The Sound of Trees: Wood Selection in Guitars and Other Chordophones

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The Sound of Trees: Wood Selection in Guitars and Other Chordophones. Until recently, luthiers have been conservative in their wood choices for guitars and other chordophones. Most soundboards (tops) were made from American or European spruces. Rosewood and, less frequently, mahogany, maple, and koa, were used for backs and sides. Spanish cedar and mahogany were the preferred species for necks; ebony or rosewood for fretboards. Due to scarcity and increasing costs, new woods are now employed. Some are congeners of traditional woods; others are more innovative. The botanical identification of many of these species is inaccurate. A common name may refer to more than one species (under–differentiation, e.g., Madagascar rosewood for several *Dalbergia* spp.). Conversely, a binomial may be known by several common names (over–differentiation, e.g., European, German, or Italian spruce for *Picea abies*). Instrument makers and wood suppliers are unreliable sources of taxonomic names, especially with newer woods. Here, I provide the full taxonomic identification (binomials, author citations, and families) for both traditional and some new guitar woods. Many factors determine a wood's suitability for lutherie. A model based on two mechanical properties of wood, density and modulus of elasticity, can be used to determine what species of wood constitutes each part of a guitar. Many of the "new" guitar woods are now becoming scarce. Luthiers face the continual task of finding suitable alternative woods. The model presented here can serve as a guide in future wood choices; further modifications, using additional wood properties, may help refine the model. These principles are also applicable to wood selection for other chordophones.

Key Words: Chordophones, guitars, mahogany (*Swietenia* spp.), Martin D–28 guitar, modulus of elasticity, rosewood (*Dalbergia* spp.), spruce (*Picea* spp.), tonewoods, wood density.

Introduction

Among the myriad values of plants is their use in the construction of musical instruments. Plant materials may be minor, yet essential components, such as clarinet and oboe reeds (e.g., giant reed), sound initiators such as drum sticks (e.g., shagbark hickory), and violin bows (e.g., pernambuco), or they may form most of the instrument such as piano, guitar, or cello (e.g., rock maple and Sitka spruce). Binomials and family names not in Tables 2 and 3 can be found in the Electronic Supplementary Material (ESM). Most musical instruments belong to one of four classes, based on the type of vibration that produces their sounds (von Hornbostel and Sachs 1914): aerophones (air column within instrument), idiophones (instrument body), membranophones (stretched membrane), and chordophones (strings). Many of these are composed of plant–derived materials, including the guitar (Figure 1) and other chordophones.

History of the Guitar

The English word "guitar" derives ultimately from "sihtar" (Persian) through "kithara" (Greek) or through "qitar" (Arabic) and "guittara" (Spanish) (Harper 2015). The guitar's ancestors, which might

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Fig. 1. From left to right: **Martin LX** (high pressure laminate – B&S, T; Stratabond® laminated birch – N); **Martin D–18GE** (Honduran mahogany B&S, N, Adirondack spruce – T); **Guild 37Bl** (laminated hard maple arched – B, hard maple – N, S, Sitka spruce T, side); **Takamine 132S** (Indian rosewood B&S, western red cedar – T, Honduran mahogany neck), where B=back, N=neck, S=sides, and T=top).

include the barbat of Central Asia (3,500 YBP) can be traced through the oud, lute, vihuela, Renaissance and Baroque "guitars," and chitarra battente (Chapman 2000).

The oldest known six–string guitar was built by Italian luthier Gaetano Vinaccia in 1779 (Rossing and Caldersmith 2010). Like modern instruments, each course had a single string. A revolution in guitar making occurred in the mid 1850s when Spanish luthier Antonio Torres Jurado established the modern dimensions of the classical guitar. He increased the instrument's size, proportions, and optimized fan bracing (Romanillo 2006). These modifications increased volume, tone, dynamic range, and projection (Gerken et al. 2003; Sandberg 2000).

Another significant innovator was the German Christian Frederick Martin, who migrated to the United States in 1833. Martin perfected X–bracing, an alternative to the commonly employed fan bracing (Gura 2003; Johnston and Boak 2008). By 1850, X–bracing was found in most Martin guitars, but was not widely used by others until steel strings became popular in the 1900s (Gerken et al. 2003). X–bracing had two significant impacts: it changed the tone of the guitar and it served as a pre–adaptation for steel strings. Steel strings created too much torsion for fan–braced tops. Martin also contributed two other significant innovations: the larger dreadnought body size and the 14–fret (clear of the body) neck. By 1934, Martin combined these features in the D–18 (mahogany) and D–28 (rosewood) models. Both are still in production and the D–28, in particular, is the standard for acoustic flattop guitars (Carter 1995; Gerken et al. 2003).

Acoustic Guitars Today

Today, guitars rank among the world's most popular instruments. In 2013, the U.S. music industry sold 1,363,000 acoustic and 1,110,000 electric guitars. China exported more than 10,000,000 guitars in the same year and guitars accounted for 42% of the instruments played in the United Kingdom (Challacombe and Block 2014). The Torres–inspired classical and the Martin dreadnought remain popular styles. Some variations, such as cutaways, represent slight modifications of the original styles. Others, such as resonator guitars, offer radical changes in construction and tone. Wood remains a crucial component, even in electric guitars.

Wood and Guitar Anatomy

The tone, volume, and projection of the guitar is determined by multiple factors. These include, guitar size and shape, bracing pattern, string gauge, neck length, and type of glue used in construction. The most important contributor to tonal characteristics in quality instruments is the choice of wood.

Species, age, and handling affect tone and there can be significant variation within a species. New woods and substitutes (e.g., carbon fibers, fiberglass, high pressure laminates, Nomex®) have been incorporated during the past few decades, due to increasing material costs and scarcity. Late 19th century and early 20th century guitars read like an endangered species list, including West Indian mahogany, Brazilian rosewood, African ebony, tortoise shell plectrum and pick guards, and ivory nuts and bridge pins.

Strings, tuners, frets, pickguards, nuts, and some bridge pins are made of metal, plastic, bone or other materials, but the guitar is mostly a wooden instrument (Figure 2). Wood forms the backs, sides, soundboard, neck, saddle, fretboard, braces, and headstock (Table 1) and other parts visible only from inside the instrument. All components affect an instrument's tone, especially the soundboard (Gerken et al. 2003) and the backs and sides. The neck's rigidity allows string vibrations to be transferred to the soundboard via the bridge. Fretboards may indirectly influence sound quality as they, along with truss rods, stiffen the neck. Bracing is often made of the same material as the top. Its shape and placement has a strong influence on tone and volume. Heavier headstocks may provide more sustain, but at the cost of treble response and volume (Gerken et al. 2003).

This paper focuses on chordophones, particularly guitars. However, the principles that determine the selection of wood for guitars apply to other chordophones. Specifically, I address four questions. 1) What are the major traditional wood species employed in the construction of guitars? 2) What new wood species are used? 3) Can the mechanical properties of wood be used to predict their use? 4) What is the value of selected traditional tone woods?

Methods

I reviewed published literature and websites of major guitar manufacturers, luthiers, and tone wood suppliers to determine what species of woods

Fig. 2. Guitar external anatomy: visible wood components.

Table 1. The use of wood in acoustic guitar components

Part	Woods Used*
Backs and sides	Rosewood, mahogany, maple, koa
Top (soundboard)	Spruce, cedar, mahogany, koa
Neck	Mahogany, maple, rosewood, Spanish cedar
Fretboard	Ebony, rosewood
Bracing	Spruce (often same as material as soundboard)
Bridge	Ebony, rosewood
Headstock	Rosewood, mahogany, maple

*Species and familial names are found in Table 2. This list includes only those species of traditional (and longstanding) use. While they are still employed today, many luthiers have incorporated alternative woods.

are used in guitar construction. The obvious limitation is the near ubiquitous use of common names. Even when binomials are provided, there is no guarantee of their accuracy since vouchered herbarium specimens are lacking. However, identification uncertainties are less severe with traditional woods, owing to their value and to CITES regulations, which limit their export. Data on wood properties and origin were employed to determine the binomials in these cases. The binomials presented here, therefore, provide the best available determinations of guitar woods. Binomials and family names follow The Plant List (2015).

Mechanical properties of wood were derived from the Wood Database (Meier 2015), except where indicated. Data from other sources were converted to the S.I. equivalents, if necessary. Values for some species were estimated from wood density or specific gravity, when not available. The comparison of wood density (ρ) to modulus of elasticity (E) follows Wegst (2006), though at a finer scale.

Examining the value of guitars based on their composition is difficult. Many factors, besides wood species, affect the tone, resonance, projection, sustain, and appearance. Nonetheless, it can be done by limiting the comparison to a single style produced by a single manufacturer. The Martin D–28 is an optimal choice, having been in continual production since 1934. It may be "the most important acoustic guitar of all time" (Gerken et al. 2003). To determine the value of Martin D–28 guitars, I searched major guitar vendors in the United States. When sales occurred before 2014, prices were adjusted to 2015 equivalents. To determine the value of selected traditional woods, I searched tonewood vendors on the Internet. Means and standard deviations were calculated in Excel and those data were used in GraphPad (2015) to test for significant differences among means.

Results

Traditional Woods

The major traditional wood species employed in the construction of guitars are well established, at least by common name. Among the traditional woods, most are distinct except *Acer saccharum*, *A. saccharum* subsp. *nigrum* (both sold as hard maple), and ebony (several *Diospyros* spp.). Table 2 lists binomials, families, and other pertinent data for these species. Spruce is the most common choice for soundboards. Engelmann spruce's inclusion could be debated, as it is not certain when this species was first utilized by American luthiers. The name European spruce is ambiguous. It often is called Norway spruce, but common names include Carpathian, French, German, Italian, Swiss, and Yugoslavian spruce, in reference to its place of origin. Mediterranean cypress is also called Italian or Spanish cypress or pencil pine. Rosewood is the most widely used species for backs and sides (Figure 3). Most rosewood species have multiple vernacular monikers. Ebony common names often refer to the place or origin and thus represent multiple taxa (e.g., African ebony). Other species' synonymous common names include West Indian mahogany/Cuban mahogany, European maple/sycamore/sycamore maple, and rock maple/hard maple/sugar maple. Common names are clearly inadequate.

New Woods

With newer tonewoods, identification is more difficult. *Diospyros* species remain problematic. *Dalbergia* species, except those from Madagascar, can be delimited by physical properties and origin. Nato or nyatoh is a generic equivalent of *Palaquium*. The common names grandadillo, mahogany, and rosewood, are under–differentiated and each can represent species and genera in different

TABLE 2. MOST COMMON TRADITIONAL WOOD SPECIES USED IN GUITARS, ARRANGED BY INCREASING DENSITY.*

Common Name	Species	Acronym (used in Fig. 1)	Family	Uses	ρ (kg/m^3)	E (GPa)
Western red cedar	*Thuja plicata* Donn ex D. Don	RC	Cupressaceae	T	370	7.66
Engelmann spruce	*Picea engelmannii* Parry ex Engelm.	NS	Pinaceae	T	385	9.44
European spruce	*Picea abies* (L.) H. Karst.	ES	Pinaceae	T	405	9.70
Sitka spruce	*Picea sitchensis* (Bong.) Carrière	SS	Pinaceae	T	425	11.03
Red spruce	*Picea rubens* Sarg.	RS	Pinaceae	T	435	10.76
Spanish cedar	*Cedrela odorata* L.	SC	Meliaceae	B&S, N	470	9.12
Mediterranean cypress	*Cupressus sempervirens* L.	MC	Cupressaceae	B&S	535	5.28
Bigleaf maple	*Acer macrophyllum* Pursh	BM	Sapindaceae	B&S	545	10.00
Honduran mahogany	*Swietenia macrophylla* King	HM	Meliaceae	B&S, N, T	590	10.06
West Indian mahogany	*Swietenia mahogani* L.	WM	Meliaceae	B&S, N, T	600	9.31
Koa	*Acacia koa* A. Gray	KO	Fabaceae	B&S, T	610	10.37
European maple	*Acer pseudoplatanus* L.	EM	Sapindaceae	B&S	615	9.92
Rock maple	*Acer saccharum* subsp. *nigrum* (F. Michx.) Desmarais	RM2	Sapindaceae	B&S, F	640	11.17
Norway maple	*Acer platanoides* L.	NM	Sapindaceae	B&S	645	10.60
Rock maple	*Acer saccharum* Marshall	RM1	Sapindaceae	B&S, F	705	12.62
East Indian rosewood	*Dalbergia latifolia* Roxb.	ER	Fabaceae	B&S, F	830	11.50
Brazilian rosewood	*Dalbergia nigra* (Vell.) Benth.	BR	Fabaceae	B&S, F	835	13.93
Ceylon ebony	*Diospyros ebenum* J. Koenig. ex Retz	CE	Ebenaceae	Br, F	915	14.07
Gaboon ebony	*Diospyros crassiflora* Hiern	GE	Ebenaceae	Br, F	955	16.89
Macassar ebony	*Diospyros celebica* Bakh.	ME	Ebenaceae	Br, F	1,120	17.3

*Species and family nomenclature follows The Plant List. Uses: B&S=back & sides, Br=bridge, F=fretboard, N=neck, T=top (soundboard). Wood physical properties from the Wood Database except where indicated. ρ = density, E = modulus of elasticity.

families. Of the new tonewoods, the majority (54 of 67) provides material for backs and sides (Table 3). The incorporation of many of these novel species is due to the scarcity and high costs of Brazilian rosewood and Honduran mahogany. Some are selected for their aesthetic appeal as well. Table 3 is not exhaustive, but represents the diversity of newer tonewoods. Nearly all of the common arborescent *Dalbergia* species are utilized including Brazilian kingwood, Cambodian rosewood, Guatemalan rosewood, tulipwood, granadillo, Madagascar rosewood, Honduran rosewood, and Amazonian rosewood. The only source of genuine mahogany is the genus *Swietenia*. The number of recognized species varies between three and five but only *S. macrophylla* and *S. mahogani* produce commercial timber. Mahogany substitutes include other Meliaceae species, such as rose "mahogany," sapele, African "mahogany," and Australian red cedar. New soundboard species include alerce, coastal redwood,

Fig. 3.. Bending rosewood guitar sides, Hill Picket Studio Avoca, County Wicklow, Ireland. Image courtesy of Ariane Factor.

Port Orford cedar, and Alaskan yellow cedar, all members of Cupressaceae.

Which Wood Where?

The mechanical properties of traditional woods, notably ρ and *E*, accurately predict which wood is used for each major part of the guitar (Figure 4). Species utilized for tops have significantly lower mean ρ (478 kg/m^3) than those used for other parts except necks (Table 4). Though the mean ρ of traditional neck woods (553 kg/m^3) is about 16% greater than that of top woods, the differences are not significant, owing to the low sample size for the former. Wood for bridges and fretboards has the highest mean ρ (931 kg/m^3). Mean *E* ranged from 9.8 to 10.3 GPa for top, neck, and back and side woods but differences among the means were not significant. As with ρ, bridge and fretboard woods had a significantly higher *E* (14.8 GPa). Mediterranean cypress is the only species that does not readily fit the model. It is used mostly for backs and sides of flamenco guitars.

Among the new tone woods, the pattern is similar (Figure 5) except that new top woods had a significantly lower mean *E* (10.1 GPa) than wood employed for backs and sides (13.1 GPa) and bridges and fretboards (14.8 GPa). Comparing traditional to new tonewoods, the only significant differences were the mean density (635 vs. 763 kg/m^3) and mean modulus of elasticity (10.3 vs. 13.1 GPa) of back and side woods.

The Value of Wood

Many factors influence the value of vintage instruments, including its wood and its age. Two highly prized woods are Brazilian rosewood and Adirondack spruce. The mean price of Brazilian rosewood guitar blanks ($1,000) was more than eight times the mean value of East Indian rosewood ($115). Similarly, Adirondack spruce blanks ($149) were nearly three times the price of Sitka spruce ($52.60) (Table 5).

Analysis of the price of Martin D–28 guitars is illustrative (Figure 6). After 1969, Martin substituted East Indian for Brazilian rosewood. The 1934–1945 instruments sold for a mean value of $49,469, nearly four times more than post–war (and pre–1970) instruments. All were constructed from Brazilian rosewood. The higher price of the pre–war instruments is due, in part, to age and design changes implemented in 1946 (including the switch from Adirondack to Sitka spruce). Guitars made after 1969 command only 30% of the mean of those sold in the first post–war period. The difference between 1969 (mean = $7,012) and 1970 (mean = $1,804) is particularly sharp, reflecting the lower appeal of East Indian rosewood. The effect of age is seen also in comparing Brazilian rosewood instruments of the same design. The

TABLE 3. NEW WOOD SPECIES USED IN GUITARS, ARRANGED BY INCREASING DENSITY. SPECIES AND FAMILY NOMENCLATURE FOLLOWS THE PLANT LIST.*

Common Name	Species	Family	Uses	ρ (kg/m^3)	*E* (GPa)
Alerce	*Fitzroya cupressoides* (Molina) I.M. Johnst.[1]	Cupressaceae	T	380	**8.8**
Coastal redwood	*Sequoia sempervirens* (D. Don) Endl.	Cupressaceae	T	415	8.4
Black spruce	*Picea mariana* (Mill.) Britton, Sterns & Poggenb.	Pinaceae	T	450	10.5
Port Orford cedar	*Chamaecyparis lawsoniana* (A. Murray bis) Parl.	Cupressaceae	T	465	11.3
Sapele	*Entandrophragma congoense* (Pierre ex De Wild.) A. Chev[2]	Meliaceae	B&S, T	474	**9.0**
Australian red cedar	*Toona ciliata* M. Roem.	Meliaceae	B&S, N, T	485	9.2
Alaskan yellow cedar	*Cupressus nootkatensis D.* D. Don)	Cupressaceae	T	495	9.8
Monterey cypress	*Cupressus macrocarpa* Hartw.	Cupressaceae	B&S	515	7.8
Sycamore	*Platanus occidentalis* L.	Platanaceae	B&S	545	9.8
Black limba	*Terminalia superba* Engl. & Diels	Combretaceae	B&S	555	10.5
Black cherry	*Prunus serotina* Ehrh.	Rosaceae	B&S	560	10.3
Freijó	*Cordia goeldiana* Huber	Boraginaceae	B&S	565	12.9
Muninga	*Pterocarpus angolensis* DC.	Fabaceae	B&S	605	8.7
Yellow siris	*Albizia xanthoxylon* C. White & Francis	Fabaceae	B&S	610	**10.9**
Black walnut	*Juglans nigra* L.	Juglandaceae	B&S	610	11.6
Tasmanian sassafras	*Atherosperma moschatum* Labill.	Atherospermataceae	B&S	620	13.0
Nato	*Palaquium luzoniense (Fern.–Vill.) S. Vidal*	Sapotaceae	B&S	620	13.4
Sipo	*Entandrophragma utile* (Dawe & Sprague) Sprague	Meliaceae	B&S, T	635	11.7
Oregon myrtle	*Umbellularia californica* (Hook. & Arn.) Nutt.	Lauraceae	B&S	635	8.5
Australian blackwood	*Acacia melanoxylon* R. Br.	Fabaceae	B&S	640	14.8
Bubinga	*Didelotia africana* Baill.[3]	Fabaceae	B&S	640	13.9
Streaked ebony	*Diospyros pilosanthera* Blanco[2]	Ebenaceae	F	**640**	**11.3**
Texas ebony	*Diospyros texana* Scheele[4]	Ebenaceae	F	**640**	**11.3**
Claro walnut	*Juglans hindsii* Jeps. ex R.E. Sm	Juglandaceae	B&S	640	**11.3**
European walnut	*Juglans regia* L.	Juglandaceae	B&S	640	10.8
African mahogany	*Khaya ivorensis* A. Chev.	Meliaceae	B&S, T	640	10.6
Balkan maple	*Acer heldreichii* Orph. ex Boiss.[5]	Sapindaceae	B&S	646	**11.4**
Narra	*Pterocarpus indicus* Willd.	Fabaceae	B&S	655	11.9
Imbuia	*Ocotea porosa* (Nees & Mart.) Barroso	Lauraceae	B&S	660	9.6
New Guinea walnut	*Dracontomelon dao* (Blanco) Merr. & Rolfe	Anacardiaceae	B&S	670	12.1
Sapele	*Entandrophragma cylindricum* (Sprague) Sprague	Meliaceae	B&S, T	670	12.0
Guatemalan rosewood	*Dalbergia cubilquitzensis* (Donn. Sm.) Pittier	Fabaceae	B&S	680	7.7
African blackwood	*Diospyros melanoxylon* Roxb.[2]	Ebenaceae	F	**680**	**11.9**

(Continued)

TABLE 3. (CONTINUED).

Common Name	Species	Family	Uses	ρ (kg/m³)	*E* (GPa)
Victoria ash	*Eucalyptus regnans* F. Muell.	Myrtaceae	B&S	680	14.0
Makore	*Tieghemella heckelii* (A. Chev) Pierre ex Dubard	Sapotaceae	B&S	685	10.7
Field maple	*Acer campestre* L.	Sapindaceae	B&S	690	11.8
Macassar ebony	*Diospyros discocalyx* Merr.[2]	Ebenaceae	F	**710**	**12.3**
African ebony	*Diospyros mespiliformis* Hochst. ex A.DC.[1]	Ebenaceae	Br, F	**710**	**12.3**
Rose mahogany	*Dysoxylum fraserianum* (A.Juss.) Benth[6]	Meliaceae	B&S	720	**12.4**
African paduak	*Pterocarpus soyauxii* Taub.	Fabaceae	B&S	745	11.7
Black bark	*Diospyros abyssinica* (Hiern) F. White[7]	Ebenaceae	F	790	10.8
Zircote	*Cordia dodecandra* DC.	Boraginaceae	B&S	805	10.9
Zebrawood	*Microberlinia brazzavillensis* A. Chev.	Fabaceae	B&S	805	16.4
Malabar ebony	*Diospyros malabarica* (Desr.) Kostel.[2]	Ebenaceae	F	825	**13.8**
Ovangkol	*Guibourtia ehie* (A. Chev.) J. Léonard	Fabaceae	B&S	825	18.6
Granadillo	*Platymiscium yucatanum* Standl.[2]	Fabaceae	B&S	**830**	**13.9**
Jarrah	*Eucalyptus marginata* Donn ex Sm.	Myrtaceae	B&S	835	14.7
Bocote	*Cordia elaeagnoides* A.DC.	Boraginaceae	B&S	855	12.2
Granadillo	*Dalbergia granadillo* Pittier	Fabaceae	B&S	860	**14.3**
Morado	*Machaerium scleroxylon* Tul.	Fabaceae	B&S	865	10.9
Wenge	*Millettia laurentii* De Wild.	Fabaceae	B&S	870	17.6
Panga panga	*Millettia stuhlmannii* Taub.	Fabaceae	B&S	870	15.7
Kamagong	*Diospyros discolor* Willd.	Ebenaceae	Br, F	**880**	**14.6**
Bubinga	*Guibourtia tessmannii* (Harms) J. Leonard	Fabaceae	B&S	895	15.1
Gonçalo alves	*Astronium graveolens* Jacq.	Anacardiaceae	B&S	905	16.6
East Indian ebony	*Diospyros ebenum* J. Koenig ex Retz.	Ebenaceae	B&S, Br, F	915	14.1
Bubinga	*Guibourtia demeusei* (Harms) J. Leonard[3]	Fabaceae	B&S	920	20.2
Madagascar rosewood	*Dalbergia madagascariensis* Vatke	Fabaceae	B&S	935	12.0
Hormigo	*Platymiscium pinnatum* (Jacq.) Dugand	Fabaceae	B&S	950	19.6
Texas ebony	*Ebenopsis ebano* (Berland.) Barneby & J.W. Grimes	Ebenaceae	F	965	16.5
Tulipwood	*Dalbergia decipularis* Rizzini & A. Mattos	Fabaceae	B&S	970	**15.8**
Tulipwood	*Dalbergia frutescens* (Vell.) Britton	Fabaceae	B&S	970	**15.8**
Gonçalo alves	*Astronium fraxinifolium* Schott[8]	Anacardiaceae	B&S	993	**16.1**
Honduran rosewood	*Dalbergia stevensonii* Standl.	Fabaceae	B&SF	1,025	**16.6**
Cambodian rosewood	*Dalbergia cochinchinensis* Pierre	Fabaceae	B&S	1,035	16.4
Muns ebony	*Diospyros mun* A. Chev. ex Lecomte	Ebenaceae	B&S, F	1,065	**17.1**
Amazonian rosewood	*Dalbergia spruceana* (Benth.) Benth.	Fabaceae	B&S	1,085	**17.4**

(Continued)

TABLE 3. (CONTINUED).

Common Name	Species	Family	Uses	ρ (kg/m^3)	*E* (GPa)
Cocobolo	*Dalbergia retusa* Hemsl.	Fabaceae	B&S, F, N	1,095	18.7
Katalox	*Swartzia cubensis* (Britton & Wilson) Standl.	Fabaceae	Br, F	1,150	25.6
Brazilian kingwood	*Dalbergia cearensis* Ducke	Fabaceae	B&S	1,200	**19.0**

[*] Uses: B&S=back & sides, Br=bridge, F=fretboard, N=neck, T=top (soundboard). Wood physical properties from the Wood Database except where indicated (underscored values are from other sources, bold values are estimates calculated from wood density). ρ = density, *E* = modulus of elasticity.
[1] Wiemann and Green (2007); [2] Chave et al. (2009), [3] Yazici (2015), [4] Miles and Smith (2009), [5] Anonymous (2015a), [6] Lake (2015), [7] PlantUse contributors (2015), [8] Anonymous (2015b).

1946–1958 Martins sold for a mean of $12,584, significantly higher than the 1959–1969 instruments, which commanded a mean of $6,579 (Table 6).

Discussion

TRADITIONAL WOODS

Assignment of binomials to musical woods is possible, but it must be done prudently. For example, Cowling (1983) lists spruce or pine as the preferred woods for cello soundboards. The common use of pine as a tonewood is doubtful. The confusion likely arises from the Linnaean name *Pinus abies*, a synonym of *Picea abies*. Spruce is the preferred choice for chordophone soundboards and, until recently, guitar soundboards (tops) were mostly Adirondack, European, or Sitka spruce. Mahogany and koa were less often employed; western red cedar was sometimes selected for classical guitars. European spruce (*P. abies*) also was the species of choice for the renowned Cremonese violins (Stoel and Borman 2008).

The most highly prized wood for guitars is Brazilian rosewood, the species of choice for backs and sides (Gerken et al. 2003). Considered the holy grail of tonewoods, it is noted for its resonance and overtones. By the early 1970s, Brazilian rosewood was largely replaced by East Indian Rosewood. Brazilian rosewood was added to CITES Appendix I in 1992 (Thomas 2008). Mahogany, once considered second rate, is valued today for its warm and “woody” tone. West Indian mahogany, however, is not commercially available due to overharvesting (Louppe et al. 2008). Maple produces “bright” tones, favored in jazz instruments. Koa first became popular in Hawaiian–style guitars in the early 1900s. It ranks between rosewood and mahogany in its tonal qualities (Sandberg 2000).

The traditional choice for guitar necks was mahogany or “cedar,” though rosewood and maple also are used. The cedar in question is Spanish cedar, a hardwood. The fretboard requires a hard and durable wood that can withstand string and finger contact. Rosewood and, especially, Gaboon ebony are the top choices. Ebony fretboards reportedly yield a brighter, crisper tone than other materials (Gerken et al. 2003).

NEW WOODS

Owing to the scarcity (and high costs) of many traditional species, alternative guitar

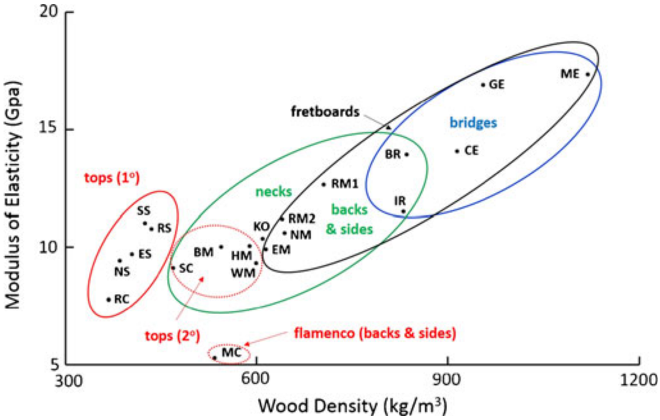

Fig. 4. Modulus of elasticity vs. density of traditional guitar woods. Species acronyms and wood data are found in Table 2. 1° top woods are those most commonly employed., 2° top woods are of lesser importance.

woods have seen increased use in the past decade. Some of the new species are listed in Table 3. East Indian rosewood remains the most widely used of the *Dalbergia* species, but several (e.g., cocobolo) are thought to have qualities closer to Brazilian rosewood. Not surprisingly, the majority of new woods are for backs and sides as the availability of rosewood and mahogany declines.

Madagascar prohibited the cutting and export of *Dalbergia* spp. (rosewoods) and *Diospyros* spp. in March 2010 (CITES 2013). Almost all of the newly employed rosewoods are listed in CITES Appendix II (CITES 2015), as instrument makers face the Sisyphean task of finding alternative tonewoods. Most new back and side woods are marketed as substitutes for rosewood or mahogany.

Wood–mania?

Why is there such a concern for tonewoods? A perusal of folk instruments reveals that virtually any durable plant material may be employed. Resonators of the banjo's African ancestors are made from gourds, those of the Andean charango from armadillo carapaces. Cheap instruments are constructed from laminated material because of its lower cost and greater stability. Bob Taylor of Taylor Guitars made 25 respectable instruments out of scrap lumber salvaged from shipping pallets (Simmons 2005). A U.S. company markets six–string guitars with bodies made from oil cans. Electric bodies can be made from acrylic, aluminum, Bakelite®, and Lucite® (and other plastics).

Table 4. Comparison of the density (ρ) and modulus of elasticity (E) of traditional and new tonewoods.*

	Traditional Woods		New Woods	
Part	ρ (kg/m^3)	E (GPa)	ρ (kg/m^3)	E (GPa)
T	478 ± 96.9^{a}	9.8 ± 0.99^{a}	511 ± 95.8^{a}	10.1 ± 1.21^{a}
N	$553 \pm 59.1^{a,b}$	9.5 ± 0.41^{a}	790 ± 305.0^{b}	$14.0 \pm 4.74^{a,b}$
B&S	$635 \pm 105.1^{b,A}$	$10.3 \pm 2.01^{a,D}$	$762.8 \pm 175.6^{b,B}$	$13.1 \pm 3.05^{b,E}$
Br & F	931 ± 96.6^{c}	14.8 ± 1.96^{b}	864 ± 163.9^{b}	14.8 ± 3.71^{b}

* For Part: T=tops, N=neck, B&S=backs & sides, Br=bridge, F=fretboard. Means within columns that share a lower case superscript are not significantly different (unpaired t–test at a Bonferroni–corrected α = 0.05/# post–hoc comparisons). The only significant difference in wood properties across columns (i.e., traditional versus new tone woods) were ρ and E of back and side woods.

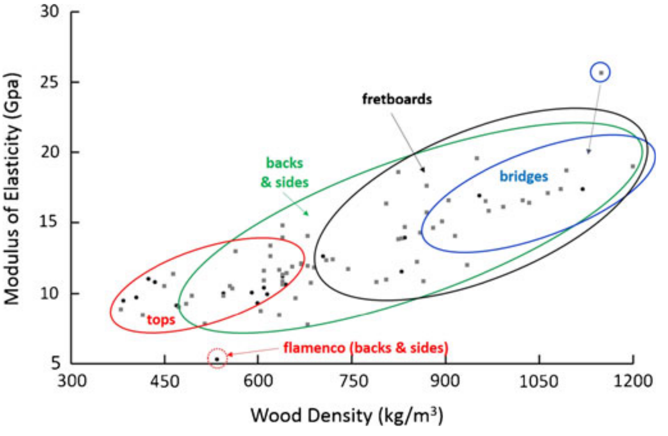

Fig. 5. Modulus of elasticity vs. density of new (gray squares) and traditional (black circles) guitar woods. Wood data are found in Tables 2 and 3.

Nonetheless, there is a cost to innovative materials—tone. Quality chordophones are still constructed from high grade solid woods.

What qualities of timber species make them suitable for use in musical instruments? Tree size is an important consideration. Tonewood species must have a clear, straight bole of sufficient diameter to yield heartwood of the proper width. Fretboard and bridges can be derived from much narrower pieces. Second, abundance and rarity must be considered. Many trees occur in such small populations that their harvest is neither economically or biologically sustainable (Bennett 2002). This is especially true in the tropics, a correlate of diversity is individual rarity. The third factor is wood quality. This is a complex factor determined by both objective measures (e.g., mechanical characteristic) and more subjective measures (e.g., color, grain, porosity, and figure). Durability, workability, bendability, and glueability are important attributes (Figure 3). Chemistry may play a role as well; some species have toxic compounds that produce irritating sawdust when milled or worked. Post–harvesting treatment of trees also determines the quality of the ultimate product including sawing (quarter–, rift–, or flat–sawn), drying, and storage.

Acoustical Properties and Wood Selection

The primary acoustical properties that determine the choice of wood in musical instruments are the speed of sound in the material, characteristic impedance, sound radiation coefficient, and the loss coefficient (Wegst 2006). These are correlated with ρ and E. Wegst plotted the modulus of elasticity against wood density to show what woods were used for various musical instruments. This methodology is also useful at a finer scale. Tops, bridges, and backs and sides form more or less distinct clusters (Figures 4 and 5). Top woods are the least dense and, not surprisingly, have the lowest E values. Bridges are made from the densest wood with back and side woods intermediate. Material for necks clusters within the back and sides group, probably because necks are often reinforced or laminated. This allows woods with a relatively low E to withstand the forces applied by the guitars' strings. Clearly, two physical properties, of ρ and E, can be used to predict a wood's utility.

Out of the Woods? or Out of Wood?

Is there a tonewood crisis? Many traditional tonewoods are either unavailable or prohibitively expensive (e.g., Cunningham 2015 and Thomas 2008). Of the three ebony species listed in Table 2, *Diospyros crassiflora* is endangered, *D. celebica* is vulnerable, and *D. ebenum* lacks sufficient data to accurately assess (IUCN 2015). Some alternative woods also are becoming scarce. Yet, the estimated number of tree species is as high as 100,000. Hubbell et al. (2008) predict

Table 5. Mean price of guitar blank components (top wood grades only).*

	Back & Sides		Tops		Necks			Fretboards	
	Brazilian Rosewood	Indian Rosewood	Adirondack Spruce	Sitka Spruce	Honduran Mahogany	Spanish Cedar	Indian Rosewood	Ebony (spp.)	Indian Rosewood
Mean	$999.8[a]	$115.0[b]	$149.1[a]	$52.6[b]	$76.8[a]	$53.3[a]	$44.2[a]	$29.4[a]	$16.7[a]
SD	$393.9	$44.6	$51.2	$12.1	$28.8	$23.2	$1.4	$8.5	$3.1
N	20	20	20	20	6	7	3	9	4

*Means for each part that share a lowercase superscript letter are not significantly different (unpaired t–test at a Bonferroni–corrected α = 0.05/# post–hoc comparisons).

that the Brazilian Amazon Basin is home to 11,210 tree species. Slik et al. (2015) estimate that the minimum number of tropical forest tree species is between 40,000 and 53,000. Why then are there so few commercial timbers? Mark et al. (2014) list 1,575 trees species that are internationally traded for timber. Bennett (pers. obs.) puts the number of timber species at 3,500. Both are probably low, due to the complexity of the task, taxonomic uncertainty, and lack of scientific review. Perhaps 500 species have been used for guitars, discounting species that have limited local use.

Until recently the instrument wood palate was limited. About 20 species were employed in the construction of most guitars, violins, cellos, mandolins, and other chordophones. Inadequate size, workability, and availability eliminate many species from consideration. Teak would be an intriguing guitar wood, due to its weather resistance, yet it does not glue well due to its oily nature. Paraná pine is a potential top wood but is prone to splitting. African blackwood is difficult to bend. Some of the light or streaked ebonies are shunned because of their appearance; luthiers and players prefer solid black fretboards. Even those species that make the initial cut face an ultimate criterion—tone. Yet that leaves 20 traditional tonewoods, 100 or so new ones, and more than 350 that have potential for wider applications. The approach pioneered by Wegst (2006) and expanded here can guide luthiers in wood selection.

Value of Wood

The value of fine music woods is significant. African blackwood, esteemed for bagpipe pipes and clarinet and oboe bodies, is valued at USD $ 14,000–20,000 per cubic meter (Cunningham 2015). In 2010, Madagascar rosewood, now restricted, sold for more than $5,000 per cubic meter (Braun 2010). In comparison, southern yellow pine sells for ca. $200 per cubic meter.

The combination of prized wood, fine craftsmanship, age, and rarity create astronomical prices for some instruments. The Lady Blunt Stradivarius violin sold for $15.9 million in 2011. Pernambuco violin bows commonly command in excess of $10,000. The price of pre–war Martin D–28

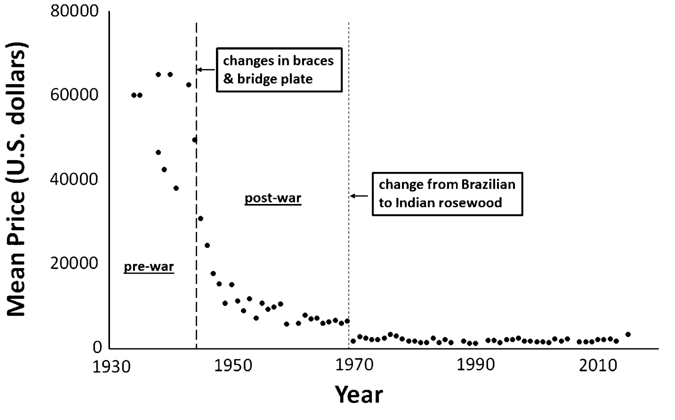

Fig. 6. Value of pre– and post–war Martin D–28 guitars

guitars was as high as $75,000 (Figure 6) with an estimated value of some 1930s guitars as high as $170,000. Comparison of the famed violins, crafted by the Cremona master Andrea Amati and his pupils Antonio Stradivari and Giuseppe Guarneri, to newer instruments is inherently biased. The tone of the ancient Italian instruments has developed over 250 years or more. Most luthiers and players believe that solid wood instruments, especially those that are played frequently, improve with time. Wood instruments generally sound better as they age, which is often correlated with how much they are applied. As one author notes, "no new guitar can ever sound like an old guitar until it is one" (Sandberg 2000). Conclusive evidence on the effects of age is lacking, but may include changes in wood chemistry, microstructure, and water content over time.

TABLE 6. PRICE (USD) OF MARTIN D–28 (MEAN ± STANDARD DEVIATION) BY CHRONOLOGICAL PERIODS.*

Period	Years	Price
Pre–war (BR)	1934–1945	$49,469 ± 11624[a]
Post–war (BR) $_1$	1946–1958	$12,584 ± 4426[b]
Post–war (BR)$_2$	1959–1969	$6,579 ± 628[c]
Post–war (IR)	1970–2015	$2,003 ± 506[d]

a:b P <0.0001; b:c P=0.0023; c:d P <0.0001

*BR=Brazilian rosewood, IR=East Indian rosewood. Superscript letters indicate significant differences among means (unpaired t–test and Bonferonni–corrected α of 0.05/3).

Conclusions

Spruce for tops; rosewood, mahogany, or maple for backs and sides; mahogany or rosewood for necks and bridges; and ebony for fretboards have been the predominant species used in guitar lutherie until present. These species are employed in the other chordophones as well. Instrument makers are notoriously unreliable sources of taxonomic names and no doubt some species have been misidentified or misreported. This is especially true of the newer tonewoods. Perhaps 500 species have been used in guitar making and some are becoming more mainstream (e.g., cocolobo, sapele). Others will be used as wood stocks, especially if old–growth timber continues to diminish. Two commonly recorded mechanical properties of wood, density and modulus of elasticity, can be used to determine what species of wood is suitable for what part of a guitar. These principals are also applicable to wood selection for other chordophones.

The search for alternative woods should proceed systematically and with rigor, not in the current haphazard manner. This requires accurate botanical identification, precise nomenclature and consideration of within–species variation owing to age and provenance differences. Bennett and Balick (2008) assert that voucher specimens are the *sine qua non* of medicinal plant research. This is equally true of lutherie. To be scientific, luthiers must first unambiguously establish the botanical identity of new woods. This requires that botanical vouchers be deposited in herbaria and wood samples in xylaria. Wood samples alone are insufficient since many cannot be identified to species or even genus using anatomical techniques (Center for Wood Anatomy Research 2016; Wheeler and Baas 1998). Improved molecular techniques may increase the accuracy of identification, but at present they remain inadequate (e.g., Tang et al. 2011). Experimentation with new woods requires minimization of the multitude of variables that affect tone. Instrument makers should construct, in replicate, identical models that vary only in the wood composition of one part. Blinded trials to measure the performance of experimental models could then objectively determine the tonal value of alternative materials.

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