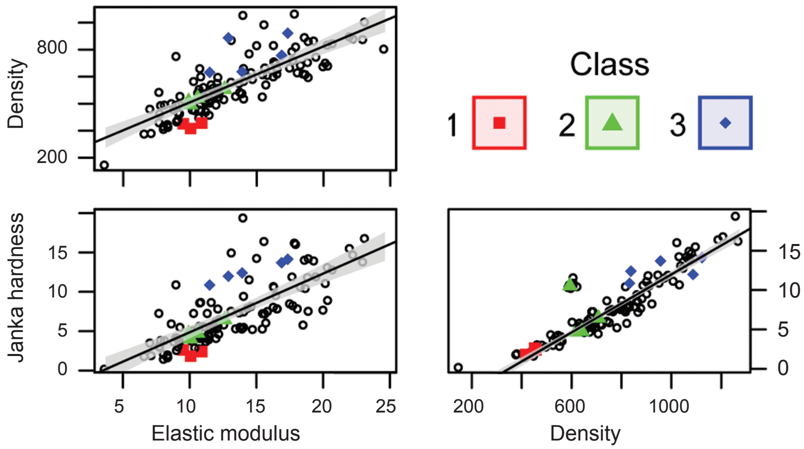

Figure 1. Relationships between density [kg/m^3], Janka hardness [kN] and elastic modulus [GPa] for 125 commercial hardwood species with woods from electric guitar classes 1 to 3 highlighted show how class 1 and 3 woods lay outside the linear region when elastic modulus in considered. Relationships between other elastomechanical properties are shown in Supplementary Figure S1.

Only one anatomical property showed a strong correlation with the elastomechanical properties: the relative fibre wall thickness (Table 1).

Class 1 woods have, on average, a low average density, 450 ± 50 kg/m^3. All other mechanical properties are also lower than the average for all commercial hardwoods, except for the specific elastic modulus (Table 3). Class 3 woods have a high average density, 910 ± 120 kg/m^3. However, for the other mechanical properties of this class,

Table 3. Properties of the three guitar wood classes and those of the average commercial hardwoods. Mean ± Standard deviation. For each property, mean values that are not statistically significantly different (p = 0.05, two-sided, weighed t-test) are highlighted with a common symbol. All mechanical parameters based on Wood Database values. Averages are calculated based on the number of entries listed at the bottom of the table, unless the number of entries is listed in parentheses. * Based on online prices of 4/4 lumber. ** Based on values from Brémaud *et al*. (2012), mean includes both hardwoods and softwoods, class 1 data unavailable.

	Mean	Class 1	Class 2	Class 3
Specific elastic modulus [10^6 m^2/s^2]	18 ± 3†	22 ± 2	17 ± 1 †	14 ± 2
Modulus of rupture [MPa]	110 ± 36†•	68 ± 10	95 ± 15†	134 ± 26•
Elastic modulus [GPa]	13 ± 4†	10 ± 1‡	11 ± 1‡•	13 ± 2†•
Density [kg/m^3]	740 ± 210	450 ± 50	640 ± 70	910 ± 120
Janka hardness [kN]	7.3 ± 4.1	2.5 ± 0.7	5.1 ± 1.2	11.9 ± 1.2
Crushing strength [MPa]	59 ± 18†	38 ± 4	51 ± 5	67 ± 10†
Price per volume * [relat.]	18 ± 20† (131)	5 ± 1	8 ± 3 (4)	51 ± 44† (5)
Damping coefficient ** [10^{-3}]	7 ± 3† (78)	-	12 ± 3 (4)	6 ± 2† (8)
Total number of entries	164	4	5	6

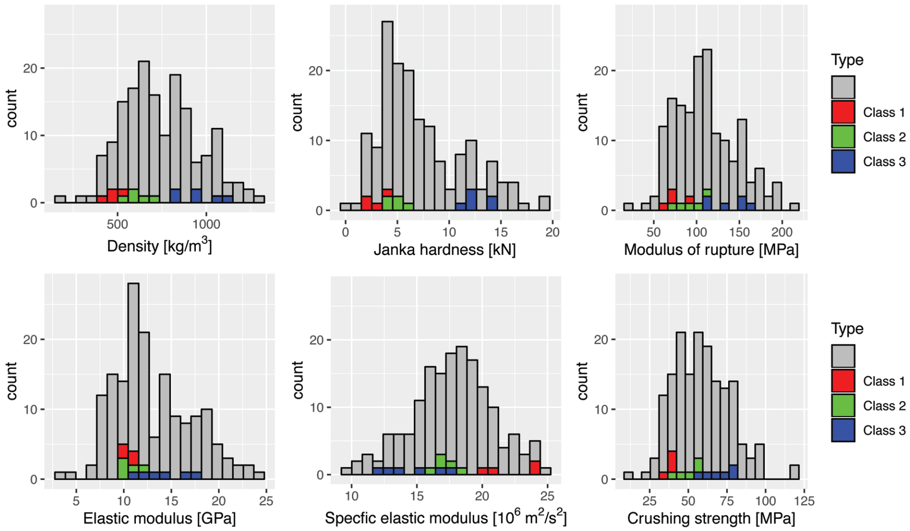

Figure 2. Distribution of various elastomechanical properties for hardwoods, with class 1 to 3 wood species highlighted. Data from 164 commercial hardwood species.

only the Janka hardness is statistically significantly higher than for the average hardwoods. The specific elastic modulus is lower than the hardwood average. For class 2 woods that have their average density closest to the average of hardwoods, the density, Janka hardness, crushing strength and the elastic modulus are lower than average. Both class 1 and class 2 woods have a lower price per volume than the hardwood average. Class 3 woods are, on average, much more expensive.

The distribution of various elastomechanical properties for commercial hardwoods are shown in Figure 2 with class 1 to 3 woods highlighted. The electric guitar woods, as a single class would span a range almost as wide as the entire commercial hardwood range for most properties. However, woods with either a very low or a very high elastic modulus are not included in any of the electric guitar classes. Each class separately covers a relatively narrow parameter space, with class 3 woods showing more variation than the other two classes. Elastomechanical properties for class 2 woods are distributed near the mode of each respective distribution, suggesting they are more easily replaceable than class 1 or class 3 woods. Apart from the elastic modulus, there is no overlap between the values of class 1 and class 3.

The damping coefficient was calculated based on the values reported in Brémaud *et al*. (2012). Due to the limited number of species and specimens with information available for the electric guitar woods, the guitar wood classes were matched by genus only for this parameter. The damping coefficient for class 2 woods were higher than average whereas class 3 showed average damping coefficients. Information for class 1 could not be obtained due to lack of information for the specific species of that class.

The anatomical properties of hardwoods were compared using the InsideWood database. Due to the statistical approach taken here, focus was on the semiquantitative properties. A total of eleven anatomical properties were found to have statistically significant variation from the average commercial hardwood properties for at least one wood class (Table 4).

As could be expected, the average quantified anatomical feature values for hardwoods are typically in the middle of the range (Table 4) apart from ring-porosity. Compared to the average properties of hardwoods, class 1 woods have, on average, smaller vessel diameters, more vessels per mm^2 and thinner fibre walls. Class 2 woods have, on average, more distinct growth ring boundaries, smaller vessel diameters, shorter vessel elements, and shorter fibre lengths. The class 1 and 2 woods are anatomically less distinct groups than class 3. Class 3 woods typically have thicker fibre walls, shorter fibres, shorter vessel elements, less vessels per mm^2, more rays per mm^2 and less wide rays. All electric guitar woods are diffuse-porous except some of the class 1 woods. The most obvious differences in the anatomy of the three classes are in the vessels per mm^2 and the thickness of the fibre walls.

The first two components of the PCA of the elastomechanical properties are shown in Figure 3. The three guitar wood classes are highlighted and the PCA is done only based on these species. Other, alternative woods could be found on this plot close to the average of the respective class. A concentration ellipse was drawn for each wood class that fits tightly over the data points of that class, centred on the average coordinates of woods of that class. All wood species that fit inside the ellipse are listed in Table 5 and can be considered as alternative, or *prospective* woods for that class. The three classes are well separated and the two principal components explain cumulatively 96% of variation in the data.

Principal component analysis was also done for the semi-quantitative anatomical properties and is shown in Supplementary Figure S2. Again the three guitar wood classes are well separated, but the first two principal components explain only 49% of variation in the data. Class 1 woods have the fewest alternatives inside their concentration ellipse whereas class 3 woods have relatively more alternatives than in Figure 3. The small number of diffuse-porous woods explains the small effect of ring-porosity in the two first principal components. The small effects of ring-porosity and vessel lumen diameter on the first principal components is also consistent with Dünisch (2017) who suggests that the size and distribution of lumina in wood are less important for the vibrational properties than the cell walls.

A third PCA was done by merging the elastomechanical data and the anatomical data. The merged data consisted of 123 species with both all the elastomechanical and anatomical information available and is shown in Supplementary Figure S3. The two first principal components account cumulatively for 61% of variation in the data. The wood classes are well separated – as long as the *Fraxinus americana* (ash) is left out. The *F. americana* may not be a good representation of the lighter, so-called swamp ash commonly used in electric guitar bodies (Koch 2001) and it is a clear outlier. The elastomechanical properties do not seem very well correlated with the anatomical properties, apart from the relative fibre wall thickness and the average vessel element length. The latter shows statistically significant correlation with the specific elastic modulus and the former with density.

Table 4. Quantified anatomical features for hardwoods and class 1–3 woods. The first column corresponds to feature numbers in the IAWA List of microscopic features for hardwood identification (IAWA Committee 1989). Mapping signifies the values given for each IAWA code, respectively. Mean values on each row that are not statistically significantly different ($p = 0.05$, two-sided, weighed t-test) are highlighted with a common symbol. Averages are calculated based on the number of entries listed at the bottom of the table, unless the number of entries is listed in parentheses.

IAWA #	Anatomical feature	Unit	Mapping	Hardwoods	Class 1	Class 2	Class 3
1–2	Distinctness of growth ring boundaries		1, 0	0.3 ± 0.4 †	0.8 ± 0.3 †‡	0.8 ± 0.4 ‡	0.1 ± 0.3 †
3–5	Ring-porosity		1, 0.5, 0	0.1 ± 0.2 † (1122)	0.1 ± 0.4 †‡•	0 ‡	0 •
				Vessels			
24–27	Intervessel pit size	µm	2, 4, 7, 10	5.9 ± 2.4 †‡ (1093)	5.0 ± 1.7 ‡	5.0 ± 2.5 †‡	7.5 ± 2.6 †
40–43	Mean tangential diameter of vessel lumina	µm	25, 50, 100, 200	110 ± 50 †‡	60 ± 40 •	70 ± 40 †•	160 ± 60 ‡
46–50	Vessels per square millimetre		2.5, 5, 20, 40, 100	12 ± 18 † (1079)	45 ± 8 (4)	22 ± 14 †	4 ± 3
52–54	Mean vessel element length	µm	175, 350, 800	370 ± 150 † (1097)	450 ± 180 †‡	290 ± 50 ‡	220 ± 70
				Fibres			
68–70	Fibre walls thick		-1, 0, 1	0.2 ± 0.5 †	-0.6 ± 0.4	0.1 ± 0.3 †	0.7 ± 0.3
71–73	Main fibre length	µm	450, 900, 1600	970 ± 240 (1090)	900 †	590 ± 240 ‡	840 ± 120 †‡
				Axial and radial parenchyma			
90–94	Number of axial parenchyma cells per parenchyma strand		1, 2, 3, 5, 8	3.8 ± 1.3 † (1100)	4.2 ± 1.0 †	3.8 ± 1.0 † (4)	2.3 ± 1.0 †
96–99	Typical width of rays	cells	1, 2, 4, 10	2.7 ± 1.5 † (1122)	2.3 ± 1.6 †•	4.2 ± 1.3 †	1.3 ± 0.6 •
106–108	Body ray cells procumbent, number of rows		1, 2, 5	2.0 ± 1.3 (830)	1.5 (1)	1.5 † (2)	1.3 ± 0.7 † (6)
114–116	Rays per millimetre		2, 4, 12	5.2 ± 2.8 † (1118)	7.9 ± 4.7 †‡•	4 ‡	7.9 ± 2.7 •
			Total number of entries	1123	5	5	7

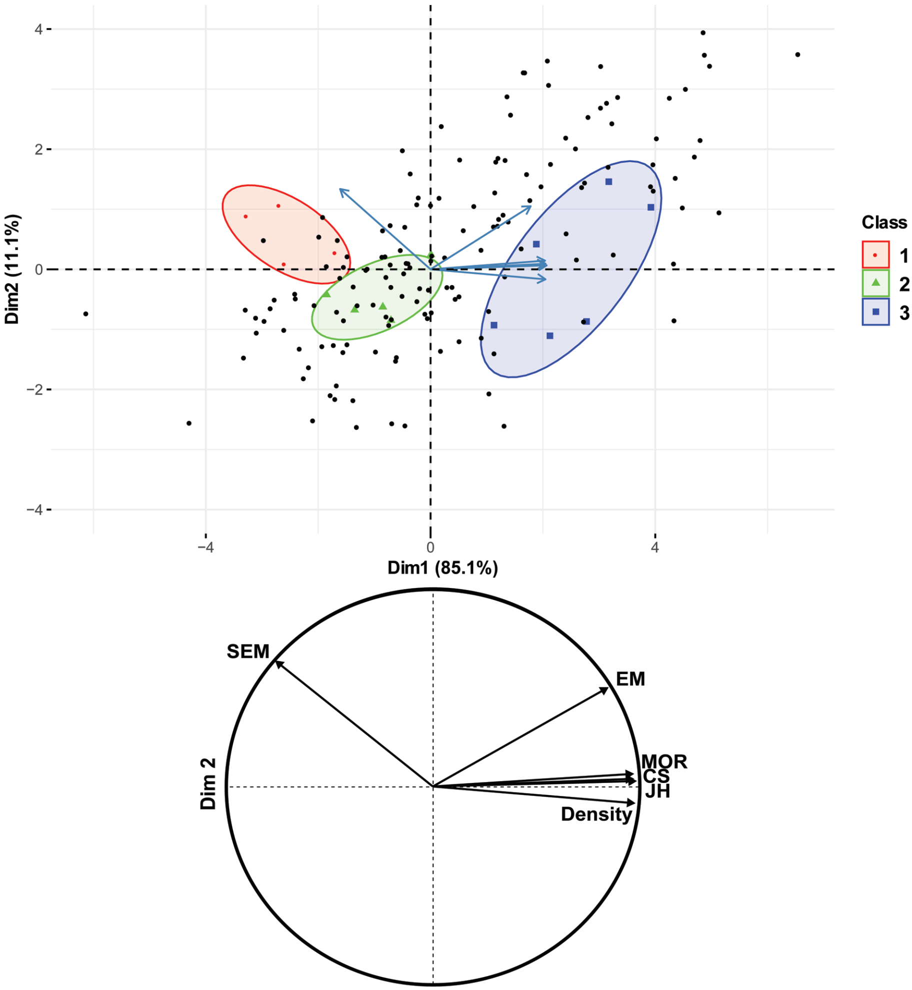

Figure 3. Principal component analysis of elastomechanical properties shown on the variables factor map (clockwise from noon): elastic modulus, modulus of rupture, crushing strength, Janka hardness, density and special elastic modulus. Concentration ellipses drawn for visualisation for class 1, 2 and 3 woods. Woods outside the three classes are shown with circular dots and are not used for determining the principal components.

In all of the principal component visualisations it is clear that the class 2 sits close to the average properties, being the closest to the origin. The class 3 concentration ellipse is the largest, and the class 1 ellipse contains the fewest alternative species. Replacements for the current electric guitar woods can be found by studying the prospective woods inside the concentration ellipses, as listed in Table 5. The vulnerability status of the wood species is also important to note when considering if the wood species are viable replacements or, alternatively, in need of replacement.

Table 5. List of species matching the class characteristics of classes 1 to 3 according to the PCA results for the elastomechanical properties (Fig. 3) and for both elastomechanical and anatomical properties (Supplementary Fig. S2). These species are considered prospective wood species for the respective class. Species belonging to the electric guitar classes *a priori* (known class 1/2/3 woods) are bolded. The species that are not available for the combined PCA are shown in parentheses.

Class	Prospective species according to PCA:
1	Both: ***Alnus rubra***[B], ***Liriodendron tulipifera***[B], ***Tilia americana***[B] Elastomechanical only: (*Cedrelinga catenaeformis*,) *Eucalyptus deglupta*, *Flindersia* spp.[1], (*Fraxinus*[B] *nigra*[‡],) *Liquidambar styraciflua*, (*Populus*[B] *grandidentata*,) *Pouteria altissima*, *Terminalia superba*[B] Combined only: *Dyera costulata*, ***Populus***[B] ***nigra***, *Populus*[B] *tremuloides*
2	Both: *Acacia koa*, ***Acer pseudoplatanus***[B], *Dracontomelon mangiferum*, *Entandrophragma cylindricum*[†B], *Entandrophragma*[B] *utile*, *Guarea* spp.[2], *Juglans regia*[B], ***Khaya***[B,N] **spp.**[†], *Lovoa trichilioides*, *Mangifera indica*, *Mansonia altissima*, ***Swietenia macrophylla***[†B,N] Elastomechanical only: (***Acer macrophyllum***[B,N,FB],) *Acer*[B,N,FB] *rubrum*, (*Dracontomelum dao*,) (*Simira* spp.[3],) *Guibourtia ehie*[B,FB], *Prunus serotina*[B], *Pterocarpus indicus*[†B], *Quercus alba*, (*Quercus robur*,) *Quercus rubra* Combined only: ***Acer saccharum***[N,FB], *Albizia lebbeck*, *Eucalyptus deglupta*, *Eucalyptus grandis*, *Eucalyptus regnans*, *Fagus grandifolia*, *Flindersia* spp.[1], *Fraxinus americana*[‡B], *Gluta* spp. and *Melanorrhoea* spp.[4], *Gonystylus* spp.[5†], *Juglans nigra*[B,FB], *Pterocarpus angolensis*[B], *Pterygota macrocarpa*[†], *Pyrus communis*, *Swietenia mahagoni*[‡], *Tectona grandis*, *Terminalia superba*[B]
3	Both: *Chloroxylon swietenia*[†], *Colophospermum mopane*, ***Dalbergia latifolia***[†B,N,FB], ***Dalbergia nigra***[†FB], ***Dalbergia spruceana***[FB], ***Diospyros celebica***[†FB], ***Diospyros crassiflora***[‡FB], *Myroxylon balsamum*, *Olea* spp., *Pterocarpus*[B,N,FB] *macrocarpus* Elastomechanical only: (*Acacia cambage*i,) *Berchemia zeyheri*, (*Bobgunnia* spp.[6],) (*Buxus sempervirens*), *Cordia dodecandra*[FB], (*Cordia elaeagnoides*[FB],) (***Dalbergia baronii***[†N,FB],) (*Inga* spp.,) *Machaerium scleroxylon*[N,FB], (*Tamarindus indica*) Combined only: *Andira inermis*, *Astronium* spp.[7], *Brosimum*[FB] *rubescens*, *Chlorocardium rodiei*, Guibourtia[B,FB] spp.[8], *Hymenaea courbaril*, *Lophira alata*, *Manilkara bidentata*, *Manilkara zapota*, *Microberlinia brazzavillensis*[†B,N], *Millettia laurentii*[‡B,N,FB], *Millettia*[B,N,FB] *stuhlmannii*

[1] Queensland Maple, [2] Bosse, [3] Chakte Kok, [4] Rengas, [5] Ramin, [6] Pau Rosa, [7] Goncalo Alves, [8] Bubinga.

IUCN Red list (IUCN 2017) status: [†] Vulnerable, [‡] Endangered/Critically endangered.

Wood available from tonewood retailers: [B] Body, [N] Neck, [FB] Fretboard; letters after a genus indicate that wood from that genus is available.

Apart from ash (*Fraxinus nigra*), no prospective wood species for class 1 (Table 5) are listed as vulnerable or endangered in the IUCN Red List, yielding a 7% vulnerable/endangered status for prospective class 1 woods. In addition to alder (*Alnus rubra*), yellow poplar (*Liriodendron tulipifera*) and basswood (*Tilia americana*), black limba (*Terminalia superba*) is available as tonewood. The only *Populus* species with tonewood availability was *P. alba*, which is not included in the elastomechanical dataset. However, several other *Populus* species were a good fit for class 1. Known class 1 species are common, inexpensive (Table 3), widely available species. The prospective class 1 wood species represent 7% (5%) of the commercial hardwood species according to the PCA of the elastomechanical (combined) properties, clearly less than the other two classes.

For class 2 woods, a total of 39 prospective wood species are listed in Table 5, nine of which (23%) are vulnerable or endangered. Most notably mahogany (*Swietenia* spp.) and African mahogany (*Khaya* spp.) are either vulnerable or endangered. Some of the prospective class 2 wood species are much more expensive than known class 2 woods, such as teak (*Tectona grandis*) and koa (*Acacia koa*) which are 4 and 5 times more expensive as the average known class 2 wood, respectively. However there are several inexpensive, non-threatened prospective class 2 woods with tonewood availability (*Acer pseudoplatanus*, *Juglans nigra*, *Juglans regia* and *Prunus serotina*). The prospective class 2 wood species represent 13% (24%) of the commercial hardwood species according to the PCA of the elastomechanical (combined) properties, more than the other two classes.

Class 3 woods are the most threatened, with 25% of the prospective class 3 woods vulnerable or endangered (Table 5). This includes most rosewoods and ebonies, meaning most fretboard woods currently used and most of known class 3 woods. Additionally, all *Dalbergia* species are as of 2017 included in the CITES appendices II for trade control due to threat of extinction, including their use in finished products such as electric guitars. Zebrawood (*Microberlinia brazzavillensis*) and wengé (*Millettia laurentii*) are available as tonewoods but they are also vulnerable and endangered, respectively. However, non-threatened alternatives exist with tonewood availability: ziricote (*Cordia dodecandra*), bocote (*Cordia elaeagnoides*), pau ferro (*Machaerium scleroxylon*) and bubinga (*Guibourtia* spp.). The prospective class 3 wood species represent 12% (18%) of the commercial hardwood species according to the PCA of the elastomechanical (combined) properties.

DISCUSSION

Most literature (with the exception of Lospennato (2015)), guitar retailers and tonewood retailers do not list wood at the species-level. Information on what species belong to a common name were taken from those tonewood retailers (n = 6, Table S2, supplementary) who provided such information. This also suggests that species-level specification is not vital for luthiers and closely related species could be used to replace current guitar wood species, especially if they have similar density and elastic modulus.

The classification presented in this article is based on the use of wood in modern electric guitars from large retailers. The classification would be different if the Finnish luthiers' opinions on guitar woods would have been used. Birch, which is the most common hardwood species in Finland, was recommended for all guitar parts. Maple was more popular than rosewood for fretboards, and alder was the most popular body wood, but also suggested for guitar necks. It is likely that the Finnish luthiers' opinions on wood are based on properties of Finnish woods to a significant extent and since the available elastomechanical and anatomical information was not of Finnish wood in particular, data analysis on Finnish woods was not included. The luthiers' personal opinion does not also consider the large-scale availability of the tonewoods, something that is vital for large manufacturers (Koch 2001).

Even with this classification, there is variability within each class depending on what species are selected as the known species. In the analysis, some simplifications were made with maple and ash. The density of various maple species varies, from 540 kg/m^3 for *Acer saccharinum* to 705 kg/m^3 for *A. saccharum* (in this study). The so-called soft maple is predominantly used for bodies and necks whereas the so-called hard maple is used for necks and fretboards. Here, all maple species used for necks were classified as class 2 woods. In electric guitar making, light-weight, so-called swamp ash (Koch 2001; Hunter 2006) is usually preferred over normal ash. In this work the elastomechanical properties of *Fraxinus nigra* were used to represent swamp ash properties instead of other, heavier *Fraxinus* species. Anatomical data from *F. nigra* was added separately as it was only listed as variedly of commercial importance in the InsideWood database. Although it is not a perfect representation of the swamp ash, leaving it out entirely would leave the anatomical data with less variation than there is.

The mechanical properties of woods also vary within one species, and as such, some individual wood pieces might fall into one of the guitar wood classes even if the wood species in general does not. A recent paper (Sproßmann *et al*. 2017) studied Indian rosewood, ziricote, African blackwood and ebony and found a 3 to 9% variation (standard deviation divided by mean) in density in these species and a 14 to 22% variation in the elastic modulus. The same article also found a very high correlation between the static and the dynamic elastic modulus, suggesting the static elastic modulus parameter also describes dynamical behaviour rather well. The tonewood retailers generally have their own quality classifications for wood pieces sold individually, but do not typically include any density information although density could offer some objective information on wood quality. Quantitative tonewood quality assessment, compared with tonewood retailers' own quality assessments should also be studied in more detail. Density, although evidently a vital parameter on guitar woods, is not reported for individual tonewood pieces, although it is relatively easy to measure non-destructively.

For electric guitar making, the vibrational properties of wood could be more important than the anatomy itself, but obviously these two must be connected somehow. A connection between the anatomy and vibrational behaviour of both hardwoods and softwoods was studied lately in Dünisch (2017). The vibrational behaviour was studied using PCA. The published data of the first two PCA components in that article showed no obvious correlation with the electric guitar wood classes (for ten guitar wood species, data not shown). The vibrational properties of 79 wood species were also studied in Brémaud *et al*. (2012) but many of the typical electric guitar wood species were missing from that dataset, including all class 1 woods. As such, further research is needed to connect the anatomy and mechanical properties of electric guitar wood classes to their vibrational properties. Recent research, Dünisch (2017), suggests that the cell walls would be more important to the spread of vibrations in wood than how the cell lumina are distributed in size and spatial distribution. Here the fibre wall thickness was seen to correlate with the guitar wood classes. Fully quantitative anatomical information would help to find additional correlations between the anatomy, mechanical properties, and acoustic properties of wood.

However, the classification presented here seems to follow the elastomechanical properties more than the anatomical ones. Recent literature from Neyses & Sandberg (2015) also lists density and elastic modulus as the two most important properties in finding suitable electric guitar wood. This is consistent with the PCA results that show density and elastic modulus contributing to different principal components (Fig. 3) that combined explain most of the variation in the elastomechanical dataset. Density and elastic modulus could therefore be considered as good first parameters to assess how a wood species could be used in an electric guitar.

In contrast, there is significant anatomical variation within each guitar class presented here. In class 1 both ring-porous and diffuse porous woods are found. In class 2, maple and mahogany differ systematically in distinctness of growth rings, vessel diameter and fibre lengths. For class 3, rosewoods have storied rays and storied axial parenchyma and/or vessel elements (IAWA Hardwood codes #118 and #120), whereas ebony does not. Storied rays have been connected to the acoustic properties of wood (Dünisch 2017) and some research suggests a difference in acoustics between ebony and rosewood fretboards (Paté *et al*. 2015). Differences in wood anatomy can thus be connected to differences in the acoustics of wood species with similar densities but additional research on this is needed.

Although endangered woods are quite commonly used in the electric guitar body, neck and especially the fretboard, non-threatened alternatives exist already. For the body alder, poplar, basswood, and black limba are available; for the neck maple, cherry, and walnut; and for the fretboard bocote, ziricote, pau ferro, and bubinga. Out of these, alder, basswood, and maple are already commonly used. Pau ferro, also known as Bolivian rosewood, is also widely available and might already be substituted as a "rosewood", although it is not a member of the *Dalbergia* genus and therefore not trade-restricted currently. Bocote, poplar (and yellow poplar), cherry, black limba, bubinga and walnut are also well known guitar woods, although less popular. Additional research is needed to compare the acoustical qualities of the less commonly used tonewoods to those of the endangered tropical ones: do the acoustical qualities justify the use of the threatened species?

CONCLUSIONS

Electric guitar wood can be separated into three distinctive classes based on how the wood is commonly used in the instrument, although the three classes were not body, neck, and fretboard wood, unlike expected. The low-density body-only wood and the high-density fretboard-only wood classes are most unlike the average commercial hardwood in anatomy and elastomechanical properties. The medium-density class wood is used for the electric guitar body and neck and has a high damping coefficient. The anatomy and mechanical properties of these guitar wood classes are distinctive although with some overlap. Differences between the classes were seen in the dimensions and distribution of vessels, fibres, rays and axial parenchyma. Commercial tonewood options exist for the threatened wood species commonly used in electric guitars. Density and elastic modulus are good parameters to consider when assessing how a prospective wood species could be used in an electric guitar.

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BRILL

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Supplementary data for:

Anatomy and mechanical properties of woods used in electric guitars

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Content: Supplementary Table 1–5 and Figure 1–3

Supplementary Table S 1: List of guitar retailers.

	Number of guitars with wood listed				
Retailer	**Country**	**Body**	**Neck**	**Fretboard**	**Website**
Thomann GmbH	Germany	1691	1771	1608	https://www.thomann.de/gb/
Sweetwater	USA	2048	2118	2050	https://www.sweetwater.com/
B & H Foto & Electronics Corp.	USA	450	382	387	https://www.bhphotovideo.com/
MUSIC STORE professional GmbH	Germany	1455	1025	1590	https://www.musicstore.de/en_de/eur
Dawsons Music	UK	902	888	892	https://www.dawsons.co.uk/
	Total:	**6546**	**6184**	**6527**	

Only guitar retailers listing guitars by used wood species were selected.
Information obtained in November 2017.
Links updated in July 2018.

DOI 10.1163/22941932-40190218

Supplementary Table S 2: List of tonewood retailers.

Retailer	Country	Species-specific	Website
ESPEN Timber	Germany	Yes	http://www.espen.de/en/tonewood/e-guitars
Exotic Woods Company	USA	Yes	http://www.exoticwoods.com/
Maderas Barber	Spain	Yes	https://maderasbarber.com/tonewood
Madinter	Spain	Yes	https://www.madinter.com/wood/bodies.html
Timberline	UK	Yes	http://shop.exotichardwoods.co.uk/body-blanks.html
A&M Wood Specialty	USA	Partially	http://www.amwoodinc.com
Guitar and Bass Build	UK	No	https://www.guitarandbassbuild.co.uk/
Kiesel Guitars	USA	No	https://www.kieselguitars.com/colorandwoodguide/
Luthiers Mercantile International, Inc.	USA	No	http://www.lmii.com/products/mostly-wood
Oregon Wild Wood	USA	No	http://tonewood.com/guitar-wood.html
Stewart-MacDonald	USA	No	http://www.stewmac.com/Materials_and_Supplies
TWOOD	Serbia	No	https://www.tonewood.rs/Tesla-Tonewood

Only tonewood retailers carrying a wide selection of different species were selected.
Information obtained in November 2017.
Links updated in July 2018.

Supplementary Table S 3: Information on the survey conducted on Finnish luthiers.

Property	Value
Survey planner	Patrik Ahvenainen (PA)
Survey funding	Personal grant (PA) from Kone Foundation
Survey mode	In-person questionnaire, anonymous
Survey collector	PA
Survey target audience	Finnish electric guitar builders, 46 members in the Guild of Finnish Luthiers
Sampling	Luthiers presenting at the Tonefest event in Helsinki, Finland
Sample size	18 responders, 16 properly filled responses
Representativeness	Although situated in Helsinki, the event is the biggest in the country and includes luthiers all over Finland
Survey response rate	23 luthiers were expected to be present, 18 were surveyed (78 %), including one luthier not presenting
Survey fielding period	February 10, 2018
Instructions to repliers	If asked, the repliers were told to fill in the survey using their subjective opinions
Average length	Approximately 2 to 3 minutes

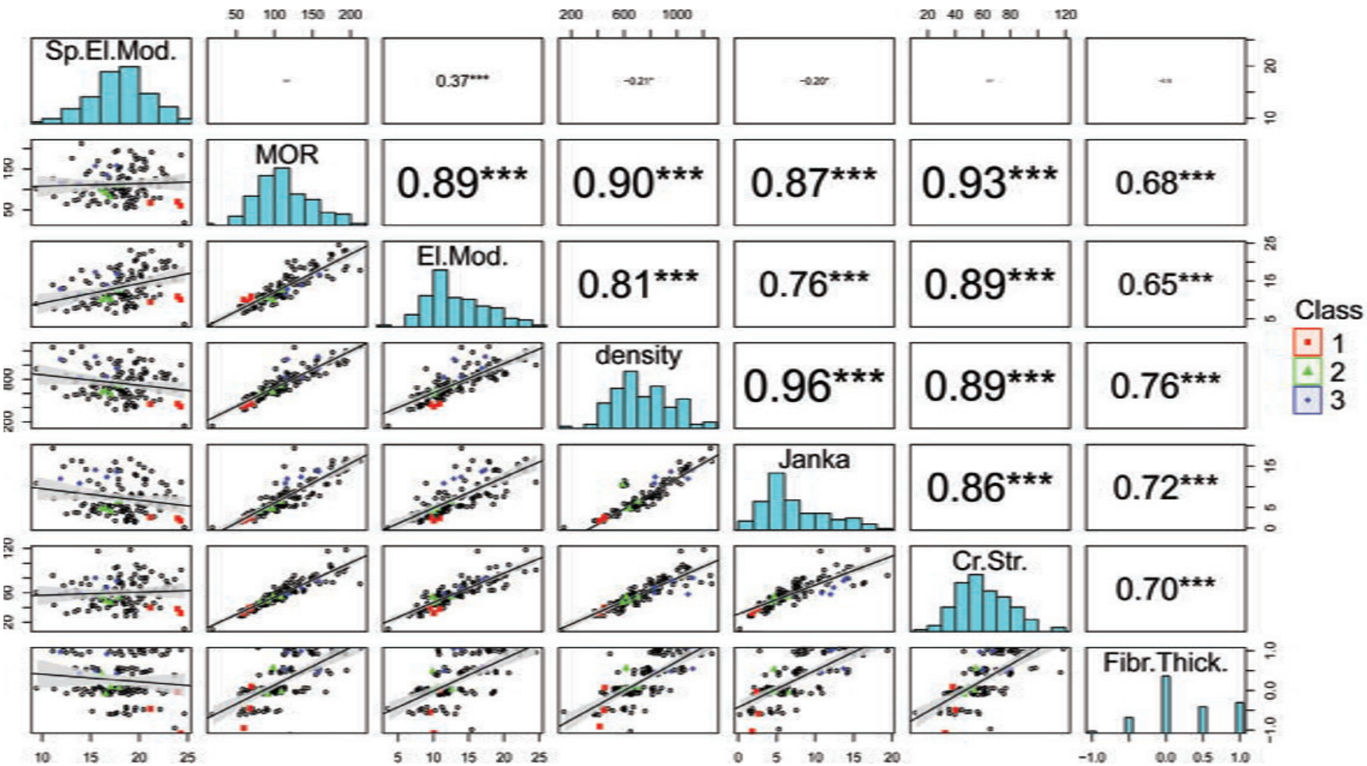
Supplementary Table S4: Weights used with the elastomechanical data from the Wood Database.

Species	Class	Weight
Alnus rubra	1	0.22
Fraxinus nigra	1	0.06
Liriodendron tulipifera	1	0.05
Tilia americana	1	0.14
Acer macrophyllum	2	0.12
Acer pseudoplatanus	2	0.18
Acer saccharum	2	0.37
Khaya spp.	2	0.13
Swietenia macrophylla	2	0.17
Dalbergia baronii	3	0.17
Dalbergia latifolia	3	0.33
Dalbergia nigra	3	0.08
Dalbergia spruceana	3	0.08
Diospyros celebica	3	0.06
Diospyros crassiflora	3	0.06

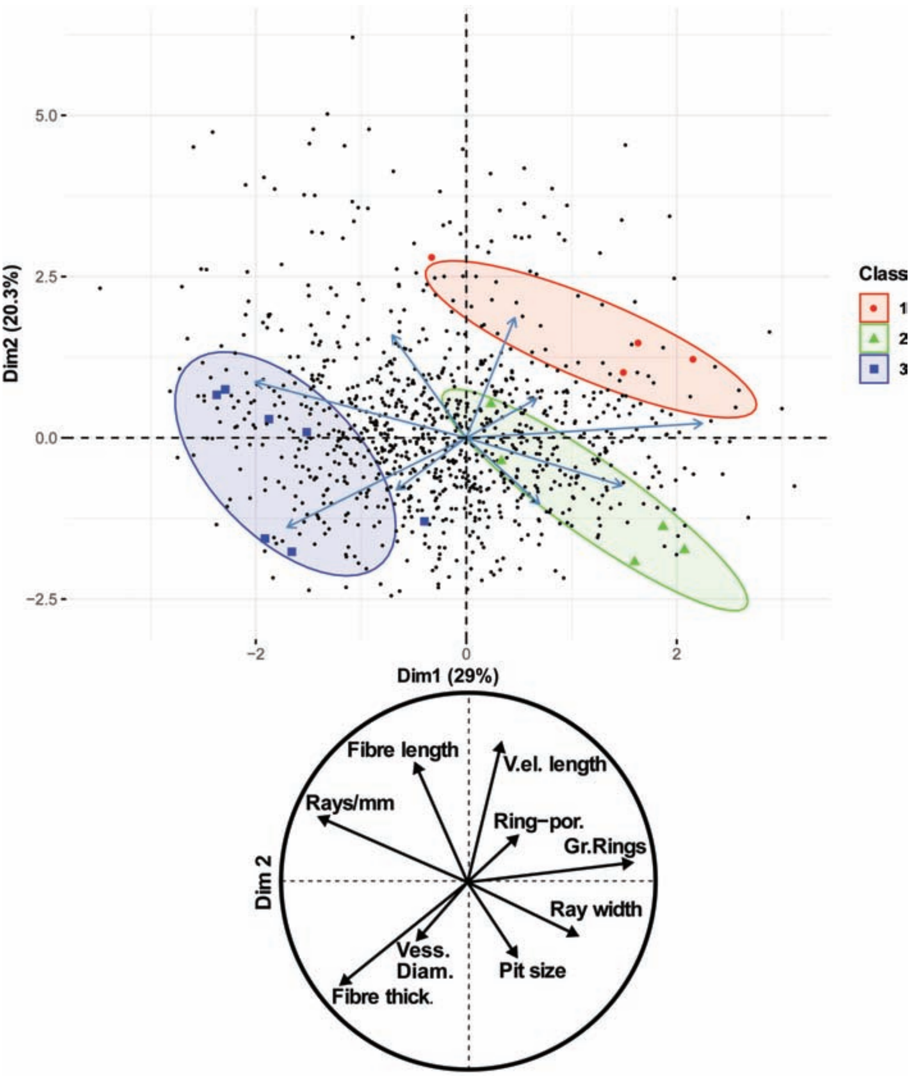
Supplementary Table S5: Weights used with the anatomical data from the InsideWood database.

Species	Class	Weight
Alnus rubra	1	0.22
Liriodendron tulipifera	1	0.03
Tilia americana	1	0.14
***Fraxinus nigra* ***	**1**	**0.06**
Populus alba	1	0.03
Khaya ivorensis	2	0.13
Swietenia macrophylla	2	0.17
Acer saccharum	2	0.37
Acer nigrum	2	0.06
Acer pseudoplatanus	2	0.24
Diospyros celebica	3	0.04
Diospyros crassiflora	3	0.04
Diospyros ebenum	3	0.01
Diospyros melanoxylon	3	0.01
Dalbergia latifolia	3	0,44
Dalbergia nigra	3	0.11
Dalbergia spruceana	3	0.11

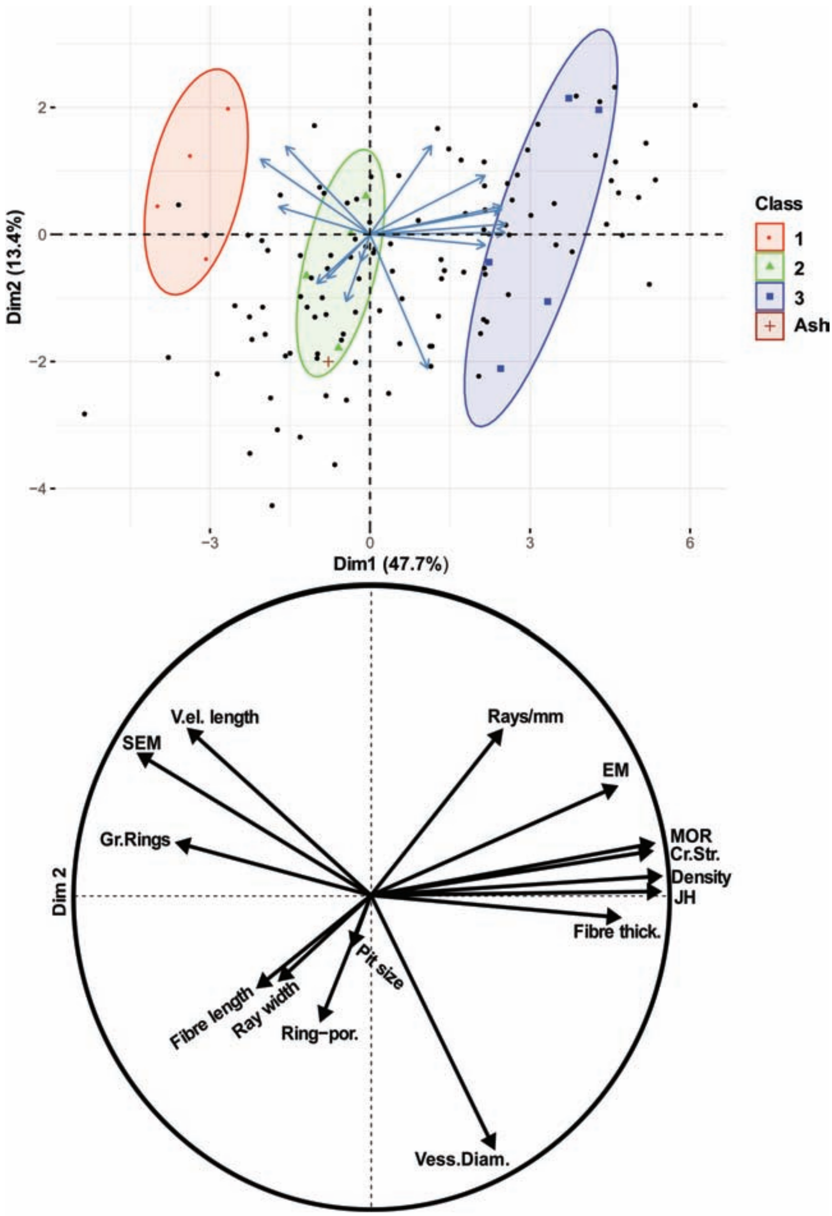
* Only used for calculating the average class values (Table 4) and not used for the PCA.



Supplementary Figure S1. The diagonal shows the distribution of various elastomechanical properties, from top to bottom: specific elastic modulus [10^6 m^2/s^2], modulus of rupture [MPa], elastic modulus [GPa], density [kg/m^3], Janka hardness [kN] and crushing strength [MPa], and the most correlated anatomical feature: relative fibre wall thickness. The lower half shows a linear fit to the data for variables named in the diagonal of the corresponding row and column. The corresponding linear correlation (r^2) is shown on the upper half and asterisks indicate significance for p-values 0.05, 0.01 and 0.001, for 1 to 3 asterisks, respectively. Data points represent 125 commercial hardwood species.



Supplementary Figure S2. Principal component analysis of the semi-quantitative anatomical properties shown on the variables factor map (clockwise from noon): mean vessel element length, ring-porosity, distinctness of growth ring boundaries, typical width of rays, intervessel pit size, mean tangential diameter of vessel lumina, fibre wall thickness, rays per millimetre, and main fibre length. Concentration ellipses drawn for visualisation for class 1, 2 and 3 woods. Woods outside the three classes are shown with circular dots and are not used for determining the principal components.



Supplementary Figure S3. Principal component analysis of both anatomical and elastomechanical properties shown on the variables factor map (clockwise from noon): rays per millimetre, elastic modulus, modulus of rupture, crushing strength, density, Janka hardness, fibre wall thickness, mean tangential diameter of vessel lumina, intervessel pit size, ring-porosity, typical width of rays, main fibre length, distinctness of growth ring boundaries, special elastic modulus and mean vessel element length. Concentration ellipses drawn for visualisation for class 1, 2 and 3 woods. Woods outside the three classes are shown with circular dots and are not used for determining the principal components. Ash (*Fraxinus americana*) is an outlier of class 1 as discussed in the Discussion.