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Scientific papers

Properties of wood from 7-year-old *Cedrela odorata* trees of two different populations growing in agroforestry systems with *Theobroma cacao*

Propiedades de la madera de árboles de siete años de edad de dos poblaciones de *Cedrela odorata* plantadas en un sistema agroforestal

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Abstract

This study evaluated the properties of juvenile wood from 7-year-old *Cedrela odorata* trees in two populations with the same provenance and planted in an agroforestry system with *Theobroma cacao* (cacao). The morphological characteristics (diameter at breast height; heartwood, sapwood, bark, and pith percentages; and eccentricity of pith), physical properties (shrinkage, green moisture content, green density, and specific gravity) and mechanical properties (modulus of rupture (MOR) and modulus of elasticity (MOE) in bending, compression stress, Janka hardness, tension stress and shear stress) were determined between two populations. The variation of the physical properties and morphological characteristics at different tree heights was also evaluated. The results showed that there were differences in both populations in terms of bark, pith, volumetric shrinkage, green moisture content, green density, MOR and MOE in bending, longitudinal compression and perpendicular tension. The results showed that population 2 presents better characteristics of growth and quality of wood for structural and furniture uses; hence, this population planted in agroforestry systems has good plantation conditions and wood quality.

Keywords: agroforestry systems, Spanish cedar, tropical species, variability, wood properties.

Resumen

En este estudio se evaluaron las propiedades de la madera juvenil proveniente de árboles de 7 años de *Cedrela odorata* de dos poblaciones con la misma procedencia, plantadas en un sistema agroforestal con *Theobroma cacao* (cacao). Se evaluaron las características morfológicas del árbol (diámetro a la altura del pecho, porcentaje de médula, duramen, albura y corteza en relación al área total y excentricidad de la médula), las propiedades físicas (contracciones y contenido de humedad, la densidad verde y el peso específico básico) y las propiedades mecánicas (módulos de ruptura (MOR) y de elasticidad (MOE). De estas últimas, se obtuvieron esfuerzos en compresión longitudinal, tensión paralela y perpendicular, cortante y la dureza. Los resultados mostraron diferencias en las dos poblaciones en porcentajes de corteza, médula, contracción volumétrica, contenido de humedad, densidad verde, MOR y MOE en flexión, así como en la resistencia en compresión longitudinal y tensión perpendicular. Los resultados muestran que la población 2 presenta mejores características de crecimiento y de calidad de la madera, por lo que la población plantada en sistemas agroforestales presenta buenas condiciones de desarrollo y de calidad de madera para su uso estructural o en mueblería.

Palabras clave: sistemas agroforestales, cedro amargo, especies tropicales, variabilidad, propiedades de la madera.

Introducción

Cedrela odorata L., known as Spanish cedar, red cedar or cigar-box cedar, belongs to the Meliaceae family, and is one of the most commercial wood species within this genus (Navarro, Ward, and Hernández, 2002). *C. odorata* grows in tropical climates from Mexico to Argentina at altitudes between 500 m and 1000 m above sea level (van der Hout, 2015). In natural conditions, it can reach up to 40 m in height (Gargiullo, Magnuso and Kimball, 2008). Its wood is in great demand in the market, competing with species such as mahogany (*Swietenia macrophylla*) and teak (*Tectona grandis*) due to its physical, mechanical and aesthetic properties (Moya, Bond, Quesada, 2014). The wood of this species is appreciated for its workability characteristics and its aesthetic value (Flórez *et al.*, 2014).

Until recently, *C. odorata* has been described as a very widespread species, but one that is highly variable due to the variability of populations (Cavers, Navarro and Lowe, 2003a). In Costa Rica, studies on the variation within or between *C. odorata* trees have been carried out, especially in relation to tolerance to dry and humid tropical conditions (Cavers *et al.*, 2003a). Such tolerance has a genetic component that has been the basis for the differentiation of this species (Cavers, Navarro and Lowe, 2003b). Therefore, some studies have determined the existence of *C. odorata* subpopulations, which are adapted to the specific conditions of their habitat in Costa Rica and other tropical countries (Cavers, Telford, Cruz, Pérez, Valencia, Navarro, Buonamici, Lowe and Vendramin, 2013). The species *C. odorata* has a high degree of population variability, which has been determined from diverse population studies where provenance variability of the species is demonstrated (Navarro *et al.*, 2002). Population differences are mainly due to the inclusion of vegetative materials from a relatively large geographic region (Sánchez, Salazar, Vargas, López, and Jasso, 2003).

Differences in growth rates of the populations within the species can be attributed in part to the adaptation to survival in a natural environment and could also be the result of adaptation to contrasting moisture regimes (Navarro et al., 2002). The climatic differences due to temperature and humidity could have led to a separation over time that would reduce gene flow between the climatic regions where trees develop (Pennington and Lavin, 2016).

Another important feature of *C. odorata* is that it has been incorporated into agroforestry systems with *Theobroma cacao* (cocoa) in Central American countries (Somarriba, Suárez-Islas, Calero-Borge, Villota, Castillo, Vílchez, Deheuvels and Cerda, 2016) with relatively short rotations (12-25 years) (Acheampong, Insaidoo and Ros-Tonen, 2014). In Panama and Costa Rica, Spanish cedar is one of the most common species in small agroforestry systems, together with other species such as *Cordia alliodora, S. macrophylla* and *Hyeronima alchorneoides* (Somarriba *et al.*, 2014). *C. odorata* is planted for use in timber products, obtaining large volumes of wood during harvest with individuals up to 30 cm wide at breast height (Cerda, Deheuvels, Calvache, Niehaus, Saenz, Kent, Vílchez, Villota, Martínez and Somarriba, 2014); however, the juvenile wood is less well known. Agroforestry systems are different than pure plantations since they consist of a combination of annual and perennial species integrated in the same area (Luedeling, Kindt, Huth and Koenig 2014). These systems contribute to environmental, socioeconomic and social development (Lorenz and Lal, 2014) since they allow for the optimization of the area of production, increasing product variety, and improving environmental conditions due to species diversification (Navarro *et al.*, 2002).

The physical-mechanical properties of timber species provide important information about the quality and characteristics of the material analyzed. Many evaluations have the objective of comparing data within the same species or between species, since there is great variability, as wood is anisotropic. Wood properties are variable in the tangential, radial and longitudinal directions.

Population dynamics and timber yield in agroforestry systems have been studied (Somarriba *et al.*, 2014), but little is known of the variations in the characteristics of wood from trees growing in agroforestry systems. Their study could improve the understanding of the differentiation and adaptation patterns of the species, as well as possible commercial uses of the different populations (Navarro *et al.*, 2002). The study objective is to identify the differences in morphological characteristics (percentages of sapwood, heartwood, bark, and pith and pit eccentricity), physical properties (green density; specific gravity; volumetric, tangential and radial shrinkage; and moisture content) and mechanical properties (module of elasticity and modulus of rupture in bending, parallel compression, Janka harness, parallel and perpendicular tension and shear stress) of wood from 7-year-old trees in two populations with the same provenance of *Cedrela odorata* growing in an agroforestry system with *Theobroma cacao* (cacao).

MATERIALS AND METHODS

Location and description of the agroforestry system

Two populations of *Cedrela odorata* (Spanish cedar) planted in an agroforestry system were studied in the community of Peralta, Turrialba, Cartago, Costa Rica (Fig. 1a). The denominated populations 1 and 2 were planted in 2009, and the sampled trees were felled in 2016. At the sampling time, the trees were 7 years old. The seeds of both populations came from the same provenance. The area where the trees originated is the Caribbean slope of Costa Rica (humid zone of Costa Rica), where precipitation levels are on average 3759 mm. The area does not present a well-defined dry season, and the months of March and April present the least amount of precipitation. The agroforestry systems consist of a plantation of *Theobroma cacao* (cacao) at 3x3 m with *C. odorata* trees as shade. The plantations are between coordinates 9° 58' 1.06"N - 83° 36' 43.97"W and 9° 57' 13.72"N - 83° 37' 12.45"W. The two plantations are easily identifiable by the type of bark: population 1 has a smoother bark (Fig. 1b) than population 2, which has a more cracked bark (Fig. 1c).

Sampling

Randomly, 9 trees from population 1 and 11 trees from population 2 (N total = 20) were selected to study morphological characteristics and wood properties, according to the methodology proposed by Moya and Muñoz (2010). The samples were obtained from these trees. The dasometric characteristics of the two populations are detailed in table 1. The selected trees had straight trunks, normal branching and had no symptoms of disease or plague. A sample of a cross-section of approximately 3 cm thickness was cut from the base of the tree at 1.3 m height. From each tree selected, two logs of 1.3 m were obtained from the base of the tree until the DBH, and another from the DBH to a 25% height. Subsequently, cross-sections were taken at 25%, 50%, 75% and 100% of commercial height (Fig. 2A). The North-South direction was marked on each cross-section.

FIGURE 1. (a) Agroforestry system of *Cedrela odorata* trees with *Theobroma cacao*, (b) tree from population 1, and (c) tree from population 2.

TABLE 1. Dasometric parameters of two *Cedrela odorata* populations growing in agroforestry plantations with *T. cacao*.

Population	*Ages*	*Density (trees/ha)*	*Total height (m)*	*Diameter breast height (cm)*	*Average growth rate (cm/years)*
1	7-yr-old	360	18.81	21.51	3.07
2	7-yr-old	533	13.05	18.52	2.57

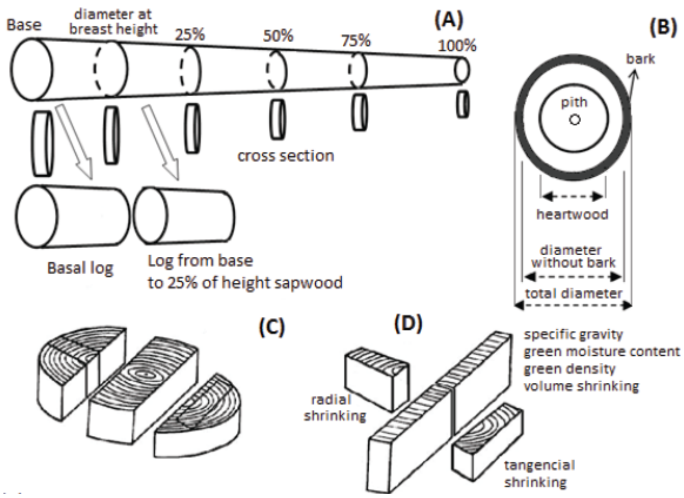

FIGURE 2. Tree sampling patterns (A), cross-section measurements obtained from each tree (B) and sampling to determine the physical properties and amount of wood shrinkage (C-D).

Determination of the percentages of heartwood, sapwood, bark and pith

The total diameter, diameter without bark, pith diameter and heartwood diameter (Fig. 2B), were measured on a transverse line drawn in two directions (north-south and east-west). The averages of all diameters were calculated using the two measurements from each transverse sample. The total heartwood area and pith from the cross-section were calculated as the geometric area of the circle. Bark thickness was obtained by calculating the difference between the total area and the area without bark. Then, its percentage was obtained by calculating the difference between total area and the area without bark, expressed as a percentage for the total area of the cross-section. The eccentricity of pith was determined by using transverse lines from the north-pith and east-pith and was applied using the method proposed by Moya, Araya and Vílchez-Alvarado (2008).

Determination of the green density, specific gravity, shrinkage and green moisture content

A 3.0 cm-thick disk (including the pith) at different heights was cut from the cross-section, which was divided into two subsamples to study the physical properties of the wood (Fig. 2C-D). Each piece was weighed, and its volume measured. Volume was measured with water displacement method, according to ASTM D2395-14 standard (American Society for Testing and Materials, US [ASTM], 2014a). Then, pieces were dried at 103 ºC for 24 hours. Afterwards, their weights and volumes were measured again. The green density was calculated as the green mass divided by the green volume, and the specific gravity was calculated as the oven dried weight divided by the green volume.

Volumetric, tangential and radial shrinkage were determined. From all transverse disks of 3.0 cm thickness, after cutting the central part (Fig. 2C), specimens to measure the shrinkage in the tangential and radial directions (Fig. 2C) were obtained. Their lengths were measured in green condition; then, the pieces were placed in the oven for 24 hours at 103 ºC and measured again to determine the amount of shrinkage that occurred. The total volumetric shrinkage was determined for the same transversal pieces obtained from the central part of the cross-section using the dimensional difference between green and dried conditions (0% moisture content), which was determined by measuring the displacement of water in both moisture conditions. For the moisture content, the specimens were weighed in the green condition, then dried at 103 °C for 24 hours and weighed again to calculate the moisture content.

Mechanical properties

From the logs obtained from the trees (Fig. 2A), 1-2 specimens were obtained to determine the modulus of elasticity (MOE) and the modulus of rupture (MOR) in bending, tension stress (parallel and perpendicular to the grain), the shear stress parallel to the grain, the longitudinal compression stress and the Janka hardness (axial and lateral direction). The samples were prepared following the norm ASTM D143-14 (ASTM, 2014b), and from each tree, 1-2 specimens (2 specimens × 9 or 11 trees = 18 or 22 specimens) were extracted.

Statistical analysis

The assumptions for homogeneous variances (Levene Test) and normal distribution through the Shapiro-Wilks test were verified for all the properties evaluated. A t-test was used for two samples assuming equal variances with a 95% confidence level. Regression analyses were applied to the characteristics of the evaluated wood (heartwood, sapwood and bark percentage, pith eccentricity, green density and specific gravity) according to the tree height, where tree height was the independent factor and the properties of wood the dependent variable.

Results

Morphological properties

The populations analyzed have similarities in some of the morphological characteristics of 7-year-old trees evaluated at DBH (Fig. 3). The diameters of population 2 trees were greater than those recorded for population 1, while the bark percentage and pith percentage were higher in the trees of population 1. The percentage of sapwood and heartwood and the eccentricity of the pith did not present differences between the trees from both populations in the agroforestry system (Fig. 3).

The analysis of the percentage of height shows that the heartwood percentage (Fig. 4a) and eccentricity (Fig. 4e) at 7 years old do not present significant differences between the populations at any height. The percentage of sapwood (Fig. 4b) and pith (Fig. 4d) only presented differences in height at 100%, being higher in population 2. The bark percentage shows differences along the entire height profile between both populations at 7 years old, being statistically higher in population 1 than population 2 (Fig. 4c).

The mathematical modeling of heartwood, sapwood, bark, pith, and pith eccentricity by height revealed that the heartwood percentage of the trees from both populations of 7-year-old trees decreases logarithmically (Fig. 5a), but the sapwood percentage and bark percentage (Fig. 5b, 5c) showed a polynomial tendency of grade 2, as well as the percentage of eccentricity (Fig. 5e). However, the eccentricity showed no differences between heights. Pith trends differed in the trees from both populations. In trees from population 1, the tendency was polynomial grade 2, while for trees from population 2, the trend was logarithmic (Fig. 5d).

The best-fit equations are presented in table 2. There is great variation within the data for all the properties analyzed in relation to height, since the percentages of R^2 are low for all equations obtained. The *f*-value indicates that morphological characteristics and physical properties are statistically significant because the *f*-value is lower than the α value (0.05) with differences between heights, except for the percentage of bark in population 1 and the percentage of eccentricity in both populations.

Physical properties of wood

The physical properties measured at DBH showed that the volumetric shrinkage and green moisture content are statistically higher in trees from population 1 than population 2 at 7 years old, but the tangential and radial shrinkage showed no significant differences between the trees from both populations (Table 3). The shrinkage ratios were lower than 2 in both populations.

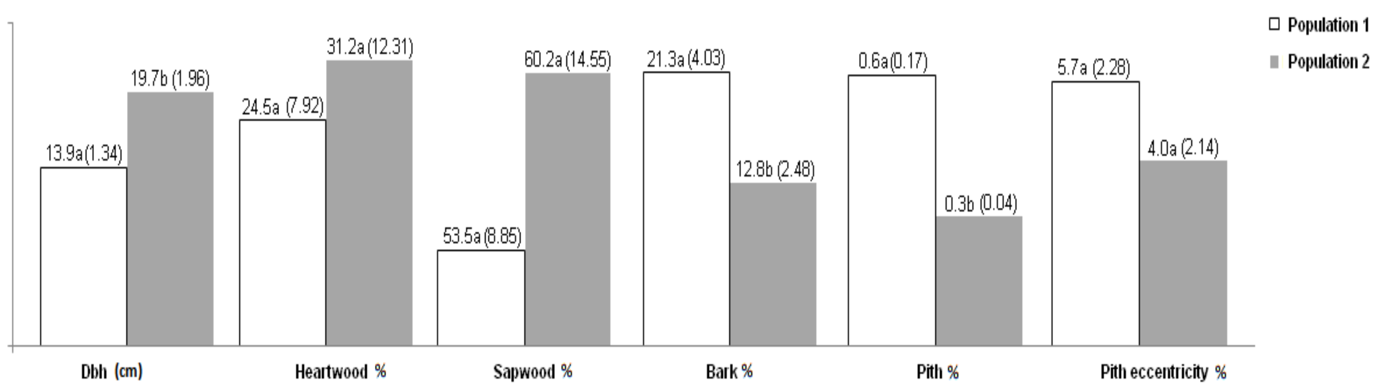

Figure 3. Averages of the morphological properties of two populations of 7-year-old trees at the diameter at breast height in *Cedrela odorata* agroforestry systems with cacao.

Legend: Different letters indicate significant differences at the 95% confidence level for the same height. Values in parentheses represent standard deviations.

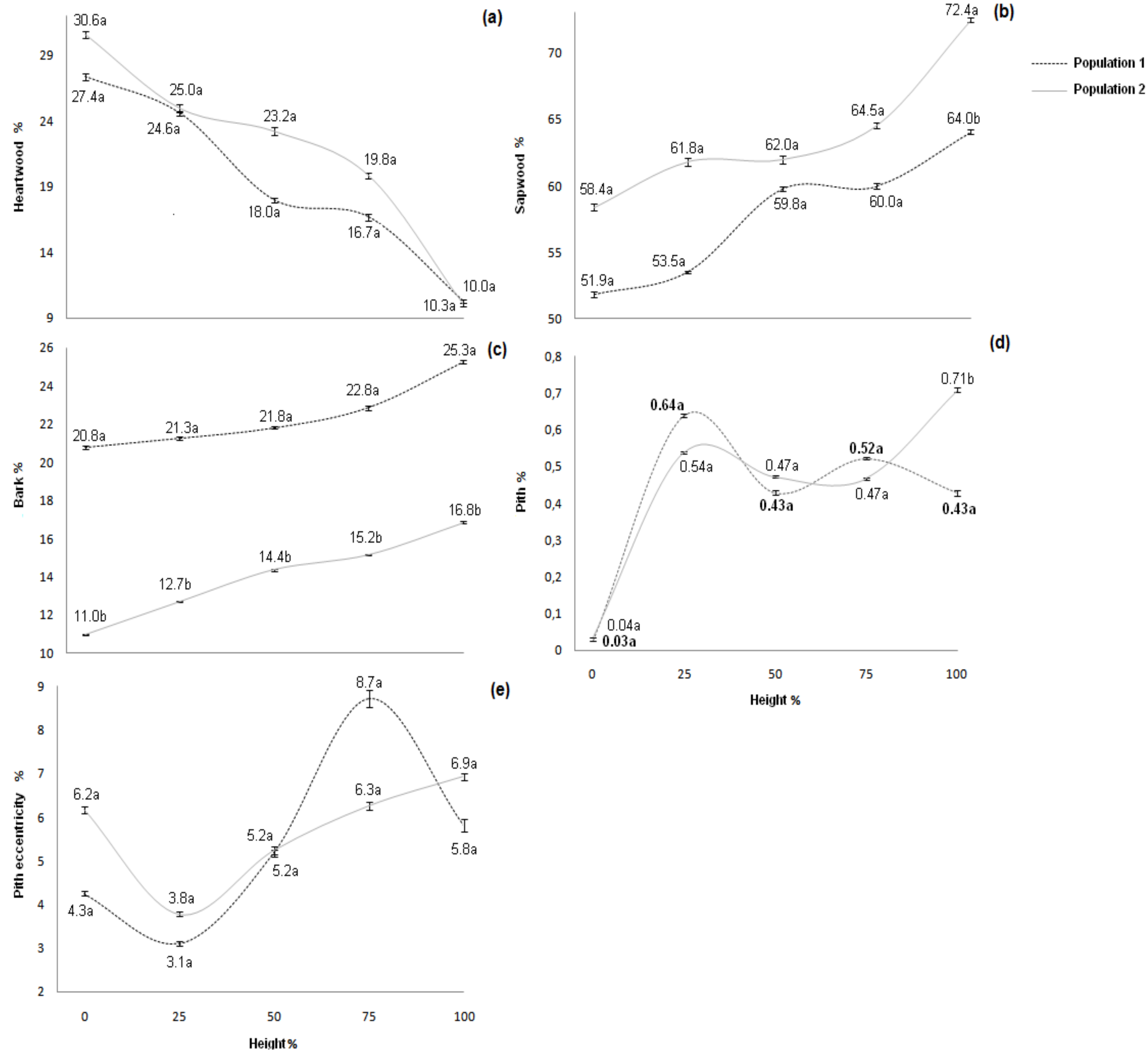

FIGURE 4. Variation of the percentages of heartwood (a), sapwood (b), bark (c), pith (d), and pith eccentricity (e) with the height (%) of the two populations of 7-year-old *Cedrela odorata* trees growing in agroforestry systems with cacao.

Legend: Different letters indicate significant differences at a 95% confidence level for the same height

At the height of the DBH in trees at 7 years old, there is variation between the populations in green density (Fig. 6), which was statistically greater in trees from population 1 than population 2; however, for specific gravity, there are no differences between the populations (Fig. 6).

The variation of the green density and specific gravity of the 7-year-old trees in relation to height showed an irregular behavior (Fig. 7). The green density was higher in the lower parts of the trees, decreasing in value to the height at 25%. The green density increased with the height in both populations starting from this height (25%) (Fig. 7a). The specific gravity had variations in trees of both populations with height, with a tendency to increase proportionally with the height (Fig. 7b). The green density showed no differences at a height of 75% between the populations, but the trees from population 1 had greater density at the other heights (Fig. 7a). Likewise, the specific gravity showed no significant differences between populations at 7 years old.

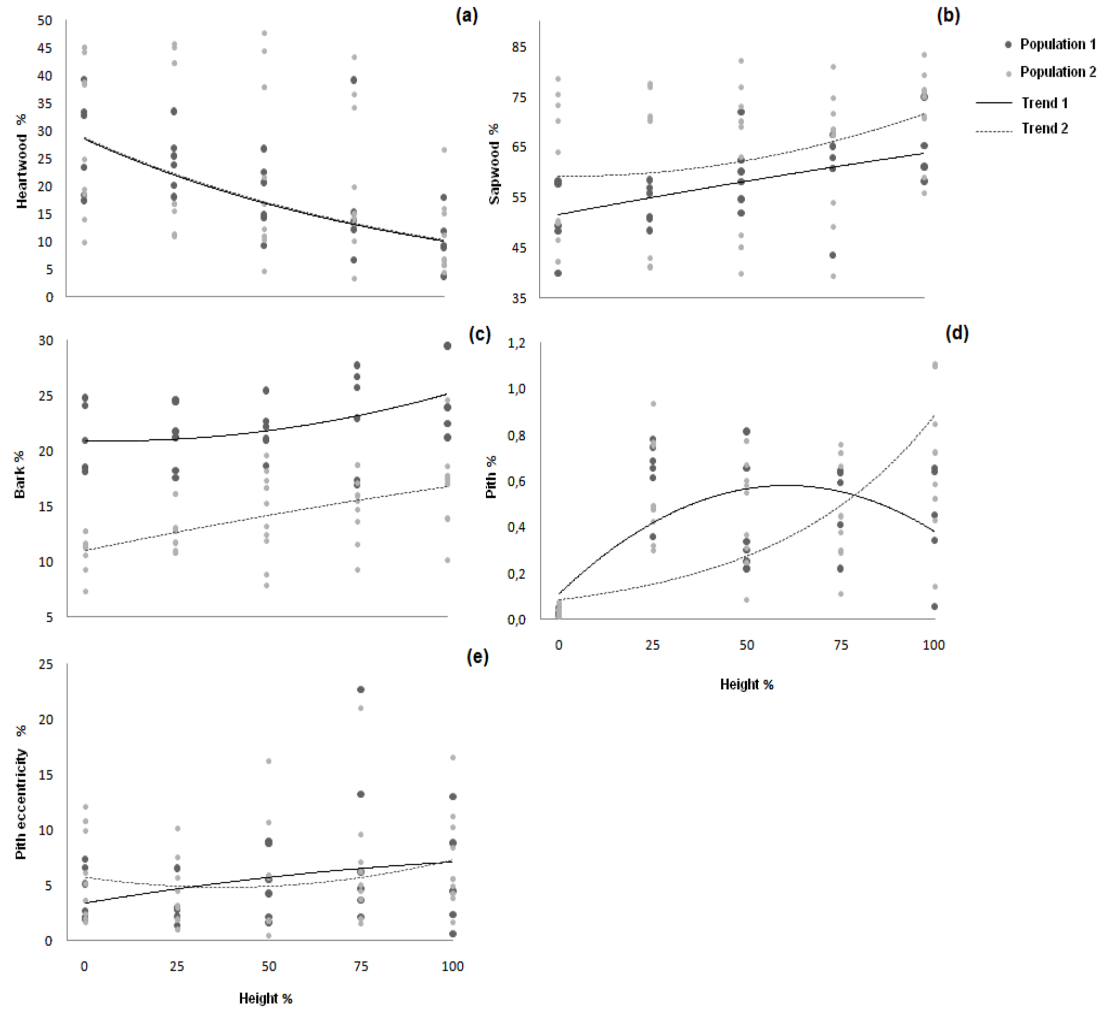

FIGURE 5. Trends in the morphological properties of two populations of 7-year-old *Cedrela odorata* trees growing in agroforestry systems with cacao.

TABLE 2. Equations and statistical parameters of morphological properties in two populations of 7 yr-old of *Cedrela odorata* trees growing agroforestry systems with cacao.

Property	*Population*	*Adjusted equation*	*R^2*	*F- value*	*N*
Heartwood (%)	1	y=e(3.351-0.010x)	0.35*	8.84×10^{-05}	29
	2	y=e(3.356-0.010x)	0.14*	7.89×10^{-05}	55
Sapwood (%)	1	$y=-0.0002x^2+0.138x+51.487$	0.31	0.008	29
	2	$y=-0.0013x^2+0.007x+59.295$	0.11	0.045	55
Bark (%)	1	$y=-0.0005x^2+0.007x+20.890$	0.19	0.067	29
	2	$y=-0.0001x^2+0.067x+11.048$	0.35	1.52×10^{-05}	55
Pith (%)	1	$y=-0.0001x^2+0.016x+0.112$	0.39	0.002	29
	2	y=e(-2.461+0.023x)	0.05*	3.13×10^{-05}	55
Pith eccentricity (%)	1	$y=-0.0002x^2+0.055x+3.392$	0.08	0.338	29
	2	$y=0.0007x^2-0.049x+5.687$	0.04	0.323	55

Legend: N: total of observations. * FI: Adjustment index for transformed models

TABLE 3. Average of shrinkage contractions and moisture content of two populations of 7 yr-old to the diameter at breast height in *Cedrela odorata* growing agroforestry systems with cacao.

Parameter	*Population 1*	*Population 2*
Volumetric shrinkage (%)	9.29 ^{a} (3.00)	6.82 ^{b} (1.43)
Tangential shrinkage (%)	4.06 ^{a} (2.84)	4.92 ^{a} (1.05)
Radial shrinkage (%)	3.56 ^{a} (3.81)	2.53 ^{a} (0.28)
Tangential/radial ratio	1.38	1.95

Legend: Different letters indicate significant differences at a 95% confidence level between both populations. Values in parenthesis represent standard deviations.

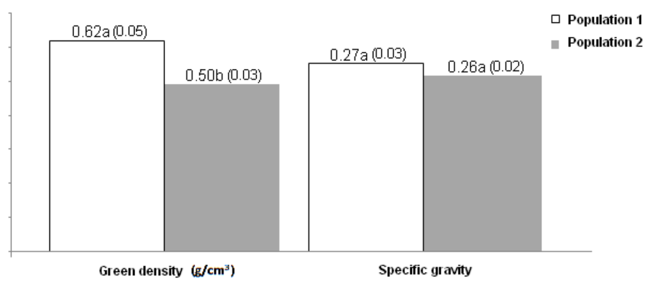

FIGURE 6. Average of the green density and specific gravity at the diameter at breast height of two populations of 7-year-old *Cedrela odorata* growing in agroforestry systems with cacao.

Legend: Different letters indicate significant differences at the 95% confidence level for the same mechanical property. Values in parentheses represent standard deviations

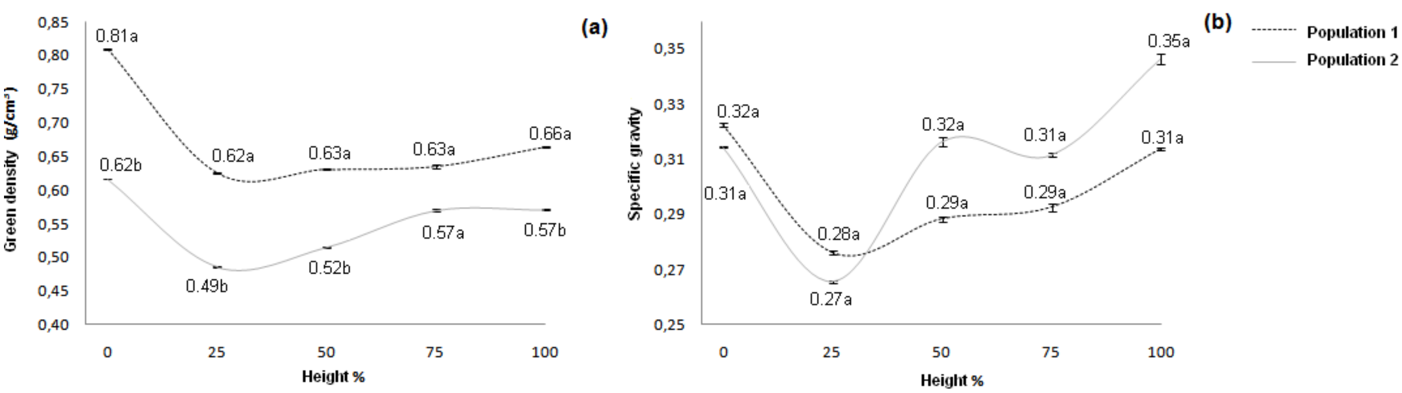

FIGURE 7. Variation with respect to the percentage of height of the green density and specific gravity in two populations of 7-year-old *Cedrela odorata* trees growing in agroforestry systems with cacao.

Mathematical models showed variations in green density and specific gravity, with a polynomial tendency grade 2 for both populations at 7 years old. There is an irregular pattern for both variables regarding height, having lower values at intermediate heights of the trees and a tendency to increase moving upwards from the intermediate part of the tree. The best-fit equations are presented in table 4 from the previous models of the green density and specific gravity within each population, which showed that the models are statistically significant (*f*-value lower than α value), with the exception of the specific gravity of population 2, but they have low correlation values (R^2).

TABLE 4. Equations and parameters for the green density and the basic specific weight with respect to the height in trees of two populations of 7 yr-old of *Cedrela odorata* trees growing agroforestry systems with cacao.

Property	*Population*	*Fitequation*	*R^2*	*F-Value*	*N*
Green density (g/cm³)	1	$y=0.00005x^2-0.006x+0.791$	0.64	1.614×10^{-06}	29
	2	$y=0.00003x^2-0.003x+0.594$	0.21	0.002	54
Specific gravity	1	$y=0.00001x^2-0.001x+0.317$	0.21	0.046	29
	2	$y=0.00001x^2-0.001x+0.305$	0.10	0.064	54

Legend: N: total of observations.

TABLE 5. Average of the mechanical properties of two populations of 7 yr-old to the diameter at breast height in *Cedrela odorata* growing agroforestry systems with cacao.

Property	*Population 1*	*Population 2*
Modulus of elasticity (MPa) in bending	4043 ᵃ (624.81)	5769 ᵇ (602.61)
Modulus of rupture (MPa) in bending	27.33 ᵃ (3.59)	44.14 ᵇ (6.00)
Compression stress (MPa) in longitudinal direction	12.72 ᵃ (5.30)	23.55 ᵇ (3.48)
Janka hardness (N) in axial direction	72.58 ᵃ (15.07)	78.46 ᵃ (13.48)
Janka hardness (N) in lateral direction	14.24 ᵃ (2.81)	15.46 ᵃ (3.73)
Tension stress (MPa) parallel to grain	41.70 ᵃ (9.93)	44.09 ᵃ (14.22)
Tension stress (MPa) perpendicular to grain	1.98 ᵃ (0.59)	3.23 ᵇ (0.61)
Shear stress (MPa) parallel to grain	4.93 ᵃ (0.94)	4.59 ᵃ (0.95)

Legend: Different letters indicate significant differences at a 95% confidence level for the same mechanical property. Values in parenthesis represent standard deviations

Mechanical properties

Table 5 shows the mechanical properties for 7-year-old trees from two populations of *C. odorata* in an agroforestry system. MOE and MOR in bending, the maximum longitudinal compression stress was statistically higher in population 2. The axial and lateral Janka hardness and shear stress values did not present differences.

Discussion

Morphological characteristics

Trees of *C. odorata* at 7 years old tended to grow better in agroforestry systems than pure plantations due to the intensive management, type of soil, topography and type of fertilization received (Navarro, Montagnini, and Hernández, 2004). Therefore, greater development at 7 years old is expected in the diameter of trees growing under these conditions. Leyva and Erguera (2014) showed that the diameter varied between 10 and 15 cm for 14-year-old *C. odorata* trees growing in agroforestry systems; these values are lower than the range of values obtained in this study (13.9 cm – 19.7 cm). Greater growth was observed in population 2 (Fig. 3), and this could have occurred because this population is probably more likely to grow in diameter than population 1, as usually occurs in different varieties due to genetic considerations (Navarro *et al.*, 2002).

As for the percentage of sapwood in 7-year-old trees, values between 56.35 and 60.20% were obtained. The heartwood percentage determines the quality of the wood since chemicals and extractives that increase the wood quality are synthetized in mature trees during the heartwood formation process (Ypushima, Salcedo, Manríquez, Silva, Zamora and Hernández, 2014; Flórez *et al.*, 2014). Therefore, it is important that trees present a high percentage of this type of wood and thus guarantee the quality of the final product when the wood will be used in furniture especially since juvenile trees have a low heartwood content.

As for bark percentage, the minimum percentage reported for tropical species is 2% and the maximum is 25% (Hegde, Kalkoor, Jha and Thakur, 2014). Population 1 of *C. odorata* at 7 years old achieved a bark percentage of 21.3%, and population 2 of 12.8%, therefore these values are within the previous range and hence, considered normal. The bark percentage is mainly influenced by temperature and is inversely proportional to precipitation (Rosell and Olson, 2014). Population 2 showed a smaller area of bark (Fig. 3), which would indicate it is the population better adapted to the area of Turrialba which is considered a rainy area, unlike population 1 that achieved a higher percentage of bark which is less well adapted to the weather conditions of the place. Fasola, Olagunju and Robert (2014) indicate this may be due to morphological differences within the species. Moreover, the bark percentage tends to vary in tree height and it does not vary based on diameter (Serrano, Moya, Berrocal, Trejos and Foglia, 2015). This pattern of height is observed in both populations, however there are differences between the diameters when an increase in the bark occurs along the stem (Fig. 4)

The decrease of heartwood with height is common in trees (Moya, Salas, Berrocal, Valverde, 2015; Tenorio *et al.*, 2016) and the trend found in 7-year-old *C. odorata* trees growing in an agroforestry system with cocoa (Fig. 4a) is congruent with this. Meanwhile, the decrease in sapwood percentage with height (Fig. 4b, 4c) is congruent with data found for trees growing in forests (Parolin, Müller and Junk, 2008). The results found for pith percentage have a variation of 0.4% to 0.7% (Fig. 4d), which are similar to those found for different tropical species growing in pure plantations (Tenorio, Moya, Salas, and Berrocal, 2016).

Prediction models

In both 7-year-old populations it was observed that there is a low relationship between height and morphological characteristics or physical properties (specify gravity and green density), lower value of R^2 (Tables 2 and 4). This could have occurred because there is high variation within each tree, or because another variable must be included in the equation that explains the low variability within each population. The morphological and physical differences within each population are evident since in several cases both populations follow a different trend (Fig. 4d, 4e), therefore each population has its own behavior.

Physical properties

Christoforo, Almeida, Almeida, Santos, Panzera and Lahr (2016) report volumetric shrinkage values of 8.68%, tangential shrinkage of 5.02% and radial shrinkage of 3.42% for mature *Cedrela* sp. trees in pure plantations. These values agree with those obtained in this study for population 1 at 7 years old but not for population 2 (Table 3).

The values of *C. odorata* trees at 7 years old are different from the values of another species from the same genus. *Cedrela fissilis* presents values for radial and tangential shrinkage of 12.8% and 17% respectively (De Avila, Gatto, Stangerlin, de Cademartori, Weinert and de Avila, 2013), a much higher percentage than those presented in the two populations in this study. Tangential shrinkage (4.06%) of trees in agroforestry systems was higher than in *S. macrophylla* (1.4%) and *C. alliodora* (5.6%) (Anoop, Jijeesh, Sindhumathi and Jayasree, 2014) for trees growing in plantations.

Cedrela fissilis reported a volumetric shrinkage of 13.2% (De Avila *et al.*, 2013), above the value obtained in both populations of *C. odorata*. Population 2 shows lower values than those previously reported by Christoforo *et al.* (2016) in volumetric shrinkage (6.82%) and radial shrinkage (2.53%), but the tangential shrinkage is similar to those found in the literature (4.92%).

The specific gravity obtained in the present study (Fig. 6) for both populations at 7 years old is within the range reported by Van der Hout (2015) of 0.25 – 0.50 for adult trees. A disadvantage of low specific gravity is that it can be categorized as soft and this type of wood does not have good mechanical resistance, however the wood is appreciated for its aesthetic value (Flórez *et al.*, 2014).

The green density tends to become smaller as height increases (Fig. 7a). The increase in density in medium zones of the tree may be due to the fact that there are more branches in that area (Trautenmüller *et al.*, 2014). The increase in specific gravity with height (Fig. 7b) does not present a common pattern in most species (Tenorio *et al.*, 2016); however, some tropical species have this type of pattern (Moya and Muñoz, 2010, Tenorio *et al.*, 2016).

Mechanical properties

The evaluation of the properties helps to make decisions regarding different objectives of use for wood in the industry (Hegde *et al*., 2014). Among the possible uses is light construction (Van der Hout, 2015). The results obtained for both *C. odorata* populations at 7 years old growing in an agroforestry system with cocoa could indicate their possible use in light construction. For *C. odorata*, 65.9 MPa is reported for MOR (Bárcenas-Pazos, Ortega-Escalona, Ángeles-Álvarez, and Ronzón-Pérez, 2014) and 6700 MPa for MOE (Venson, Guzmán, Talavera and Richter, 2008); in this study, with lower MOR and MOE values were found for both populations (Table 5).

The longitudinal compression stress reported for *C. odorata* is 26.87 MPa (Bárcenas-Pazos *et al*., 2014). The values obtained in this study are lower than those. The value for the shear stress (Table 5) is lower than those reported for *C. odorata* by Bárcenas-Pazos *et al.* (2014). In all cases, this is certainly due to the fact that the populations studied here are of juvenile wood from young trees and those found in the literature are from mature trees.

Variation within the *Cedrela odorata* populations

The vegetative material used for this agroforestry system was material obtained from a seed stand, that is, seeds from the same source were used to establish the plantation. The lack of knowledge about the dynamics of the initial population does not allow to explain the difference in the development of trees in the plantations studied, which is expressed in differences between individuals. In this case, for example, there is evidence of differences between the bark of different trees (Fig. 1).

The variation between two populations of 7-year-old *C. odorata* is mainly explained by genetics. For example, the migration of genetic material (pollen and seeds) changes the species due to adaptation to an external change and loss of information due to excessive use of trees. In addition to this, the size of the sampled population has an influence in the results obtained since small populations harbor less variability than large populations; furthermore, fragmentation leads to cross-breeding between related individuals and loss of genetic information. This is why different populations occur, as was the case in this study. This has repercussions on the quality of the wood, mainly morphological aspects such as heartwood, pith and bark. Differences in population growth in a single site with evidence of distinction in the physical characteristics of the material is due to differences in the genetic base (Cavers, Navarro, and Lowe, 2004). The variability of the species and their differentiation within the same population in a geographic area can occur due to the environmental changes that produce modifications in the trees at the genetic level (Barbour, O'Reilly-Wapstra, Little, Jordan, Steane, Humphreys, Bailey, Whitham and Potts, 2009). This occurs over time through the adaptation of a population to a specific site (Navarro *et al*., 2002). Variations in the environment, such as over-exploitation, reduce the size of the population and therefore produce loss of the species' own characteristics. The genus *Cedrela* tends to present diversification within the populations due to historical changes that have produced fragmentation of the initial population (Soldati, Fornes, Van Zonneveld, Thomas and Zelener, 2013), and consequently, this diversity is transmitted to agroforestry systems, as in the present study. The maintenance of the characteristics causes differences between populations.

Several studies have shown morphological changes in individuals within the same species, and these studies concluded that we can discuss different varieties for populations (Fajardo and Piper, 2011). The adaptation occurs through changes in the soil in the same site, where morphological differences have been found within a population (Misiewicz and Fine, 2014) and in the quality of the wood because of the differences previously presented. The most marked differences were in diameter, bark, pith, volumetric shrinkage, green density, MOE, MOR, longitudinal compression and perpendicular tension.

Conclusions

In a study of the different properties of two populations of *Cedrela odorata* at 7 years old, it was found that morphological properties showed differences between the two populations in terms of the diameter at breast height and bark and pith percentages, the latter being different in both populations and along the different heights studied. Physical properties showed differences only in volumetric shrinkage and in moisture content percentages, both being higher in population 1 than those found for population 2. When studying the different heights, it was found that the green density showed no differences only at a height of 75%, but presented differences at the other heights. There was no difference in specific gravity along the stem between the populations studied. In terms of mechanical properties, the MOR and MOE in bending, longitudinal compression and perpendicular tension were significantly different between the two populations, being statistically higher in population 2.

Both populations of *Cedrela odorata* showed that there are significant differences in some morphological, physical and mechanical properties of wood, which are probably produced by different adaptations that the species underwent in different growth conditions. In this study, it was found that trees from population 2 present better diameters than trees from population 1.

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