BRILL

IAWA Journal 34 (1), 2013: 34–48

EXAMINATION OF WOOD PROPERTIES OF PLANTATION-GROWN PERNAMBUCO (*CAESALPINIA ECHINATA*)

Laurence R. Schimleck[1*], **Jorge Luis Monteiro de Matos**[2], **Graciela Inez Bolzon Muniz**[2], **Charles Espey**[3], **Adam Taylor**[4] and **David Harper**[4]

[1]Warnell School of Forestry and Natural Resources, The University of Georgia, Athens, GA 30602, U.S.A.
[2]Department of Forestry and Wood Sciences, Federal University of Paraná, Curitiba, PR, Brazil
[3]Charles Espey Ltd., Port Townsend, WA, U.S.A.
[4]Department of Forestry, Wildlife and Fisheries, University of Tennessee, Knoxville, TN, U.S.A.
*Corresponding author; e-mail: laurence.schimleck@oregonstate.edu

ABSTRACT

Caesalpinia echinata (pernambuco or pau-brasil), is recognized as the premier wood for manufacturing stringed instrument bows. Owing to limited supplies and concerns regarding species survival, interest exists in establishing pernambuco plantations to provide future bow-quality wood. For native forest- and plantation-grown woods we examined several wood properties considered important in determining bow quality including basic density, modulus of elasticity (MOE), modulus of rupture (MOR) measured using static bending samples, air-dry density, microfibril angle (MFA), and stiffness using SilviScan. Color, extractives content and loss tangent (tan δ) were measured for a subsample of the static bending samples. Finally, the samples were also ranked based on their potential for manufacturing high-quality bows (0 = poor, 1 = good and 2 = excellent) by an experienced bow maker. No evidence of differences between means for density, MOE and MOR for native, and 25- and 30-year-old plantation-grown pernambuco was observed; however, when sorted based on quality, the excellent group had higher density, MOE and MOR. MFA and tan δ were low, especially for native forest samples. Extractive contents were low for plantation samples; 5.7% and 12.7% respectively for the 25- and 30-year-old samples, compared to the native forest samples (set 1 = 23%, set 2 = 22.5 %) and few samples had heartwood. Overall, plantation-grown samples provided promising results in terms of their quality.

Keywords: *Caesalpinia echinata*, density, extractives, loss tangent, microfibril angle, modulus of elasticity, modulus of rupture, pernambuco, SilviScan.

INTRODUCTION

Caesalpinia echinata (pernambuco or pau-brasil) is a legume species that is found in the Atlantic forest of Brazil. Once harvested for the manufacture of dye, it is now recognized as the premier wood for making stringed instrument bows (Brown 1978; Rymer 2004). Utilization of the species as a dyewood commenced in the early 1500's

Published by Koninklijke Brill NV, Leiden
DOI 10.1163/22941932-00000004

and as early as 1605 efforts to regulate harvest of the species were instigated, partly to control supply to Europe but also because of concerns over wasteful cutting (Dean 1995). Despite concerns over the availability of trees, pernambuco remained a source of dye for over 300 years. In the mid 1800's the development of synthetic dyes from coal tar saw an end to the trade (Rymer 2004); however, pernambuco continued to be a source of important forest products. The wood has several desirable properties: it is hard and heavy but easy to work, gives a high natural polish, and is extremely durable and has long been used for fence posts, railway ties and flooring (Brown 1978). Owing to its long history of utilization, and the loss of much of the Atlantic forest, of which less than 7% of the original 1.35 million km^2 is estimated to remain (Morell 2004), and concerns regarding the long-term survival of the species, it has received a CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) Appendix II listing (http://www.cites.org). Species listed in this appendix are not necessarily now threatened with extinction, but may become so unless trade is closely controlled. The wood anatomy of *Caesalpina echinata* has been described and illustrated many times, recently in Gasson *et al.*'s (2011) atlas of CITES-Listed tree species.

The literature indicates that several wood properties are important in determining the suitability of pernambuco for bow manufacture (Matsunaga *et al.* 1996; Angyalossy *et al.* 2005; Alves *et al.* 2008; Schimleck *et al.* 2009). The wood must be of very high density (mass divided by volume at a given moisture content) with Alves *et al.* (2008) reporting that sticks with densities greater than 1,000 kg/m^3 are suitable for manufacturing high-quality bows. Schimleck *et al.* (2009) suggested there is an upper density limit after observing that the two highest density sticks in their study (both had densities of 1,197 kg/m^3) were evaluated as being good, but not excellent, quality. Alves *et al.* (2008) also noted that very high density sticks should be avoided as bows made from very high density wood are excessively thin (to meet the desired weight requirements), and as a result are more susceptible to breakage and less dimensionally stable.

High modulus of elasticity (MOE), a material property that contributes to the stiffness of a bow, is also necessary (Wegst 2006). Alves *et al.* (2008) reported that the highest quality woods they examined had an average MOE of 20.2 GPa, while Schimleck *et al.* (2009) observed an average of 25.2 GPa (estimated by SilviScan) for the best woods they tested. In addition to density, MOE is also influenced by microfibril angle (MFA) (Cave & Walker 1994; Megraw *et al.* 1999; Evans & Ilic 2001), the angle that the helical windings of cellulose chains within the fiber wall make with the fiber axis. Schimleck *et al.* (2009) examined the influence of MFA on bow quality and found that it had little influence; however, the MFA range of the samples they examined was very narrow (6.1 to 14.6 deg.).

Consideration of properties that will influence the physical durability of a bow is also important (Alves *et al.* 2008) hence the modulus of rupture (MOR) should be evaluated. Alves *et al.* (2008) observed that MOR varied greatly among the samples they examined, ranging from 216.0 MPa (highest quality samples) to 135.8 MPa (poorest quality samples).

While density, MOE and MOR are among the most important factors determining bow performance there are other properties that are also important to consider. One that is often reported in the literature is the loss tangent (tan δ), a measure of the degree to which a material dissipates vibrational energy by internal friction (Wegst 2006). For a perfectly elastic material, δ, the phase angle between the elastic and viscous material response, is 0, whereas a perfectly viscous material has a δ of π/2. Matsunaga *et al.* (1996) showed that the tan δ of pernambuco is exceptionally low (the average for the samples they examined was 4.12×10^{-3}); compared to other species considered suitable for bow manufacture (for example, the average tan δ for the *Manikara bidentata* [massaranduba] samples they examined was 10.04). The influence that tan δ has on quality is unclear, but a low value indicates that pernambuco dissipates little mechanical energy (Wegst 2006). Wegst (2006) noted that the mechanism of dissipation is complex and is dependent upon the temperature and moisture content within a sample, in addition to the type and amount of extractives present. Matsunaga *et al.* (1996) suggested that the low tan δ of pernambuco was related to its extractives content and later demonstrated that the impregnation of *Picea sitchensis* Carr. (Sitka spruce) wood with pernambuco water soluble extractives lowered its tan δ (Matsunaga *et al.* 2000). The extractives content of pernambuco has been reported by several authors and average values range from approximately 20 to 25 % (Matsunaga *et al.* 1996; Alves *et al.* 2008; Schimleck *et al.* 2009). Within this range, both Alves *et al.* (2008) and Schimleck *et al.* (2009) observed that extractive content was inversely related to quality; the wood with the greatest suitability to produce high-quality bows had the lowest average extractives contents (21–22 %), while those of low potential averaged around 25 %.

With uncertainty regarding the future availability of pernambuco for bow manufacture, interest has grown in using plantation-grown pernambuco as an alternative. Considering the specific requirements of wood used to manufacture high-quality bows, *i.e.* defect free wood having high density, MOE, MOR, low tan δ and extractives in the range of 20–25 %, an examination of the properties of the wood from plantation-grown trees and a comparison with wood from native forest trees is important. Plantation trees are now approaching a size that makes wood property evaluation possible and the objectives of this study were:

- to report the wood properties of plantation-grown pernambuco for trees aged 25 and 30 years;
- to compare the wood properties of the plantation-grown trees with pernambuco obtained from native forest trees; and
- to evaluate how measured wood properties correlate with the quality of the wood for bow production.

MATERIALS AND METHODS

Sample origin

Plantation-grown pernambuco — The samples were obtained from 5 trees aged 25 years and 5 trees aged 30 years from a plantation located in Guaraná district, within the Aracruz metropolitan area, in the state of Espírito Santo, Brazil. The plantation area has the coordinates 19° 54' 21.6" S and 40°18' 2.3" W, and is 50 m above sea level. The average annual temperature is 23 °C with an average annual rainfall of 1,400 mm/yr. For the 25-year-old trees, average height and diameter at breast height (dbh) were 10.7 m and 143 mm respectively, while for the 30-year-old trees, average height was 11.3 m and average dbh was 178 mm.

The initial spacing between trees was 2.0 × 2.0 m and the pernambuco trees were companion planted with eucalyptus species. Two logs 1.20 m in length were obtained from each tree for the production of short clear samples. The first log was from the base of the tree, while the second log was taken above breast height. A bark-to-bark slab including the pith was cut from each log for the preparation of clear wood samples for static bending testing. The reader is referred to Santos Marques (2009) for more information on the plantation-grown pernambuco.

Native forest pernambuco set 1 — Native forest pernambuco from the state of Bahia was donated by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) to the Federal University of Espírito Santo. The wood consisted of quartersawn boards of dimensions 30 × 50 × 800 mm without sapwood. The plantation samples and native wood had not been preselected by a bow maker (as with set 2, see below) but later were assigned, based on their suitability for making a high-quality bow, to one of three subjective quality categories by C. Espey, a widely known and highly respected bow maker with more than 30 years experience in the manufacture and restoration of stringed instrument bows. The categories were:

- Poor (class 0) – unsuitable wood for high-quality bows due to its low strength, low density and interlocked grain;
- Good (class 1) – low but adequate density with straight grain, suitable for better grade bows; and
- Excellent (class 2) – strong, high density wood with straight grain, suitable for the manufacture of high-quality bows.

Native forest pernambuco set 2 — Thirty pernambuco sticks from different locations and of varying quality for making high-quality bows were assembled by C. Espey. The sticks were assigned to one of the three quality categories: poor (3 samples), good (17 samples), and excellent (10 samples). Sticks were obtained from three Brazilian states: Bahia (9 samples), Espírito Santo (11 samples) and Pernambuco (3 samples). For seven sticks the state of origin was unknown. From the end of each stick a sample was cut for wood property analysis. The dimensions of the samples depended on the size of the stick averaging 11.5 mm tangentially by 11.5 mm radially by 6.0 mm longitudinally. For more information regarding the samples see Schimleck *et al*. (2009).

Wood property analysis

Static bending properties — From the slabs cut from the plantation-grown trees and boards cut from the native forest set 1 *Caesalpinia echinata* clear wood samples with dimensions 20 × 20 × 300 mm were prepared for the determination of modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending tests. The samples were conditioned to an equilibrium moisture content of about 12% (temperature = 20 ± 2 °C and relative humidity = 65 ± 3%) and then tested using an Emic Universal Testing Machine (EMIC Equipamentos e Sistemas de Ensaio LTDA, São José dos

Pinhais, PR, Brasil) according to the COPANT (1973) standard – Maderas – Método de ensayo de flexión estática ("Timber. Method for testing static flexure"). Each sample was loaded to failure and the slope of the stress strain curve between 10% and 50% of the maximum load determined, at these points the load and deformation of the sample was recorded and used to calculate MOE.

Basic density of the samples was determined using the dimensions (measured using calibrated Mitutoyo calipers, in 0.01 mm increments) and weight of each piece at 12% moisture content. For the purposes of this research a subset of 25 samples that covered the range of measured density, MOE and MOR were selected (native forest = 10 samples, plantation-grown samples 25 years old = 7 samples and plantation-grown samples 30 years old = 8 samples) and sent to FPInnovations (Vancouver, Canada) for SilviScan analysis and for loss tangent (tan δ) and extractives analysis at the University of Tennessee.

SilviScan samples — A block measuring 20 × 20 × 20 mm was cut from the end of each sample. The blocks were sent to FPInnovations Paprican (Vancouver, Canada) where radial strips (2 mm tangentially, 7 mm longitudinally, 20 mm radially) were cut using a twin blade saw. The radial strips were then analyzed by FPInnovations SilviScan instrument.

The set 2 samples were analyzed as part of an earlier study by Schimleck *et al.* (2009) and had been analyzed on the SilviScan instrument located at CSIRO in Australia.

The following wood properties were measured:

- Air-dry density (kg/m^3) in 25$^{\mu}$ steps using X-ray densitometry;
- MFA (deg.) over 5 mm intervals for the plantation-grown and set 1 samples, and 0.1 mm intervals for the set 2 samples using scanning X-ray diffractometry (Evans 1998, 1999); and
- Wood stiffness (MPa) estimated at the same resolution as MFA by combining X-ray densitometry and X-ray diffraction data (Evans 2006).

The SilviScan measurements were made in a controlled environment of 40% relative humidity and a temperature of 20 °C.

Determination of extractives content — From the samples used for bending properties determination, 25 small pieces of wood were ground using a Cyclotech mill fitted with a 1 mm screen. The ground wood (approximately 2.0 g oven-dried) was weighed and enclosed in heat-sealable polyester filter bags (mesh size 25, ANKOM Technology, Macedon, NY). The bags were extracted according to ASTM D1105-96 (2007) Standard Test Method for Preparation of Extractive-Free Wood, which involves successive extraction steps with toluene/ethanol (2:1), 95% ethanol, and hot water. The extracted samples were oven-dried at 103 °C for 24 hours and re-weighed. Total extractive content of each sample was determined as the mass lost by extraction, expressed as a percentage of the extracted, oven-dry mass. Two extractions were done for each sample. Previous work has shown that the coefficient of variation of the extraction method is approximately 5% (Taylor *et al.* 2006).

Determination of loss tangent (tan δ = E'/E") and Dynamic Young's Modulus (E'/ρ) — Loss tangent (tan δ) of the subset of 25 samples was determined using a Dynamic

Mechanical Analyzer Pyris Diamond DMA (Perkin Elmer Instruments) at the Center for Renewable Carbon at the University of Tennessee (Knoxville, TN). From these samples 2 strips measuring 2 mm tangentially, 10 mm radially and 40 mm longitudinally were cut. Vibrational properties were measured under a single cantilever, using a span length of 20 mm and a temperature range increasing from 10 to 40 °C (6 steps) with 300 s at each temperature. The samples were tested under vibrational frequencies of 1, 10, 20 and 100 Hz. The measurements were made inside a closed chamber. The DMA measures changes in rheological behavior under dynamic conditions such as storage or Dynamic Young's modulus (E'), dynamic loss modulus (E"), and tan δ. For this study, data collected at a vibration frequency of 20 Hz are used.

Color measurements — Wood color was measured directly from the transverse surface of the samples (25 samples reforested and native wood for set 1 and 30 samples wood for set 2) using a Technidyne TB1c colorimeter (Technidyne Corporation, New Albany, IN, USA) with an aperture size of 1 cm^2. A single color measurement was made per sample, using illuminant type C and diffuse geometry, and the color model for L*, a*, b* of the Commission Internationale d'Eclairage (CIE). CIELAB (CIE L*, a*, b*) is a color space that describes all the colors visible to the human eye and was created to serve as a device independent model to be used as a reference. CIELAB color is defined by three coordinates: the lightness of the color (L*), its position between red/magenta and green (a*) and its position between yellow and blue (b*).

Principal Component Analysis (PCA) — PCA was conducted on the measured wood property parameters using Unscrambler software (version 10.1 CAMO Software AS, Oslo, Norway).

RESULTS AND DISCUSSION

Static bending properties

Conventional static bending properties (MOE, MOR) and density were obtained only for the set 1 native and plantation wood samples. Mean values and standard deviations of the properties are shown in Table 1. For each of the properties examined, the native forest samples had the highest individual values but also showed the greatest variability. When averages for the three properties were considered and compared amongst the native and plantation woods, they were quite similar and statistical analysis of the bending strength data indicated that there was no evidence of differences between means for density, MOE and MOR for the native, 25-year and 30-year-old pernambuco samples. Interestingly the 25-year-old plantation-grown pernambuco actually had a higher average density than the native samples (set 1).

Based on rankings of the samples for bow production the bending strength data was split into 3 classes: 0 = poor (15 samples), 1 = good (7 samples), and 2 = excellent (3 samples) (Table 2). The average density of samples in class 2 (1146 kg/m^3) was higher than samples in class 1 (1005 kg/m^3) and class 0 (932 kg/m^3) with the differences in means for each class being statistically significant. The data corroborate the importance of density in selecting pernambuco for the manufacture of high-quality bows. Even

Table 1. Properties of pernambuco samples, plantation-grown 25- and 30-years-old and native forest (set 1 and 2). SS = measured by Silvi-Scan.

		Density kg/m³	MOR MPa	MOE MPa	Density SS kg/m³	MFA SS deg	MOE SS MPa	L*	a*	b*	Extractives %	Tan δ	E'/ρ MPa
	Mean	978	193	19,068	972	8.6	20,793	28.7	5.0	7.4	23.4	0.01785	27,746.0
Native	Max	1,174	273	27,179	1,156	9.8	27,301	36.0	7.5	13.7	33.9	0.02842	39,109.5
set 1	Min	860	114	12,087	840	7.2	14,678	25.3	3.5	3.9	16.3	0.01244	19,646.6
n=10	Std Dev	123	54	5,503	119	0.9	4,722	3.2	1.4	3.3	6.3	0.00578	6,982.0
	CV	13	28	29	12	10.0	23	11.3	27.0	45.3	27.0	32.36	25.2
	Mean	954	175	16,472	935	13.2	16,325	34.8	4.7	12.1	12.7	0.05390	28,087.1
30 Years	Max	1,021	221	20,663	1,019	21.6	24,382	41.6	7.2	13.9	17.5	0.15378	38,151.3
set 1	Min	873	103	12,716	828	6.5	11,996	29.8	1.2	9.3	3.6	0.01072	21,308.1
n = 8	Std Dev	65	43	2,949	70	4.5	3,961	4.3	2.3	1.5	5.7	0.05743	5,612.2
	CV	7	25	18	7	33.7	24	12.5	48.3	12.2	44.7	106.55	20.0
	Mean	1,007	185	19,021	1,015	10.9	21,448	38.8	2.0	12.9	5.7	0.06188	28,098.4
25 Years	Max	1,068	228	22,649	1,098	12.8	24,440	42.2	2.8	15.2	8.0	0.17093	37,701.3
set 1	Min	901	117	14,936	901	9.5	18,462	35.2	0.8	12.0	4.4	0.01191	18,335.2
n=7	Std Dev	72	37	2,774	77	1.0	1,983	2.3	0.8	1.1	1.4	0.06320	6,932.5
	CV	7	20	15	8	9.5	9	6.0	39.9	8.2	24.5	102.13	24.7
	Mean	–	–	–	1,080	8.7	24,428	31.0	10.9	13.1	22.5	–	–
Native	Max	–	–	–	1,197	14.6	31,679	42.9	18.4	29.7	38.5	–	–
set 2	Min	–	–	–	855	6.1	15,401	23.7	3.6	1.1	15.8	–	–
n=30	Std Dev	–	–	–	75	1.8	4,153	4.7	4.0	6.4	4.7	–	–
	CV	–	–	–	7	20.7	17	15.3	36.8	48.4	20.7	–	–

Table 2. Static bending and vibrational properties for Pernambuco wood, ranked according to their potential to make a high quality bow (as assigned by Charles Espey).

		Density kg/m^3	MOR MPa	MOE MPa	20 Hz-E' MPa	20 Hz-E" MPa	Tan δ	E'/ρ MPa
	Mean	932	164	16,341	25,758,391	957,983	0.03714	27,708.9
Poor	Max	1,060	241	22,412	33,615,650	4,021,220	0.13814	33,895.8
class=0	Min	860	103	12,087	17,054,500	212,220	0.01244	18,920.3
n=15	Std Dev	68	37	3,149	4,437,468	1,106,691	0.04081	4,832.1
	CV	7	23	19	17	116	109.87	17.4
	Mean	1,005	201	19,002	28,411,699	1,404,040	0.06070	28,389.6
Good	Max	1,068	228	22,649	39,265,060	3,563,820	0.17093	38,013.3
class=1	Min	890	136	14,124	20,123,380	379,920	0.01072	18,838.9
n=7	Std Dev	56	31	2,638	6,920,404	1,441,072	0.07005	7,070.0
	CV	6	15	14	24	103	115.41	24.9
	Mean	1,146	253	25,824	30,202,257	556,580	0.02031	26,250.0
Excelent	Max	1,174	273	27,179	45,194,180	649,030	0.02842	38,682.5
class=2	Min	1,095	240	24,242	22,574,370	447,060	0.01271	19,459.3
n=3	Std Dev	44	18	1,481	12,984,057	102,061	0.00786	10,782.1
	CV	4	7	6	43	18	38.72	41.1

though the trees were only 25 or 30 years old when sampled some plantation-grown pernambuco have densities that could be considered acceptable for bow production.

Mean MOR was similar for the plantation and native forest woods but when grouped according to quality, the high-quality samples presented the highest mean (253 MPa) which was considerably higher than those observed for class 1 (201 MPa) and class 0 (164 MPa); however, only the means for class 2 and class 0 showed a statistically significant difference. Average MOR for the highest quality samples was higher than that observed by Alves *et al*. (2008) for their best samples which had an average MOR of 216.0 MPa.

MOE averages were also similar among the different sample sets. When grouped according to quality the best samples had an average MOE (25,824 MPa) that was far superior (and statistically significantly different) to the lower quality groups (class 1, 19,002 MPa and class 2, 16,341 MPa). The average MOE of the class 2 samples was also higher than the average stiffness (23,077 MPa) of the best samples analyzed by Alves *et al*. (2008).

Examination of relationships among properties for the 3 sample sets (Table 3) revealed that density was strongly related to MOE (r-value = 0.914) and MOR (0.867) for the native forest woods. Relationships were weaker for plantation-grown woods, ranging from 0.704 to 0.849, but this can be expected considering that the samples are the same age and are from the same site.

SilviScan analysis

Mean values and standard deviations of physical and mechanical properties of plantation-grown and native forest pernambuco (set 1 and set 2), analyzed by SilviScan are shown in Table 1. The set 2 native forest pernambuco, presented a statistically sig-

Table 3. Relationships among measured properties for the set 1 native forest, 30-year-old plantation-grown and 25-year-old plantation-grown pernambuco. SS = measured by SilviScan.

		Density	MOR	MOE	Density SS	MFA SS	MOE SS	20Hz-Tan δ	CIE-L	CIE-a*	CIE-b*	Extractives
Native	Density	1.000	0.867	0.914	0.976	-0.835	0.891	0.333	-0.748	-0.431	-0.749	0.080
	MOR	0.867	1.000	0.982	0.940	-0.878	0.853	0.370	-0.692	-0.348	-0.688	0.028
	MOE	0.914	0.982	1.000	0.966	-0.902	0.924	0.411	-0.662	-0.421	-0.665	-0.069
	Density SS	0.976	0.940	0.966	1.000	-0.870	0.905	0.333	-0.752	-0.503	-0.778	0.083
	MFA SS	-0.835	-0.878	-0.902	-0.870	1.000	-0.823	-0.469	0.593	0.301	0.554	-0.093
	MOE SS	0.891	0.853	0.924	0.905	-0.823	1.000	0.523	-0.518	-0.480	-0.538	-0.290
	20Hz-Tan δ	0.333	0.370	0.411	0.333	-0.469	0.523	1.000	-0.244	0.056	-0.191	-0.287
	CIE-L	-0.748	-0.692	-0.662	-0.752	0.593	-0.518	-0.244	1.000	0.202	0.961	-0.352
	CIE-a*	-0.431	-0.348	-0.421	-0.503	0.301	-0.480	0.056	0.202	1.000	0.436	-0.010
	CIE-b*	-0.749	-0.688	-0.665	-0.778	0.554	-0.538	-0.191	0.961	0.436	1.000	-0.380
	Extractives	0.080	0.028	-0.069	0.083	-0.093	-0.290	-0.287	-0.352	-0.010	-0.380	1.000
		Density	MOR	MOE	Density SS	MFA SS	MOE SS	20Hz-Tan δ	CIE-L	CIE-a*	CIE-b*	Extractives
30 years	Density	1.000	0.712	0.826	0.919	-0.548	0.542	-0.029	-0.806	0.690	-0.711	0.558
	MOR	0.712	1.000	0.903	0.600	-0.289	0.518	0.198	-0.582	0.652	-0.516	0.356
	MOE	0.826	0.903	1.000	0.692	-0.623	0.744	0.099	-0.573	0.508	-0.742	0.251
	Density SS	0.919	0.600	0.692	1.000	-0.550	0.590	-0.014	-0.896	0.721	-0.644	0.753
	MFA SS	-0.548	-0.289	-0.623	-0.550	1.000	-0.901	-0.250	0.265	0.025	0.770	0.000
	MOE SS	0.542	0.518	0.744	0.590	-0.901	1.000	0.192	-0.425	0.184	- 0.832	0.188
	20Hz-Tanδ	-0.029	0.198	0.099	-0.014	-0.250	0.192	1.000	0.254	-0.211	0.058	-0.260
	CIE-L	-0.806	-0.582	-0.573	-0.896	0.265	-0.425	0.254	1.000	-0.916	0.607	-0.921
	CIE-a*	0.690	0.652	0.508	0.721	0.025	0.184	-0.211	-0.916	1.000	-0.398	0.857
	CIE-b*	-0.711	-0.516	-0.742	-0.644	0.770	-0.832	0.058	0.607	-0.398	1.000	-0.341
	Extractives	0.558	0.356	0.251	0.753	0.000	0.188	-0.260	-0.921	0.857	-0.341	1.000
		Density	MOR	MOE	Density SS	MFA SS	MOE SS	20Hz-Tan δ	CIE-L	CIE-a*	CIE-b*	Extractives
25 years	Density	1.000	0.849	0.704	0.987	0.412	0.679	-0.062	-0.910	0.938	0.194	0.485
	MOR	0.849	1.000	0.946	0.878	0.041	0.861	-0.061	-0.879	0.822	-0.058	0.096
	MOE	0.704	0.946	1.000	0.743	-0.219	0.904	0.085	-0.775	0.691	-0.238	-0.135
	Density SS	0.987	0.878	0.743	1.000	0.438	0.652	0.025	-0.938	0.915	0.209	0.419
	MFA SS	0.412	0.041	-0.219	0.438	1.000	-0.375	0.076	-0.347	0.303	0.649	0.632
	MOE SS	0.679	0.861	0.904	0.652	-0.375	1.000	-0.180	-0.658	0.719	-0.269	-0.014
	20Hz-Tanδ	-0.062	-0.061	0.085	0.025	0.076	-0.180	1.000	-0.227	0.024	-0.266	0.013
	CIE-L	-0.910	-0.879	-0.775	-0.938	-0.347	-0.658	-0.227	1.000	-0.941	-0.010	-0.467
	CIE-a*	0.938	0.822	0.691	0.915	0.303	0.719	0.024	-0.941	1.000	0.069	0.612
	CIE-b*	0.194	-0.058	-0.238	0.209	0.649	-0.269	-0.266	-0.010	0.069	1.000	0.230
	Extractives	0.485	0.096	-0.135	0.419	0.632	-0.014	0.013	-0.467	0.612	0.230	1.000

nificant difference between mean density values (1080 kg/m^3), when compared with the mean density of native forest set 1 samples (972 kg/m^3). However, means for MFA and MOE were not different for both sets.

The 30-year-old plantation-grown pernambuco had the lowest mean density (935 kg/m^3) and MOE (16,325 MPa) and both means were statistically significantly different from the corresponding means for the set 2 native forest pernambuco samples. The 30-year-old samples also had the highest mean MFA (13.2 deg.) that differed significantly from the mean MFA for both native forest pernambuco sets. Interestingly, plantation-grown 25-year-old pernambuco and native forest woods had means for density, MOE, and MFA that were not significantly different. Native forest trees had a low average microfibril angle (8.6 and 8.7 deg., for set 1 and 2 respectively) and a very narrow range. Plantation woods had higher average MFA (10.9 deg - 25 years, and 13.2 deg - 30 years) with large ranges.

SilviScan measured wood properties were strongly interrelated for the native woods (range of r-values = -0.823 to 0.905) and were strongly related to density, MOE and MOR measured using short clears. Again, relationships were weaker for the plantation-grown woods.

Extractives

Average extractive contents are shown in Table 1. Statistical analysis demonstrated that the native woods had the highest mean extractive contents and that data set 1 (23.4%) and 2 (22.5%) were equal. The mean extractive contents of the plantation-grown pernambuco were lower for both the 25-year-old (5.7%) and 30-year-old (12.7%) samples.

Based on the quality classification (Table 4) the average extractive content of samples varied by class (but differences were not statistically significant), with class 0 (16.9%) and class 1 (19.3%) having lower extractive contents than class 2 (21.9%). Class 2 mean extractives content was very similar to those reported by Alves *et al.* (2008) and Schimleck *et al.* (2009). Extractives content has been noted by Longui *et al.* (2012) to be negatively related to a property referred to as the performance index (PI) which was proposed by Wegst (2006) and determined using the following relationship:

$$\sqrt{MOE} / \rho$$

where ρ is specific gravity. In addition it appears that if extractives are too high (as noted by Schimleck *et al.* 2009) or low (as with the majority of our plantation-grown samples) quality is influenced. Despite their lower extractive contents some plantation-grown pernambuco were included in class 1 (good). It should be noted that these samples had some heartwood present. If the samples were all sapwood they were ranked class 0 (poor).

Extractives content was generally poorly related to the static bending and SilviScan measured wood properties for the native and plantation-grown sample sets (Table 3). The strongest relationship observed (0.753) was with SilviScan density for the 30-year-old samples; this may be caused by some samples having some heartwood present and whose density and extractive properties were noticeably different from samples having only sapwood.

Table 4. Silviscan wood properties, color parameters, and extractives content for native and plantation-grown pernambuco, ranked according to their potential to make a high-quality bow (as assigned by Charles Espey). SS = measured by SilviScan.

		Density SS kg/m³	MFA SS deg	MOE SS MPa	L*	a*	b*	Extractives %
	Mean	934	10.6	18,649	34.7	5.6	13.0	16.9
Poor	Max	1,077	21.6	24,440	42.9	17.6	29.7	33.9
class=0	Min	840	7.6	11,996	27.3	0.8	4.6	3.6
n= 18	Std Dev	72	3.1	3,477	5.3	4.6	5.8	9.7
	CV	8	28.9	19	15.2	82.6	44.8	57.4
	Mean	1,055	9.4	23,086	32.5	9.4	12.9	19.3
Good	Max	1,197	16.6	31,680	41.6	18.4	23.0	38.5
class=1	Min	828	6.1	12,072	23.7	1.2	1.2	4.1
n=24	Std Dev	81	2.6	4,726	4.3	4.9	4.8	7.9
	CV	8	27.8	20	13.4	52.2	37.7	41.1
	Mean	1,121	8.7	25,521	27.8	7.7	8.6	21.9
Excelent	Max	1,164	14.6	31,102	34.7	13.5	16.0	30.2
class=2	Min	1,047	6.8	17,114	23.9	3.5	3.9	17.7
n=13	Std Dev	35	2.0	3,815	3.6	3.3	4.6	3.0
	CV	3	23.1	15	13.0	42.0	53.0	13.9

Color

Mean values for L* (lightness of the color), a* (red - green) and b* (yellow - blue) measured from the wood samples are presented in Table 1; a* varied from a minimum of 0.8 (25-year-old wood) to a maximum of 18.4 for native wood (set 2), with the 25-year-old pernambuco having the lowest mean (2.0). When the woods were classified based on their potential for the manufacture of high-quality bows (Table 4) a* was lowest for the poorest quality woods with a value of 5.6; b* varied from 1.1 to 29.7 (native set 2) and was highest for the poorest quality wood (Table 4) compared to the excellent class (8.6); L* was lowest for the highest ranked wood (27.8), and was different from that of the lower quality wood (class 0 = 34.7 and class 1 = 32.5).

For the native woods all color parameters were poorly related to extractives content (Table 3); however, L* and b* had moderate correlations with density, MOE and MOR. For the 30-year-old woods L* (-0.921) and a* (0.857) were strongly related with extractives content, but again the presence and absence of heartwood explains the strength of these relationships. L*, and to a lesser degree a* and b*, had moderate to strong relationships with both measures of density (r-values ranged from -0.896 to 0.690). The 25-year-old samples (all sapwood) had weaker relationships among L* (-0.467), a* (0.612) and b* (0.230) and extractives content but L* and a* continued to have strong relationships with density (both static bending samples and SilviScan).

Loss tangent (tan δ = E'/E") and Dynamic Young's Modulus (E'/ρ)

The mean values and standard deviation of tan δ and dynamic Young's modulus are shown in Table 1. No differences between the means of native, 25-year-old and

30-year-old pernambuco were observed; however, the native woods clearly had the lowest average tan δ (0.01785), and also demonstrated the least variation. Based on rankings of the samples for bow production the excellent class had the lowest average tan δ (Table 2).

Relationships between extractives content and tan δ were poor for the various data sets ranging from -0.287 for the native woods to 0.013 for the 25-year-old plantation-grown woods (Table 3). The strongest relationships observed between tan δ and any of the properties examined in this study was 0.523 and -0.469 respectively for SilviScan measured MOE and MFA for the native woods.

According to Matsunaga *et al.* (1996) wood with high E'/ρ and low tan δ is generally suitable for the soundboards of musical instruments. Our mean tan δ values (Table 1 and 2) are low but an order of magnitude higher than those reported by Matsunaga *et al.* (1996). The differences may be attributed to vibration frequencies (20 Hz vs. 11 Hz in their study) and the conditioning of the specimens, where Matsunaga *et al.* (1996) oven dried their specimens and ours were stored in a desiccator for three weeks and tested under ambient conditions.

PCA

Relationships between samples from the different sets were examined using PCA (Fig. 1a). The 25- and 30-year-old samples formed individual groups that were clearly different from the 2 sets of native forest woods, which had considerable overlap. The set 1 native forest woods formed 2 groups – one had three samples that were ranked highly (class 2) and had positive PC-1 scores, while the other group was comprised of 7 class 0 samples. PC-1 was found to be strongly associated with sample density, while PC-2 was related to extractive content (Fig. 1b).

Figure 2 shows how the samples related to each other in terms of quality. Apart from 3 samples (2 aged 25 years, 1 aged 30 years) the lowest quality samples (class 0) formed a distinct group. The two higher quality groups overlapped, with the class 2 samples forming a small cluster relative to the class 1 samples.

Examination of the wood properties of 25- and 30-year-old plantation pernambuco provided promising results in terms of their potential for bow manufacture. Many samples had high density, MOE and MOR values and those that had started to develop heartwood were ranked good (class 1) in terms of their potential to make quality bows.

Compared to the set 1 native forest woods the strength properties of the samples compared well but it should be noted that the set 1 samples had not been preselected for their potential to make high-quality bows and many of the samples (70%) were considered unsuitable (class 0) for bow manufacture. Interestingly this may be more typical of what can be expected in a natural population of pernambuco where many trees are considered unsuitable for making bows (Rymer 2004) as opposed to the sets examined by Alves *et al.* (2008) and Schimleck *et al.* (2009). When compared to the native forest set 2 samples (preselected) density and stiffness (estimated by SilviScan) did not compare as well but the differences were only statistically significant for the 30-year-old samples.

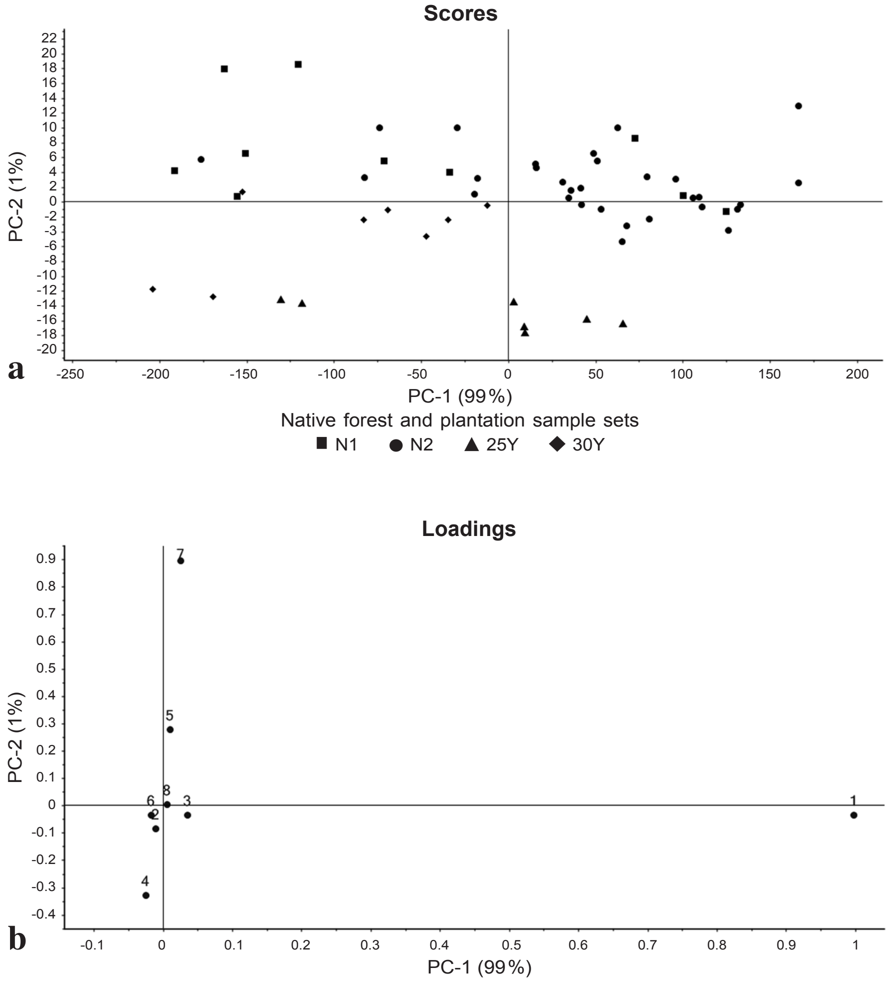

Figure 1. – **a**: Plot of scores for principal component 1 (PC-1) versus scores for principal component 2 (PC-2) for the native forest and plantation sample sets. N1 = set 1 native forest woods, N2 = set 2 native forest woods, 25Y = plantation-grown pernambuco 25 years old and 30Y = plantation-grown pernambuco 30 years old. – **b**: Plot of loadings for PC-1 versus PC-2.

Extractive contents were low for the plantation-grown woods, which could be expected as few samples had heartwood. An important question for the future will be consideration of a suitable rotation age for plantation trees as it must be sufficiently long for the trees to accumulate extractive levels in the range of 20–22% (Alves *et al.* 2008; Schimleck *et al.* 2009).

Properties such as MFA and tan δ had low values for all sample sets and this finding is consistent with data reported by Matsunaga *et al.* (1996) and Schimleck *et al.* (2009). Matsunaga *et al.* (1996) also suggested that the low tan δ of pernambuco is related to

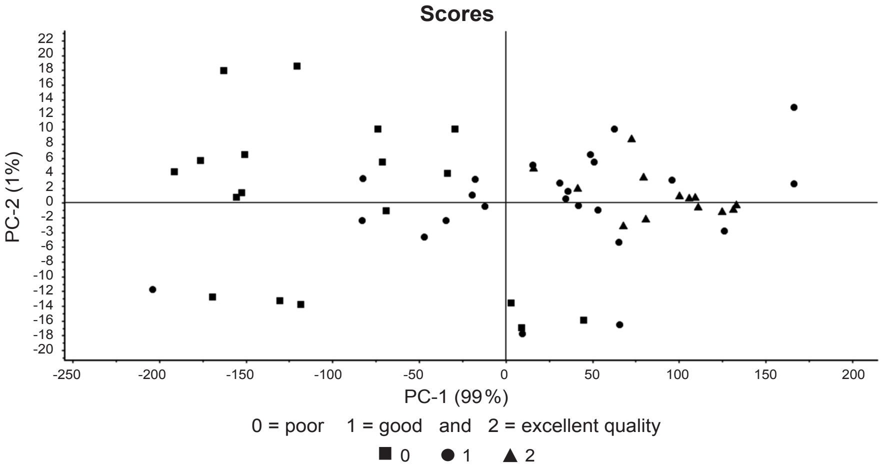

Figure 2. Plot of scores for principal component 1 (PC-1) versus scores for principal component 2 (PC-2) for the native forest and plantation samples classified into different quality groups. 0 = poor quality, 1 = good quality and 2 = excellent quality; rankings were assigned by Charles Espey.

the presence of extractives which is supported by our findings (native forest woods had the highest average extractives contents and lowest average tan δ) but it is important to note that the relationship between extractive content and tan δ was poor for all sets (Table 3). Interestingly some 25- and 30-year-old pernambuco samples had very low tan δ values that were comparable to the lowest values observed for the native forest woods despite having lower levels of extractives.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support for this research provided by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil.

REFERENCES

Alves ES, Longui EL & Amano E. 2008. Pernambuco wood (*Caesalpinia echinata*) used in the manufacture of bows for string instruments. IAWA J. 29: 323–335.

American Society for Testing and Materials (ASTM). 2007. D1105-96, Standard test method for preparation of extractive-free wood.

Angyalossy V, Amano E & Alves E. 2005. Madeiras utilizadas na fabricação de arcos para instrumentos de corda: aspectos anatômicos. Acta Bot. Bras. 19: 819–834.

Brown W. 1978. Timbers of the world. 2. South America. TRADA Technology Ltd, High Wycombe, Buckinghamshire, England.

Cave ID & Walker JCF. 1994. Stiffness of wood in fast grown plantation softwoods: The influence of microfibril angle. For. Prod. J. 44: 43–48.

COPANT. 1973. Norma Panamericana: Maderas – Método de ensayo de flexión estática 555.

Dean W. 1995. With broadax and firebrand. Destruction of the Brazilian Atlantic forest. University of California Press, Ltd.

Evans R. 1998. Rapid scanning of microfibril angle in increment cores by X-ray diffractometry. In: Butterfield BG (ed.), Microfibril angle in wood. Proc. IAWA/IUFRO International Workshop on the Significance of microfibril angle to wood quality: 116–139. University of Canterbury Press, Christchurch.

Evans R. 1999. A variance approach to the X-ray diffractometric estimation of microfibril angle in wood. Appita J. 52: 283–294.

Evans R. 2006. Wood stiffness by X-ray diffractometry. In: Stokke DD & Groom LH (eds.), Characterization of the cellulosic cell wall: 138–146. Blackwell Publishing, Ames.

Evans R & Ilic J. 2001. Rapid prediction of wood stiffness from microfibril angle and density. For. Prod. J. 51: 53–57.

Gasson P, Baas P & Wheeler EA. 2011. Wood anatomy of CITES-listed tree species. IAWA J. 32: 155–198.

Longui EL, Brémaud I, Gomes da Silva Jr F., Lombardi DR & Alves ES. Relationship among extractives, lignin and holocellulose contents with performance index of seven wood species used for bows of stringed instruments. IAWA J. 33: 141–149.

Matsunaga M, Sakai K, Kamitakahara H, Minato K & Nakatsubo F. 2000. Vibrational property changes of spruce wood by impregnation with water-soluble extractives of pernambuco (*Guilandia echinata* Spreng.). II. Structural analysis of extractive components. J. Wood Sci. 46: 253–257.

Matsunaga M, Sugiyama M, Minato K & Norimoto M. 1996. Physical and mechanical properties required for violin bow materials. Holzforschung 50: 511–517.

Megraw RA. 1985. Wood quality factors in loblolly pine. TAPPI Press, Atlanta, GA.

Megraw *et al.* 1999 ??

Morell V. 2004. The rain forest in Rio's backyard. National Geographic 205: 2–23.

Rymer R. 2004. Saving the music tree. Smithsonian 35: 52–63.

Santos Marques S. 2009. Características de madeiras de *Caesalpinia echinata* Lam. proveniente de reflorestamento e de floresta natural para confecção de arco de violino. Master of Science Dissertation (Plant Production), Federal University of Espirito Santo.

Schimleck LR, Espey C, Mora C, Evans R, Taylor A & Muniz G. 2009. Characterization of the wood quality of pernambuco (*Caesalpinia echinata* Lam.) by measurements of density, extractives content, microfibril angle, stiffness, color and NIR spectroscopy. Holzforschung 63: 457–463.

Taylor *et al.* 2006 ??

Wegst UGK. 2006. Wood for sound. Amer. J. Bot. 93: 1439–1448.

Accepted: 10 November 2012
Associate Editor: Lloyd Donaldson