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Silviculture conditions and wood properties of *Samanea saman* and *Enterolobium cyclocarpum* in 19-year-old mixed plantations

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Abstract

Aim of study: The objective of this work is to examine wood properties of a mixed plantation of *Samanea saman* and *Enterolobium cyclocarpum*, combined with native species of Costa Rica.

Area of study: Mixed plantation in dry tropical zone of Costa Rica

Material and methods: It was measured by total diameter, heartwood, bark thickness, several physical wood properties (green density, specific gravity, volumetric, tangential and radial shrinkage and moisture content) and wood color.

Main results: The largest of this diameter are reached when *S. saman* is planted with *E. cyclocarpum*, *E. cyclocarpum* and *Swietenia macrophylla* and S*imarouba glauca*. Meanwhile the largest total diameter and heartwood in *E. cyclocarpum* was found when this species is planted with *Dalbergia retusa*. Heartwood percentage, bark percentage, and some physical properties are not affected when *S. saman* or *E. cyclocarpum* are planted with other species. However, parameters of wood color were affected mixture plantation of *S. saman* or *E. cyclocarpum* with other species. The lowest difference between wood from mixed plantations and wood from trees growing in native forests is produced when *S. saman* is mixed with *E. cyclocarpum*, but this last species is mixed with *Hymenaea courbaril* and produced wood with the lowest difference in wood color compared to trees growing in the natural forest.

Research highlights: *S. saman* and E. cyclocarpum tress planted in a mixed plantation produce variation in breast diameter, physical properties, heartwood percentage and wood color.

Key words: plantation species; silvicultural condition; tropical species; wood properties.

Introduction

Enterolobium cyclocarpum (Guanacaste) and *Samanea saman* (Cenízaro) are important species used in furniture and craftwork industries. They have moderate wood density, attractive wood color, excellent workability properties and natural durability (Flores and Obando, 2003). Both species grow in dry tropical conditions, with temperatures from 18 to 25°C and elevation levels over 300 meters. (OFI/CATIE, 2003). However, these species have become scarce (Griscom and Ashton, 2010), resulting in consequent problems for the industry. Important efforts are being made towards reforestation. These *Enterolobium cyclocarpum* and *Samanea saman* species were tested in fast-growth condition plantations (Foroughbakhch *et al.*, 2006). The excellent productivity and growth achieved with these species are considered important for fast-growing plantations in Costa Rica, Panama, Mexico and some African and Asian countries (Piotto *et al.*, 2004).

Mixed plantations (MP) have shown promising productivity (Alice *et al.*, 2004). Higher stand-level productivity in mixed species has been found with two kinds of species interactions: (1) complementary resource use between species that arise from development of a stratified canopy (and possibly root stratification); and, (2) Facilitative improvement in nutrition of a valuable timber species growing in combination with a nitrogen-fixing species (Kelty, 2006). Furthermore, mixed plantations combining fast and slow-growth species show maximum productivity and profitability (Piotto *et al.*, 2004).

Just a few studies on wood properties of native forest species from mixed plantations are reported in literature and are limited to a reduced number of species and wood characteristics (Moya *et al.*, 2009; Moya and Muñoz, 2010). However, the properties of wood from

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natural forest of species used in mixed plantations, such as *E. cyclocarpum* and *S. saman* are well known (Carpio, 2003). *E. cyclocarpum* wood has moderate specific gravity (from 0.35-0.60), green density moderate values (0.77 g/cm^3), 0.45 g/cm^3 in air dry density, medium to fine texture, moderate shrinkage (2.6 % in tangential direction, 0.9% in radial direction, and 3.5% in volume), and excellent durability (Arévalo and Londoño, 2006; OFI/CATIE, 2003). Its heartwood is dark brown and its sapwood is white or pale yellow (OFI/CATIE, 2003). On the other hand, *S. saman* has moderate mechanical resistance, moderate specific gravity (from 0.42 to 0.64), interlocked grain, moderate shrinkage and wood color difference between sapwood and heartwood (Carpio, 2003).

The aim of the present study was to evaluate some physical properties of wood (green density, specific gravity, tangential, radial, and volume shrinkage, initial moisture content), aesthetic features such as color determined through Lab systems and heartwood presence from *Enterolobium cyclocarpum* and *Samanea saman* trees planted with other native Costa Rican species in mixed plantations.

Methodology

Geographic position

This study was performed in mixed plantations from the Estación Experimental Forestal Horizontes in the Guanacaste Conservation Area (ACG acronyms in Spanish) in Liberia, Guanacaste, Costa Rica (N 10° 42’ 48” W -85° 35’ 42”) on a 30 hectare field. Mixed plantations are located in the Northern region of Costa Rica, with a dry tropical climate (Holdridge, 1987), where typical conditions are an average temperature of 24.0 to 24.5°C, annual precipitation of 1,500 to 2,000 mm, and a dry season from November to May. The soil has a loam to clay loam texture, it is moderately acid (pH 5-6) and the slope is less than 2%. Some sectors in the plantation are susceptible to flooding during the rainy season and mixed plantations T6, T7, T10 and T13 (Fig. 1) were affected by this fact.

Characteristics of a mixed plantation

Fourteen different mixed plantations located one next to the other were selected for the study (Fig. 1). Each mixed plantation was planted in 1 hectare. Main species were *Enterolobium cyclocarpum* (Jacq.) Griseb. and *Samanea saman* Merrill, Elmer Drew and they were planted in combination with other native Costa Rican species (*Swietenia macrophylla* King, *Hymenaea courbaril* L., *Handroanthus impetiginosus* (Mart. ex DC.) Mattos, *Albizia adinocephala* (Donn. Sm.) Record, *Diphysa americana* (Mill.) M. Sousa, *Tabebuia rosea* (Bertol.) Bertero ex A.DC., *Dalbergia retusa* Hemsl. and *Simarouba glauca* DC.). The percentage of combination of different species on each mixed plantation (MP) and its respective codification are detailed in Fig. 1.

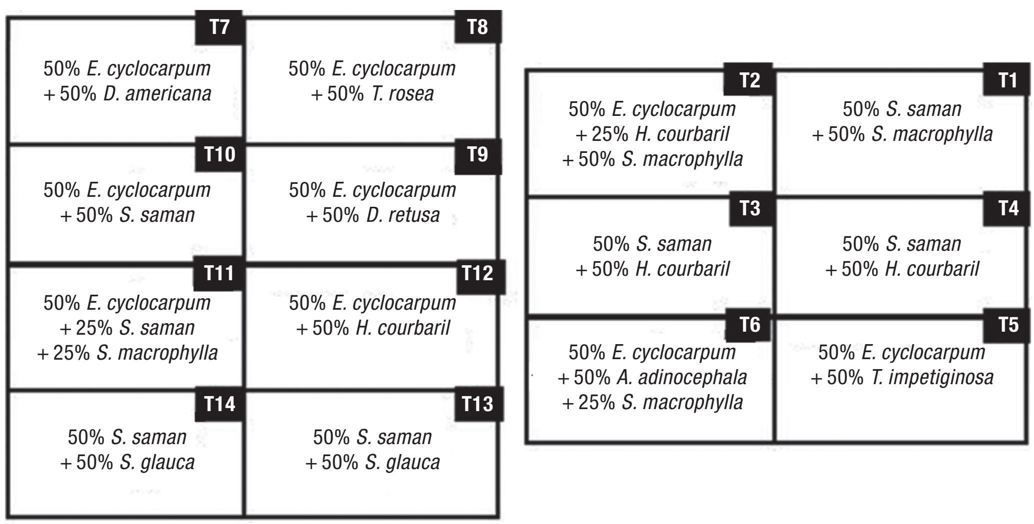

Figure 1. Distribution of mixture plantation of *S. saman* or *E. cyclocarpum* with different native species of 19 years-old in Costa Rica.

Plantation management

The initial planting density was 1,111 trees/ha (3 × 3 m spacing) and each species were planted in alternating rows (inter cropping systems). At the moment of evaluation, the stands aged 19 years presented a density of between 495 and 575 trees/ha (Table 1). Trees were planted at the beginning of the rainy season (June and July). After one year, it was necessary to replant some trees as trials. The trial had a sanitary thinning at age 6 and systematic thinning (33%) was applied at 11 years old. Each trial was pruned at the age of 6.

Trees sampled

Two plots (400 m^2) were established to characterize each MP (Fig. 1). The diameter at breast height and total height of all trees of *S. saman* or *E. cyclocarpum* within each plot were measured. Three trees were selected to represent all the diameter range in each MP. The harvested trees had straight boles with normal branching and without any visible disease or pest symptoms. Before cutting the trees, their north-facing side was marked. Then, a 200 cm long log from the basal part of the trunk was obtained. Two 4 cm thick discs (cross section) were obtained in the upper part of this log (200 cm from the soil line).

Heartwood and bark percentage determination

First, on each disc, a cross-sectional line was drawn from north to south passing through the pith and another was marked perpendicularly to the first, from east to west. Total diameter, diameter without bark,

Table 1. Morphologic characteristics of trees of *S. saman* and *E. cyclocarpum* from mixture plantation with different native species of 19 years-old in Costa Rica

Mixture plantation	d (cm)	d_H (cm)	*b* (cm)
S. saman			
T1	31.17^{BCD} (±0.94)	20.28^{BC} (±2.54)	1.01^{A} (±0.17)
T4	30.62^{DC} (±0.35)	19.90^{BC} (±1.76)	1.16^{A} (±0.19)
T10	35.92^{AB} (±1.82)	28.18^{A} (±1.85)	0.85^{A} (±0.12)
T11	37.90^{A} (±2.21)	25.40^{AB} (±0.88)	1.06^{A} (±0.34)
T13	35.05^{ABC} (±1.79)	24.08^{AB} (±3.09)	0.90^{A} (±0.07)
T14	29.38^{D} (±1.46)	17.18^{C} (±2.15)	1.02^{A} (±0.14)
Average	32.90 (±3.42)	22.10 (±4.11)	1.02 (±0.18)
E. cyclocarpum			
T2	31.08^{B} (±5.37)	16.20^{B} (±4.63)	0.77^{A} (±0.13)
T5	32.23^{B} (±0.08)	15.70^{B} (±0.83)	0.85^{A} (±0.13)
T6	34.38^{B} (±1.59)	16.10^{B} (±0.62)	0.82^{A} (±0.22)
T7	35.90^{B} (±2.22)	23.25^{A} (±1.65)	0.79^{A} (±0.15)
T8	33.00^{B} (±0.89)	18.55^{AB} (±1.00)	0.77^{A} (±0.12)
T9	45.12^{A} (±2.07)	24.50^{A} (±1.72)	1.03^{A} (±0.15)
T10	35.55^{B} (±2.21)	20.70^{AB} (±1.61)	0.71^{A} (±0.14)
T11	36.33^{B} (±1.12)	22.58^{A} (±1.77)	0.80^{A} (±0.16)
T12	34.57^{B} (±1.25)	19.22^{AB} (±2.07)	0.74^{A} (±0.09)
Average	35.35 (±4.27)	19.64 (±3.56)	0.81 (±0.15)

d_T: total diameter. d_h: heartwood diameter. *b*: bark thick. T1: 50% *S. saman* + 50% *Swietenia macropylla.* T2: 25% *E. cyclocarpum* + 25% *Hymenaea courbaril* + 50% *S. macrophylla.* T3: 50% *E. cyclocarpum* + 50% *Hymenaea courbaril.* T4: 50% *S. saman* + 50% *Hymenaea courbaril.* T5: 50% *E. cyclocarpum* + 50% *Tabebuia impetiginosa.* T6: 50% *E. cyclocarpum* + 25% *Albizia adinicephala* + 25% *S. macrophylla.* T7: 50% *E. cyclocarpum* + 50% *Diphysa americana.* T8: 50% *E. cyclocarpum* + 50% *Tabebuia rosea.* T9: 50% *E. cyclocarpum* + 50% *Dalbergia retusa.* T10: 50% *E. cyclocarpum* + 50% *S. saman.* T11: 50% *E. cyclocarpum* + 25% *S. saman* + 25% *S. macrophylla.* T12: 50% *E. cyclocarpum* + 50% *H. courbaril.* T13 y T14: 50% *S. saman* + 50% *S. glauca. Note:* Different letters for each general characteristic indicate that values are statistically different at a 99% confidence level and same letters for each general characteristic indicate that values are not statistically different.

pith diameter, and heartwood diameter (see Fig. 1 in Moya and Muñoz, 2010) were measured on a cross-sectional line drawn in two directions (north-south and east-west). Means for all diameters were calculated as the average of two cross-sectional measurements on each stem section. Next, the total heartwood and pith cross-sectional areas were calculated as a geometric circle, and the bark content was determined for the difference between the total area and the area without bark.

Wood physical properties

The following wood physical properties were determined: radial shrinkage (RS), tangential shrinkage (TS) and total volume shrinkage (VS), wood density at green condition (GD), initial or green moisture content (IMC) and specific gravity (SG). They were determined according to ASTM D-143 (ASTM, 2003a). A second 4 cm thick diametric section was cut into the cross section from north to south and it was cut at pith, obtaining two diametric sections. North diametric sections were re-cut to obtain 2.0 cm thick samples tangential to the growth rings and in bark-pith direction. The volume and weight of each sample were measured. The volume was defined as the volume of water it displaced when submerged, according to ASTM D2395-02 standards (ASTM, 2003b). Afterwards, the GD, SG and VS were determined. GD was calculated as weight divided by volume, while IMC was calculated as the difference between green and dry weight and divided by dry weight; and both values are expressed as percentages, according to ASTM D-143-92 (ASTM, 2003a). SG was calculated as the oven-dry weight divided by volume in green condition. VS was determined as the difference between green and oven-dry volume and divided by green volume. The east and west sides of the disk were used to measure RS and TS. Refer to Moya and Muñoz (2010) for details regarding type of sample cut. They were determined as the difference between green and oven-dry dimensions, and divided by green dimension.

Wood color

A cross section used for heartwood and bark determination was also used for wood color determination. A 3 cm wide diametric section was extracted for all sample trees. These samples were conditioned at 22°C and at a relative humidity of 66% in order to obtain a 12% in equilibrium moisture content. Wood color was measured along radial transect at four distances from the pith (near the pith, midway between pith and sapwood/heartwood boundary, sapwood/heartwood boundary, and halfway into sapwood thickness). Wood color was measured on the tangential side of the block according to ISO 7724/1-1984 and ISO 7724/2-1984 (ISO 1984). A HunterLab MiniScan® XE Plus spectrophotometer was used. Measurements were taken at room temperature and color characteristics were determined using the CIELab system, which determines lightness, redness and yellowness (parameters L*, a*, and b* respectively). Measurement range was 400 to 700 nm, with a 13 mm aperture at the measurement point. The specular component (SCI mode) was included to observe reflection at a 10º angle, which is normal for the specimen surface (D65/10), as well as a 2° field of vision (standard observer, CIE 1931), and standard D65 illumination (corresponds to daylight at 6,500 K).

Color difference

According to ASTM D2244 (ASTM, 2003c), the color difference between two wood samples measured using the CIELab system can be expressed as an index called ΔE* (Equation 3). In this study, heartwood difference was calculated (ΔE*) between different mixed plantations of the same species (*S. saman* or *E. cyclocarpum*). Also, the ΔE* was calculated between wood color of trees from different mixed plantations and wood color of trees from natural forests. The calculation of ΔE* heartwood was deemed important in order to assess the color quality of different mixed plantations. Therefore, the standard heartwood color was obtained from samples from natural forest in Xylariorum "Víctor Rojas" at the Costa Rica Institute of Technology. The wood samples were TECw-29 for *S. saman* and TECw-83 for *E. cyclocarpum*. Values L*, a*, and b* were averaged out for this pattern and then ΔE* was calculated in accordance with ASTM D2244 (ASTM, 2003c) using equation 1:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad [1]$$

where: $\Delta L^* = L^* - \Delta L^*_P$, $\Delta a^* = \Delta a^{*M} - \Delta a^*_P$, $\Delta b^* = b^{*M} - \Delta b^*_P$, M = value of sample color coordinate of a mixture plantation and p = value of pattern color coordinate or other mixture plantation.

Statistical analysis

A descriptive analysis was first conducted to evaluate the normal distribution of data, homogenous variance, and absence of extreme data in the heartwood and bark percentage, physical properties and color parameters. Additionally, average values, standard deviation, and variation ranges were calculated using the SAS UNIVARIATE procedure (version 8.1 for Windows). After that, analysis of variance (ANOVA) was used to determine the causes for wood properties measured in this study, then the Tukey test was applied to establish differences between the averages of wood properties from different mixture plantations. Regression analysis was used to determine the relationships of color coordinates (L*a*b*) or specific gravity and pith distance. SAS (SAS Institute Inc.) and STATISTICA 6.0 (Statsoft Inc.) programs were used for the statistical computations.

Results

Morphologic characteristics at 200 cm in height

The average diameter from total diameter and heartwood (Table 1) of *S. saman* are highest when this species was planted next to *E. cyclocarpum* (50%-50%, known as T10); with *E. cyclocarpum* and *S. macrophylla* (50%-25%-25%, named as T11) and when it is planted together with *S. glauca* (50%-50%, known as T13). The total diameter varied from 35.0 to 38.0 cm and heartwood diameter ranged from 24.0 to 28.5 cm (Table 1). For other MP of *S. saman*, the total diameter varied from 29.0 to 31.5 cm and from 17.0 to 20.5 cm in heartwood diameter (Table 1). For *E. cyclocarpum*, the highest diameter was found in MP of this species planted with *D. retusa* (50-50%, named T9), but heartwood diameter was not statistically different among MPs (Table 1).

The highest value of heartwood percentage (HWP) in *S. saman* appeared when this species was mixed with *E. cyclocarpum* (T10). However, statistical differences with other MP with *S. saman* and other native species (Fig. 2a) were not found with the exception of MP of *E. cyclocarpum* and *S. glauca* (T14), which presented the lowest values of HWP (Fig. 2a). On the other hand, MP with *E. cyclocarpum* produced lower values of HWP than *S. saman*. Meanwhile, MP of *S. saman* and other native species of Costa Rica produced no significant differences in HWP (Fig. 2a). Regarding BP or pith diameter, it was found that MP with *S. saman* or *E. cyclocarpum* and other native species did not produce statistical differences in BP and pith diameter (Table 1 and Fig. 2b).

Physical properties

Table 2 shows the average values for physical properties (GD, IMC and different types of shrinkages) at 200 cm for MP of *S. saman* or *E. cyclocarpum*. IMC varied from 99 to 124% in MP of *S. saman*, meanwhile IMC in MP of *E. cyclocarpum* was slightly higher, the average varied from 111 to 150% (Table 2). It was found that GD ranged from 0.95 to 1.03 g/cm^3 in *S. saman*. The highest values were found in *E. cyclocar-*

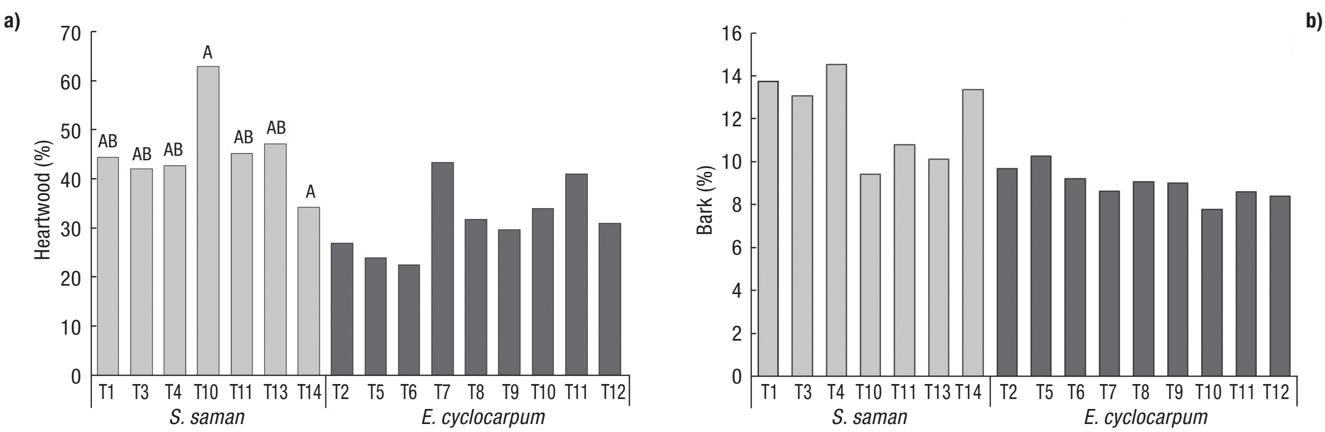

Figure 2. Heartwood (A) and bark (B) proportions in trees of *S. saman* and *E. cyclocarpum* from mixture plantation with different native species of 19 years-old in Costa Rica. For treatment name see legend oT table 1 and Fig. 1. Different letters for each general characteristic indicate that values are statistically different at a 99% confidence level.

Table 2. Physical properties of wood of trees of *S. saman* and *E. cyclocarpum* from mixture plantation with different native species of 19 years-old in Costa Rica

Mixture plantation	Initital moisture content (%)	Green density (g/cm^3)	Shrinkage Volume (%)	Shrinkage Radial (%)	Shrinkage Tangential (%)
S. saman					
T1	99^A (±37)	0.95^A (±0.14)	6.27^A (±1.20)	2.76^A (±0.53)	3.72^A (±0.62)
T3	101^A (±26)	1.03^A (±0.11)	6.59^A (±1.10)	3.47^A (±0.70)	4.64^A (±0.51)
T4	100^A (±36)	0.99^A (±0.14)	6.93^A (±1.41)	2.85^A (±0.54)	4.94^A (±1.70)
T10	124^A (±48)	0.98^A (±0.13)	6.33^A (±1.32)	2.51^A (±0.46)	3.80^A (±0.86)
T11	102^A (±38)	0.96^A (±0.13)	6.75^A (±1.34)	2.92^A (±0.53)	3.06^A (±1.16)
T13	105^A (±37)	1.01^A (±0.11)	6.44^A (±1.09)	2.81^A (±0.47)	4.00^A (±0.15)
T14	102^A (±29)	1.00^A (±0.12)	6.52^A (±1.15)	2.23^A (±0.71)	4.40^A (±0.88)
Average	105 (±38)	0.99 (±0.13)	6.55 (±1.25)	2.79 (±0.58)	4.08 (±0.98)
E. cyclocarpum					
T2	149^A (±69)	0.80^A (±0.28)	2.91^A (±1.20)	1.10^A (±0.74)	2.84^A (±0.41)
T5	138^A (±72)	0.76^A (±0.26)	3.25^A (±1.09)	2.20^A (±0.51)	3.18^A (±0.10)
T6	125^A (±55)	0.82^A (±0.23)	3.63^A (±1.16)	1.17^A (±0.90)	3.28^A (±0.80)
T7	130^A (±64)	0.86^A (±0.23)	3.80^A (±1.17)	2.07^A (±0.82)	3.71^A (±0.26)
T8	122^A (±66)	0.76^A (±0.27)	2.88^A (±0.85)	1.20^A (±0.10)	3.61^A (±0.36)
T9	107^A (±57)	0.70^A (±0.26)	3.63^A (±1.17)	1.95^A (±1.19)	4.52^A (±0.11)
T10	119^A (±71)	0.72^A (±0.24)	5.26^A (±1.23)	1.97^A (±0.72)	3.91^A (±1.95)
T11	134^A (±70)	0.84^A (±0.27)	3.32^A (±0.92)	1.97^A (±0.63)	3.46^A (±0.21)
T12	111^A (±55)	0.83^A (±0.25)	2.91^A (±0.92)	2.14^A (±0.55)	3.55^A (±0.50)
Average	125 (±65)	0.78 (±0.26)	3.66 (±1.13)	1.74 (±0.75)	3.56^A (±0.76)

For treatment name sees legend of Table 1. Different letters for each general characteristic indicate that values are statistically different at a 99% confidence level and same letters for each general characteristic indicate that values are not statistically different.

pum, varying from 0.70 to 0.86 g/cm^3. For SG, it was determined that MP of *S. saman* presented values from 0.48 to 0.51 and these values are higher than values measured in *E. cyclocarpum*, varying from 0.31 to 0.38 (Fig. 3). Finally, different shrinkages show same performance of SG, the highest shrinkage (VS, TS and RS) were presented in *S. saman* (Table 2). An important result from the ANOVA analysis was that no physical properties were statistically different among different MP of *S. saman* or *E. cyclocarpum* (Table 2 and Fig. 3).

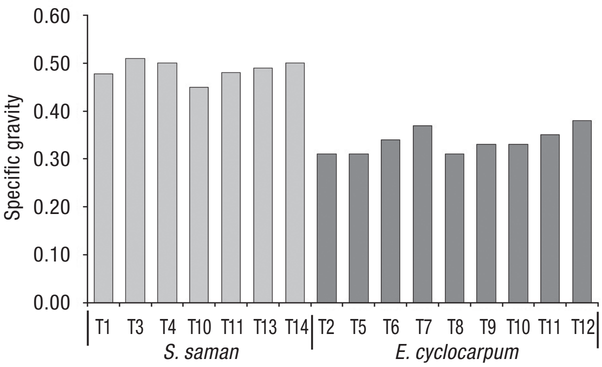

Figure 3. Variation of specific gravity of *S. saman* and *E. cyclocarpum* from mixture plantation with different native species of 19 years-old in Costa Rica. For treatment name sees legend of Table 1 and Fig 1.

Radial variation of physical properties shows that both species evaluated in different MPs presented different performance from pith to bark direction. SG increased from pith to bark direction in *S. saman* trees from MP, the lowest values are presented near the pith and afterwards the SG increases with distance from pith (Fig. 4a). However, *E. cyclocarpum* SG did not present any relation to distance from pith, SG was slightly constant (Fig. 4b). IMC decreased in both species, however the variation of IMC of *E. cyclocarpum* was irregular and high variation (Fig. 4c), meanwhile the decreasing in *S. saman* was uniform (Fig. 4d). Green density in both species was constant from basal tree part until 50% of distance from pith to bark, afterwards this physical properties decreased with distance from the pith (Fig. 4e and 4f). Finally, volumetric shrinkage

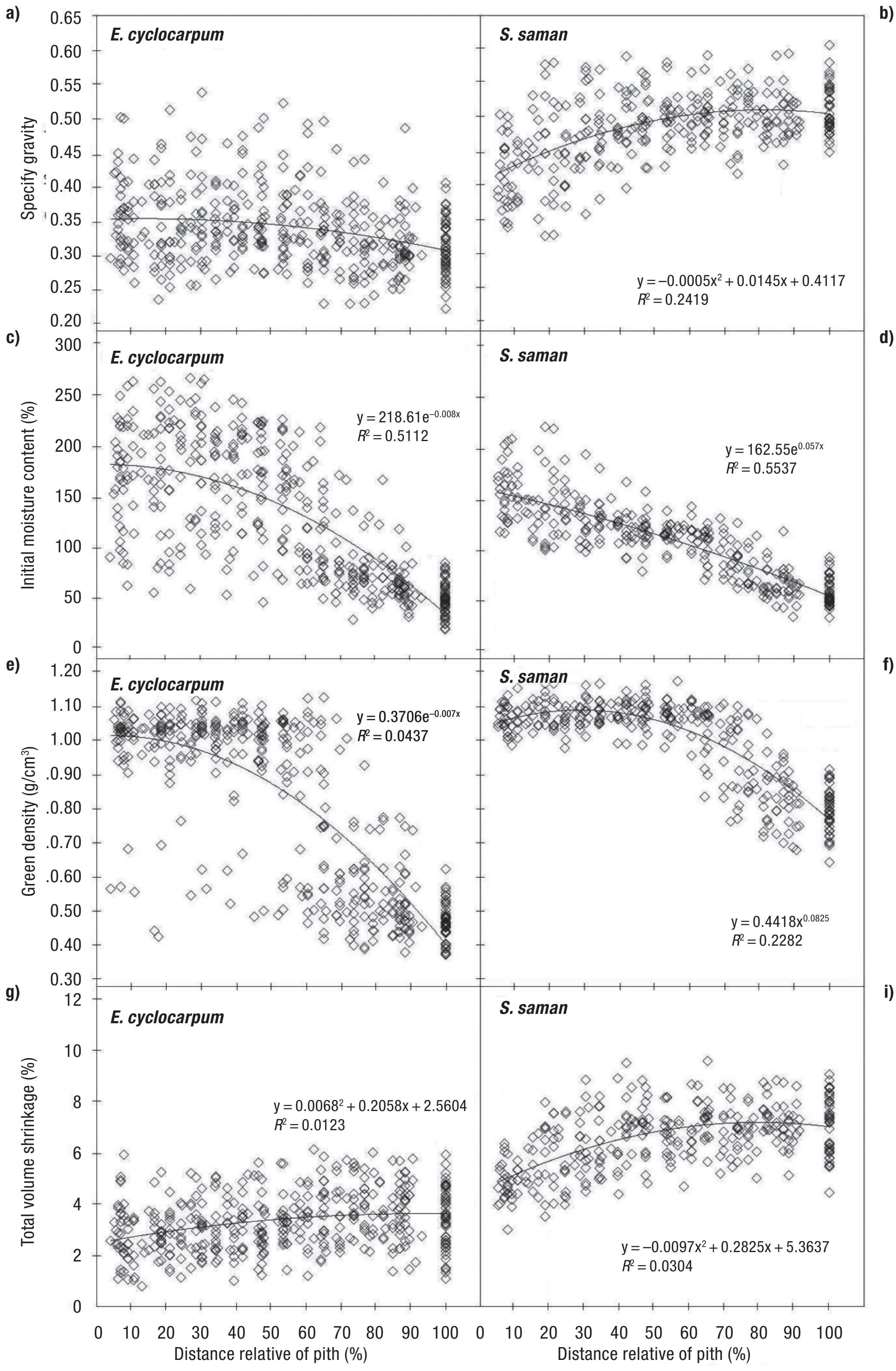

Figure 4. Variation of specific gravity, initial moisture content, green density and total volumen shirinkage in trees of *S. saman* (a) and *E. cyclocarpum* (b) from mixture plantation with different native species of 19 years-old in Costa Rica.

was not relation with pith distance in *E. cyclocarpum* (Fig. 4g), but there was an increasing with distance from pith in *S. saman* (Fig. 4h).

Wood color

The color composition of *S. Saman* or *E. cyclocarpum* wood can be described using the combination of different tonalities of lightness (L*), redness (+a*) and yellowness (+L*). Sapwood color was different than heartwood in trees from MP of *S. Saman* or *E. cyclocarpum*. Wood color of sapwood was whitish or yellowish and heartwood was reddish or brownish. This difference was produced by a statistical difference in two of three color parameters. Heartwood of both species presented the lowest values of L* (lightness) and they were statistically different from sapwood. The a* color parameter (redness) was higher in heartwood than sapwood. A statistical difference in b* color parameter between heartwood and sapwood from both planted species was not found (Fig. 5).

ANOVA shows that three color parameters (L*, a* y b*) of sapwood of two species from different MP was not found statistically different among them (Table 3). In relation to heartwood, it was demonstrated that wood from *S. saman* trees growing in different MP, lightness parameter (L*) and redness parameters (a*) were not different in different MP. But yellowness tonality (b*) was affected when *S. saman* was planted with other

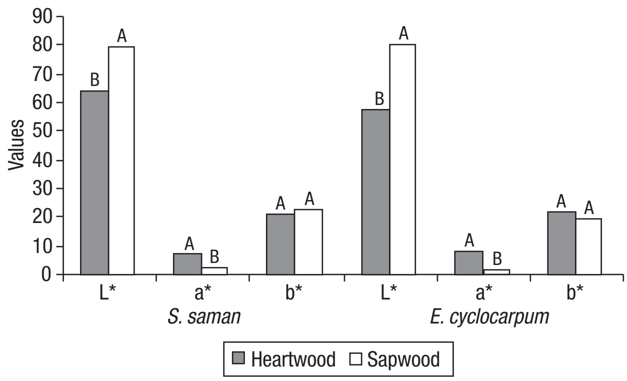

Figure 5. Wood color parameters of sapwood and heartwood of trees of *S. saman* and *E. cyclocarpum* from mixture plantation with different native species of 19 years-old in Costa Rica. For treatment name sees legend of Table 1. Different letters for each general characteristic indicate that values are statistically different at a 99% confidence level.

Table 3. Wood color parameters measured by CIE Lab of *S. saman* and *E. cyclocarpum* from mixture plantation with different native species of 19 years-old in Costa Rica

Mixture plantation	Heartwood			Sapwood		
	L*	a*	b*	L*	a*	b*
S. saman						
T1	65.02^{A} (±4.78)	7.65^{A} (±1.65)	20.47^{AB} (±0.89)	79.85^{A} (±4.43)	2.55^{A} (±1.54)	20.65^{A} (±1.38)
T3	63.92^{A} (±2.52)	6.98^{A} (±0.88)	20.62^{AB} (±1.73)	79.62^{A} (±5.94)	2.47^{A} (±1.51)	22.62^{A} (±0.69)
T4	62.75^{A} (±3.73)	7.90^{A} (±0.93)	20.03^{AB} (±3.06)	82.11^{A} (±0.67)	2.44^{A} (±0.12)	21.96^{A} (±1.46)
T10	60.36^{A} (±6.38)	7.22^{A} (±2.20)	21.72^{AB} (2.99)	78.11^{A} (±3.26)	2.12^{A} (±1.18)	24.39^{A} (±4.33)
T11	64.04^{A} (±1.59)	7.73^{A} (±0.24)	19.17 ^{B} (0.97)	80.18^{A} (±0.79)	3.16^{A} (±0.27)	18.97^{A} (1.52)
T13	65.08^{A} (±3.24)	7.04^{A} (±0.63)	20.5^{AB} (±2.48)	77.79^{A} (±3.15)	2.71^{A} (±0.95)	22.59^{A} (±5.48)
T14	64.81^{A} (±3.11)	6.79^{A} (±0.93)	23.44^{AB} (±1.02)	80.80^{A} (±3.98)	2.37^{A} (±0.84)	25.93^{A} (±2.49)
E. Cyclocarpum						
T2	60.44^{AB} (±2.60)	6.93 ^{B} (±0.32)	23.50^{A} (±0.44)	82.48^{A} (±1.12)	0.98^{A} (±0.47)	20.20^{A} (±0.68)
T5	56.12^{AB} (±0.85)	8.27^{AB} (±0.57)	21.08^{A} (±1.65)	76.62^{A} (±5.15)	1.45^{A} (±0.26)	17.04^{A} (±3.43)
T6	58.57^{AB} (±7.73)	7.05 ^{B} (±0.98)	23.33^{A} (±1.45)	82.26^{A} (±2.45)	1.18^{A} (±0.26)	20.56^{A} (±1.41)
T7	54.36 ^{B} (±5.47)	7.72^{AB} (±0.53)	22.94^{A} (±2.07)	75.26^{A} (±7.91)	1.04^{A} (±0.59)	19.70^{A} (±1.17)
T8	57.03^{AB} (±1.23)	8.86^{A} (±0.81)	20.93^{A} (±1.56)	78.56^{A} (±1.06)	1.55^{A} (±0.54)	16.90^{A} (±2.12)
T9	56.74^{AB} (±4.56)	8.27^{AB} (±0.97)	20.39^{A} (±3.29)	81.67^{A} (±2.80)	1.34^{A} (±0.94)	20.48^{A} (±2.04)
T10	63.86^{A} (±4.97)	7.87^{AB} (±1.81)	21.92^{A} (±0.90)	84.25^{A} (±0.87)	1.10^{A} (±0.44)	18.64^{A} (±3.05)
T11	57.27^{AB} (±2.14)	8.29^{AB} (±0.90)	20.35^{A} (±0.53)	83.08^{A} (±1.30)	1.19^{A} (±0.21)	17.40^{A} (±1.26)
T12	52.98 ^{B} (±2.51)	7.62^{AB} (±1.51)	21.28^{A} (±0.33)	79.00^{A} (±3.68)	1.33^{A} (±0.20)	21.96^{A} (±2.02)

L*: lightness from black (0) to white (100). a*: redness (+) to greeness (–). b*: yellowness (+) to bluness (–). For treatment name sees legend of Table 1. Different letters for each general characteristic indicate that values are statistically different at a 99% confidence level and same letters for each general characteristic indicate that values are not statistically different.

tropical species (Table 3). Wood from *S. saman* trees planted with *S. glauca* (T13 and T14) had higher b* than wood from trees *S. saman* planted with *E. cyclocarpum* and *S. macrophylla* (T11). In relation to *E. cyclocarpum*, it was found that b* color parameters were not affected by different MP. But for L* and a* parameters some differences were established. Wood from trees growing in MP of *E. cyclocarpum* and *S. saman* (T10) presented higher values than wood from trees growing in MP of *E. cyclocarpum* and *D. americana* (T7). Furthermore, wood from these MP were not different from other MP. The a* color parameter of heartwood was highest in wood from trees growing in MP planted with *E. cyclocarpum* and *T. rosea* (T9) and this value was significantly different than wood from trees in MP of *E. cyclocarpum*, *H. courbaril* and *S. macrophylla* (T2) (Table 3).

Wood color parameters of *S. Saman* and *E. cyclocarpum* varied according to distance from the pith (Fig. 6). L* and b* color parameters (lightness and yellowness respectively) decreased from near the pith up to the heartwood boundary, afterwards the value increased in the sapwood section (Fig. 6a and 6c), with the exception of b* parameter of *E. cyclocarpum*, which decreased in the sapwood section (Fig. 6c). On the other hand, the redness parameter (a*) tends to remain with distance from pith in the heartwood section, and then this value decreased in the sapwood part (Fig. 4b). This variation of wood color parameters in the wood in inner part of heartwood produced a lighter color than the wood near the heartwood boundary, which means that the wood becomes increasingly dark.

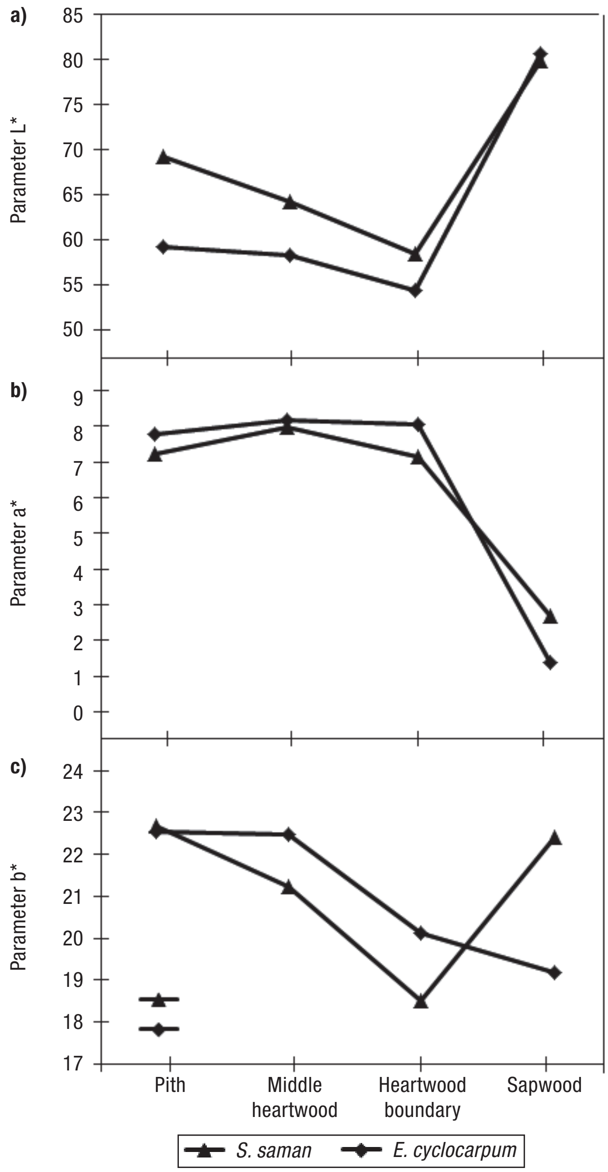

Figure 6. Relationship between distance from the pith and L*, a*, b* for wood of trees of *S. saman* and *E. cyclocarpum* from mixture plantation with different native species of 19 years-old in Costa Rica.

Discussion

Trees from MP with higher HWP are considered an advantage because their wood is an important factor for determining specific uses such as furniture and decorative veneers, both very important marketing attributes (Mazet and Janin, 1990) associated with high decay resistance as well (Moya and Berrocal, 2010). According to that, MP of *S. saman* with *S. glauca* (T14) is less favourable because it produced trees with the lowest HWP values. However, this result must be considered with care, because other MP with *S. saman* and *S. glauca* (T13) located near T14 (Fig. 1) did not present statistical differences in HWP and total diameter regarding other MP of *S. saman* (Table 1). The difference found in total diameter and heartwood in two MPs of *S. saman* with *S. glauca* (T13 and T14) may be due to the difference in site. The T14 MP was planted on a site susceptible to flooding. Hocking and Islam (2011) studied the growth of *S. saman* in natural forests and they found that the diameter was reduced in sites susceptible to flooding.

HWP in all MPs was lower than 50%. However this percentage is common in tropical species growing in fast-growth plantations. For example, Moya and Muñoz (2010) and Moya *et al.* (2009) found similar or higher values of HWP than our results in *Terminalia amazonia*

(J. F. Gmel.) Exell, *T. oblonga* (Ruiz & Pav.) Steud., *Vochysia guatemalensis* Donn. Sm., and *Bombacopsis quinata* (Jacq.) Dugand, except *Acacia mangium* Willd. and *Cupressus lusitanica* Mill. in pure plantations, which resulted in 65% and 70% respectively.

Another important result of this study was that HWP was not affected in any MP of *S. saman* or *E. cyclocarpum* (Fig. 2b), but total diameter and heartwood diameter was higher in some MPs of these species (Table 1). For example, *S. saman* and *E. cyclocarpum* (T10) MP mixing *S. saman* with *E. cyclocarpum* and *S. macrophylla* (T11) or *S. saman* with *S. galuca* (T13) produced the highest total diameter (Table 1). Lumber recovery Factor (LRF) is associated to log diameter (Steele 1984). In general, the overall conversion factor, volume yield, and output of saw milling increased with increasing log diameter. In other words, lumber recovery is higher for logs with larger diameters (Pnevmaticos *et al.*, 1970; Wang *et al.*, 2003). Therefore, trees from MP with the highest total diameter will produce higher LRF than trees from MP with the lowest total diameter.

On the other hand, BP found in two native species of Costa Rica in MP conditions corresponds to other native species planted in fast-growth conditions in this country. Moya and Muñoz (2010) reported a range in variation of 8.7 to 20.1% for lumber from trees coming from fast-growth plantations. Bark of trees has different physiological properties; they are related to the ecology of the different tree species and provide different habitats for bark living arthropods (Nicolai 1986) or genetic control (Zhong *et al.*, 2009). The thickness of the bark correlates with factors such as moisture availability, tree age, genetic and diameter classes (Sonmez *et al.*, 2007). The lack of difference in bark thickness (Table 2) or percentage of bark (Fig. 1b) among mixed plantations can be attributed to a genetic control of bark in each species (Zhong *et al.*, 2009).

S. saman SG average was 0.48. This result agrees with other reports. OFI/CATIE (2003) reported values ranging from 0.42 to 0.64. However, different shrinkage values (VS, TS and RS) disagreed with our results. Meanwhile, Arevalo and Londoño (2006) reported a range from 0.35 to 0.60 for *E. cyclocarpum* trees growing in natural forests in Colombia. The SG found for this species in our study (from 0.35 to 0.38) is included in Arévalo and Londoño's range. Tamarit and Fuentes (2003) studies for *E. cyclocarpum* also from natural forest, found values of SG (0.35) and volume shrinkage (8.40%) similar to our results; however, they reported values in IMC (220%) higher than values found in different MP.

This divergence between our results and these references suggests a probable influence from the site, environmental conditions or juvenile presence on wood quality. Zobel and Van Buijtenen (1989) suggest that large structure variations are produced by changes in climate, site, juvenile wood and management characteristics. The differences between those references and our findings may be due to: (1) trees were harvested in fast-growth condition, (2) trees age is only 19 years old, and (3) high juvenile wood proportions.

SG can increase with tree age or pith distance in trees from all *S. saman* MPs, but *E. cyclocarpum* mixed plantations did not showed any relation with pith distance. SG is a measurement of the amount of wood fiber cell walls and void space, and therefore this parameter determines the amount of water in wood (Moya and Tomazello, 2007). In hardwood species, the wood density variation depends on the amount or proportion of different cell types and spatial arrangements. Four different cell types are present in hardwood, each more or less specialized in structure and restricted in function; rays; vessels; fibers; axial parenchyma. In addition, many molecular and physiological changes occur in the vascular cambium during the aging process (Plomion *et al.* 2001). Thus, this explains the SG increase with the aging of *S. saman* and we can associate aging with thick-walled fibers and vessel diameter, but a vessel frequency decrease in *S. saman*. Whereas anatomical variations in *E. cyclocarpum* are different and they may be affecting the typical development of SG with tree age, anatomical variations of fiber, vessels or ray tissue affect SG differently (Moya and Tomazello, 2007).

Wood with low uniformity of SG from pith to bark is one of the greatest problems for the industrial face. Echols (1973) attributed wood density uniformity degree as a limiting factor for the end use of the wood considering the effect in the sawing, drying, machining, gluing, finishing and other wood quality. According to this, the log of *E. cyclocarpum*, with low uniformity in SG across transversal sections, may present better performance in sawing, drying, machining, gluing and finishing processes than the *S. saman* log.

The difference in color between heartwood and sapwood of *S. saman* and *E. cyclocarpum* is due to the process of heartwood formation, with the extractives produced accumulating in the heartwood, resulting in color (Gierlinger *et al.*, 2004). The process depends on several factors, such as tree age, soil composition and location within a tree. Some precursors of the synthesis of extractives are located in sapwood tissue, but the content is lower than in heartwood (Gierlinger *et al.*, 2004). For various other species, tree age or pith distance has shown significant correlations with color parameters, similar to the two native species of Costa Rica. For example, Gierlinger *et al.* (2004), studying hybrids of Japanese larch, have shown that old trees have significant redder hue (a*) than young trees. Klumpers *et al.* (1993) found that the heartwood became increasingly redder (a*) with age in *Quercus robur*. Moya and Berrocal (2010) studying wood color variation for *Tectona grandis*, showed that * L* and a* were negatively and positively respectively correlated with pith distance in heartwood, but not for b*.

In this case, there are differences between two native species, a* color parameters were maintained and b* parameters decreased across heartwood in *S. saman* and *E. cyclocarpum*, but for *T. grandis* this relationship was different, a* increased and b* was maintained across heartwood sections (Moya and Berrocal, 2010).

The wood color difference index ΔE* (Equation 1) is expressed as a distance between two points in the color coordinate system, a quadratic addition of the difference in each coordinate (Gonnet 1993). Cui *et al.* (2004) mentioned the value of color change (ΔE*) to define the levels of perceived difference in color. ΔE* varying for 0 to 0.5 is defined as negligible, between 0.5 and 1.5 is slightly perceivable, from 1.5 to 3.0 is noticeable, from 3.0 to 6.0 is appreciable, and from 6.0 to 12.0 is very appreciable. Consequently for this study, a* value higher than 1.5 units in wood color difference index (ΔE*) from two different mixed plantations will produce a difference noticeable or appreciable in visual perception. Table 4 includes a matrix comparing the color difference index ΔE* among mixed plantations of *S. saman* and *E. cyclocarpum*. From this table we can observe that mixed plantations of these two tropical species produce different wood color in heartwood.

It was found that the ΔE* values in *S. saman* mixed plantations were higher than 1.5 units in most comparisons of two MPs except in comparison between T4 with T1 (*S. saman* with *S. macrophylla* plantation and *S. saman* with *H. courbaril* plantations, respectively) and T3 with T13 (*S. saman* with *H. courbaril* and *S. saman* with *S. glauca* plantation respectively). The other color comparisons between mixed plantations with *S. saman* showed that wood color difference between different mixed plantations is cataloged as noticeable and appreciable (ΔE* ranged from 1.56 to 4.88). Another important result is that wood from mixed plantations produced large wood color differences in relation to wood from tree growing in natural forests. ΔE* was higher than 35 in all comparisons (Table 4). The mixed plantations of *S. saman* and *E. cyclocarpum* produced trees with the lowest difference in wood color compared to wood color from trees growing in the natural forest (ΔE* = 35.71).

E. cyclocarpum heartwood color comparison between different MP (Table 4) showed that MP T8 (*E. cyclorcarpum* with *T. rosea*) and T5 (*E. cyclocarpum* with *T. impetiginosa*) did not produced any color difference than other MPs. No difference was found between T8 and T5 (*E. cyclorcarpum* with *T. rosea* and *E. cyclocarpum* with *T. impetiginosa* plantation, respectively), T9 and T5 (E. cyclorcarpum with *D. retusa* and *E. cyclocarpum* with *T.impetiginosa* plantation, respectively), T9 and T8 (*E. cyclorcarpum* with *D. retusa* and *E. cyclocarpum* with *T. rosea*), T11 and T5 (*E. cyclorcarpum* with *S. saman* and *S. macrophylla* and *E. cyclocarpum* with *T.impetiginosa* plantation, respectively) and T11 and T9 (*E. cyclorcarpum* with *S. saman* and *S. macrophylla* and *E. cyclocarpum* with *D. retusa* plantation, respectively). Whereas, wood from T2, T6, T7, T10 and T12 MPs was different among them, and different than T5, T8, T9 and T11. It is important to observe that trees from T10 MP (*E. cyclorcarpum* with *S. saman*) produced wood with large differences in heartwood color compared to wood from other mixed plantation, especially T5, T7, T8 and T9. Trees from T12 produce too large wood color differences than T2 and T10 (Table 4). Other color comparisons showed that color differences between MPs are catalogued as noticeable and appreciable (ΔE* ranged from 1.56 to 4.88). Furthermore, comparisons between *S. samam* (?) and *E. cyclocarpum* wood from mixture plantation produced large wood color difference in relation to wood from trees growing in natural forests. ΔE* varied from 25.49 to 34.24 (Table 4). According to these results, mixture plantation T7 (*E. cyclocarpum* with *D. americana*) produced wood with the lowest difference in wood color extracted from trees growing in the natural forest (ΔE* = 25.49).

Wood color differs widely among species as well as within a single tree (Liu *et al.* 2005). Pith distance is the main factor of heartwood color variation within a tree (Klumpers *et al.*, 1993; Moya and Berrocal, 2010). Some tropical species growing in fast-growth pure plantation agreed with the variation of color parameters in relation to pith distance for L* and b* parameters (Moya and Berrocal, 2010). And these variations in color parameters are attributed to extractive content, especially to phenol extractive types (Gierlinger *et al.*, 2004).

Silvicultural implications

Higher diameter is reached when *S. saman* and *E. cyclocarpum* are planted together in a MP, specifically when they are planted in a relation of 50%-50%. Another important mixture is when *S. saman* is planted with *E. cyclocarpum* and *S. macrophylla* (50%-25%-25%) and with *S. glauca* (50%-50%). According with these results, these MPs are the best combination for production of *S. saman* and *E. cyclocarpum*. However, the combination of *E. cyclocarpum* with *D. retusa* (50%-50%) reached the largest heartwood diameter in *E. cyclocarpum* was found when this species is planted with *D. retusa* (50%-50%). Then, if these species are important for its heartwood properties, the management of MP may be oriented for heartwood increment. Silvicultural practices such as the usage of spacing and thinning help to heartwood proportions (Gartner, 2005).

Another important aspect is that the physical properties are lightly affected when *S. saman* or *E. cyclocarpum* are planted with other native Costa Rican species. Therefore the management can be oriented in the heartwood increment and wood properties were not affected. On the other hand, if we want to produce wood with little wood color difference with wood from trees growing in native forests, the management of MP of *S. saman* or *E. cyclocarpum* with other tropical species must be different. For example, large heartwood proportion is reached when *S. saman* is planted next to *E. cyclocarpum* (50-50%), but this combination produce wood with large color difference in relation to wood from native species. Therefore, this management help productivity but not wood color.

Conclusion

S. saman and *E. cyclocarpum* planted in MP with other native tropical species in Costa Rica produce some variations in total and heartwood diameter of a tree. The largest of these diameters is reached when *S. saman* is planted with *E. cyclocarpum* (50%-50%), with *E. cyclocarpum* and *S. macrophylla* (50%-25%-25%) and with *S. glauca* (50%-50%). Meanwhile, the largest total and heartwood diameter in *E. cyclocarpum* was found when this species is planted with *D. retusa* (50%-50%). Large variations in these tree parameters were also found.

Heartwood percentage, bark percentage, some physical properties (IMC, SG, GD and different shrinkage) are not affected when *S. saman* or *E. cyclocarpum* are planted with other native Costa Rican species. However, wood color, an important wood characteristic for commercial use, was affected when *S. saman* or *E. cyclocarpum* were planted with other tropical species. The lowest difference between wood from mixed plantations and wood from trees growing in native forests is produced when *S. saman* is planted next to *E. cyclocarpum* (50-50%). But this last species, when mixed with *H. courbaril*, produced wood with the lowest difference in color than wood extracted from trees growing in a natural forest.

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