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RESEARCH ARTICLE

Acacia melanoxylon in Argentina: heartwood content and its relationship with site, growth and age of the trees

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Abstract

Aims of study: To characterize the wood of *Acacia melanoxylon* in relation to its potential use in the construction and furniture industry, here we determined the heartwood and sapwood content and distribution within the stem and analyzed their relationship with the growing site, age and growth rate of the trees. Finally, we predicted heartwood content by two easy-to-measure variables.

Area of study: Buenos Aires, Argentina.

Methods: 20 trees aged between 9 and 32 years were sampled in four sites. Axial sampling was carried out at four heights of the stem (base, breast height, and 30% and 50% of the total height), and the heartwood content (percentage and volume) and sapwood content (cm) determined.

Results: The trees analyzed presented conical-shaped heartwood following the outline of the stem along all its commercial height. Within the stem, the highest volume of heartwood was observed at the basal region (53%) and up to 30% of total height, a feature observed in all the sites studied. The sapwood content was constant along the entire stem (2.18 cm). The age of the trees did not influence the heartwood content, whereas the environmental conditions provided by each site (heartwood/volume and heartwood/diameter growth positive ratios) did affect this feature.

Research highlights: The absolute amount of heartwood was driven by growth rate, due to the forest structure of non-uniform age. The heartwood volume can be estimated through fitting linear equations (R^2 0.78 - 0.89) with two easily measurable variables such as diameter at breast height and tree height.

Keywords: axial variation; general linear models; heartwood; sapwood; wood quality.

Abbreviations used: BH: breast height; DBH diameter at breast height; TH: total height of tree; ob: over bark; ub: under bark.

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Introduction

The southeastern region of Buenos Aires province (Argentina) has a forest resource of *Acacia melanoxylon* R. Br., which has recently begun to be characterized as regards its dasometric parameters and the technological aptitude of its wood (Igartúa *et al*., 2009; Igartúa & Monteoliva, 2009; Monteoliva *et al*., 2009; Monteoliva & Igartúa, 2010; Monteoliva *et al*., 2012; Igartúa *et al*., 2015). These forests are located largely on hilly sites, either in pure composition or associated with *Eucalyptus globulus* Labill., are grown with no commercial purposes (forest of non-uniform age) and are not subject to plans of forest management (Igartúa, 2013).

In Australia, *Acacia melanoxylon* is a forest species that grows naturally in a wide range of forest ecosystems, with a wide latitudinal distribution along its east coast, which has versatile applications (sawn timber for all types of use including wood carving, joinery, veneer making, furniture, firewood and livestock forage) and high adaptability (Maslin & Pedley, 1982a; Maslin & Pedley, 1982b). Thus, in Argentina, it could become part of the offer of the regional market of quality wood for solid applications related to the construction and furniture industries, which regionally demand this kind of wood (DPE 2005a, 2005b).

The value of *A. melanoxylon* wood is mainly given by its heartwood content and its golden-brown color, often containing darker veins or reddish streaks (Searle, 2000; Monteoliva *et al*., 2009). For more than one century, the wood of this tree has been internationally considered as one of the most decorative in the world, belonging to the same category as that of the walnut, mahogany and teak (Nicholas & Brown, 2002; Bradbury *et al*., 2011), and has been the mainstay of the fine furniture industry in Tasmania (Tasmanian Timber Promotion Board, 2012).

The contents of sapwood and heartwood are quality attributes that are important for the different end uses of wood. Heartwood contains extractives and a smaller content of moisture than sapwood, whereas sapwood contains living parenchyma cells. The cell walls in heartwood can be infiltrated by polyphenols, which allow reducing both shrinkage and the swelling ability of wood, and increasing its durability and other properties (Hillis, 1987; Taylor *et al.*, 2002). Although the presence of extractives does not necessarily mean a high mechanical resistance, it can prevent warping in the central part of juvenile wood. Heartwood usually has lower permeability than sapwood, which suggests that it is more difficult to dry and less penetrable by preservatives, paint and dyes (Zhang, 1997). Wood for sawn products is much appreciated when it presents a high proportion of heartwood. In the pulp, on the other hand, the high content of extractives in the heartwood requires additional costs of bleaching, and the tylosis of the heartwood formation process prevents the penetration of impregnation liquors (Lourenço *et al.,* 2008).

In the living tree, the sapwood, in contrast with heartwood, is physiologically active, conducting water and nutrients from roots to leaves and storing food materials (Bamber, 1976; Hillis, 1987). The transformation of sapwood into heartwood is characterized by the death of parenchyma cells, development of tyloses in the vessels of many species and the biosynthesis of nonstructural compounds, leading to an important accumulation of extractives and to the differences in physical and chemical properties between sapwood and heartwood (Bamber, 1976; Hillis, 1987). Heartwood and sapwood in a tree vary with many factors, including species, age, rate of growth, climate, foliage area, site quality and tree vitality. Functions and causes of heartwood formation in trees are complex and consequently a great number of hypotheses, sometimes contradictory, may be found in the bibliography from the past decades, as reviewed by Bamber & Fukazawa (1985) and Hillis (1987). The regulation of water-conducting area in the stem and the preservation of non-functional wood are widely accepted features linked to heartwood formation (Bamber, 1976; Berthier *et al*., 2001). Besides this, the economic interest in heartwood/sapwood ratio for a number of forest species has directed numerous research efforts to the study of the relations between heartwood and other traits of the tree, eg. the relevance of tree age or radial growth on heartwood width (Bamber, 1976; Taylor *et al.*, 2002; Climent *et al*., 2002, 2003; Bradbury, 2005; Searle & Owen, 2005; Knapic *et al.,* 2006; Gominho & Pereira, 2000, 2005**;** Miranda *et al*., 2009).

Several researchers have reported on the content of heartwood in *A. melanoxylon* plantations in New Zealand (Haslett, 1986; Nicholas *et al.,* 1994; Nicholas & Brown, 2002), Australia (Searle & Owen, 2005), Portugal (Knapic *et al*., 2006), Tasmania (Bradbury, 2005) and South Africa (Harrison, 1974). Their results will be shared in relation to the results of this research in Argentina.

The aims of this study were: 1- to determine the heartwood and sapwood content and their distribution within the stem, 2- to analyze their relationship with the growing site, age and growth rate of the trees, and 3- to predict heartwood content by means of easy-to-measure variables (diameter at breast height and tree height), in relation to its potential use in the construction and furniture industries.

Hypothesis

Given the structure of non-uniform age forest, the age of the trees and the site of growth affect differently the heartwood content. Despite of that, it is possible to adjust a linear model to predict the heartwood content.

Material and methods

The study material consisted of four non-implanted forests of *A. melanoxylon* developed without forest management in the following sites of the province of Buenos Aires (Argentina), in each of which a study plot was delimited: Mar Chiquita (MCh); Cinco Cerros (CC); Los Tuelches (LT); and Las Cortaderas (LC). The origin of the material which originated these forests is unknown. The four sites show not relevant differences with respect to thermal and water regimes (National Institute of Agricultural Technology (INTA); Experimental Station Balcarce, 2014; Servicio Meteorológico Nacional, 2014). Table 1 shows the climate data, soil types and other features of the sampling sites.

The experimental material was obtained from 20 trees (five from each of the sites), randomly selected with two restrictions: they belonged to the higher diametric classes (greater than 10 cm in diameter at breast height - DBH-) and to the co-dominant stratum (Table S1, [supplementary]). The trees age varied between 9-32 years. Total trees height (TH) range was 12.6-18.8 m and DBH range was 12.5-32.2 cm. As shown in Table

Table 1. Climate data, soil and other features of the sampling sites

Site	Mean temperatures (coldest-warmest month) °C	Mean annual rainfall mm/year	Soil	Other characteristics, geographic coordinates and altitude
LT	7.2-20.9	850	Lithic Hapludol Fine slime	Southwest slope area, with rocks near the surface. Low capacity to store water 37°55´67´´S, 58°06´27´´W, 155 m a.s.l.
LC	8.2-20.9	820	Argiudol Fine	Extended flat zone, with moderate to imperfect drainage and moderate alkalinity at the bottom of the profile 38°17´29´´ S, 58°09´09´´ W, 31 m a.s.l
CC	7.5-20.5	903	Typic Argiudoll Fine slime	Northeastern slope area, with rock out-crops 37°43´59´´ S, 58°14´30´´ W, 163 m a.s.l
MCh	7.7-20.9	924	Hapludoll Fine slime	Flat zone of accumulation deflation, with slight danger of water erosion 37°43´58´´ S, 57°27´18´´ W, 1 m a.s.l

LT: Los Tuelches; LC: Las Cortaderas; CC: Cinco Cerros; MCh: Mar Chiquita.

S1 [supplementary], trees of similar diameters showed different ages and vice versa. The same age was found in trees of different DBH values (development), typical of forest of non-uniform age.

A. Estimation of the volume and age of the trees selected

To estimate the volume of the trees selected, we used Smalian's formula (Caillez, 1980; Prodan *et al*., 1997). The part of interest was the portion of the stem between the base (15-30 cm above the ground level) and the start of the crown, and we considered it the commercial portion of the tree, hereinafter referred to as trunk or stem. The height of the tree up to the start of the crown was considered as the commercial height, whereas that up to the upper limit of the crown was considered as the total height (Caillez, 1980). The stem was divided into 2-m logs, and the volumes of each log with and without bark were calculated. The sum of the volumes of each log was considered as the real commercial volume of the tree.

The age was estimated from a basal disc (taken 30 cm above ground level) by microscopic observation of histological cross-sections covering the entire radius with an optical microscope (Olympus BX50, Japan).

B. Sampling of trees and conditioning of the material

We defined four sampling heights in the stem: the base, the breast height (BH) (corresponding to 1.3 m above soil level), 30% of the total height (30%TH) and 50% of the total height (50%TH). The commercial height represented on average 57.5% (± 6.2) of total height (Table S1 [supplementary]), for which sampling up to 50%TH can be considered corresponding to the commercial portion of the trunk. A 5-cm-thick sample disc was taken from each sampling height. This material was naturally dried for 6-10 months in a covered storage room at room temperature. Sandpaper with decreasing grain size (80-100-120) was used to polish the cross-sectional surface of each slice on which naked-eye observations were made to delimit the heartwood region and the measurements.

C. Calculation and expression of the heartwood content.

The following measurements were performed with millimeter ruler on polished discs: a) North-South and East-West diameters of each slice, with and without bark, centered in the pith; and (b) North-South and East-West diameters of the heartwood area, centered in the pith.

The heartwood content was expressed in terms of:

1. Its proportion in the cross-section: area of heartwood in relation to the total area of the cross-section with bark; area/area ratio, for the analysis of the axial variation in heartwood content.

For the calculation of the areas, it was assumed that the cross-sections of the discs and heartwood were circular, with mean diameter resulting from the average of those measured in North-South and East-West direction, already mentioned. The following expressions were applied:

$$AT_{ob} = (\pi/4)\, D_{ob}^{\;2} \qquad [1]$$

$$A_{HW} = (\pi/4)\, D_{HW}^{\;2} \qquad [2]$$

where AT_{ob}: total over bark area of the cross-section [cm^2]; A_{HW}: heartwood area [cm^2]; D_{ob}: mean over bark diameter of the cross-section [cm]; and D_{HW}: mean diameter of the heartwood [cm].

2. Its proportion in volume in each conical cross-section defined by the sampling: volume of heartwood in relation to volume with bark of each log into which the trunk was divided; volume/volume ratio, for the analysis of the axial variation in heartwood content. For this analysis, the trunk was divided into three conical sections or log (Base-BH; BH-30%TH; 30%TH-50%TH) each of which was measured for the calculation of its volume with bark and heartwood volume. For this calculation, we used Smalian's formula.

The estimation of the total volume with bark and heartwood volume of each log was based on the stem heights (determined at the time of felling) corresponding to each axial position of the sampling (BH, 30%TH and 50%TH) and the respective transverse areas determined in accordance with [1] and [2].

3. Its absolute value in heartwood volume of the whole tree (m^3), resulting from the sum of the heartwood volumes in each conical section (log) into which the trunk was divided.

4. Its proportion (%) estimated for the whole tree (used in the regression analyses):

I. as the simple average value per tree of the percentage of heartwood of each cross-section (area/area ratio),

II. as the simple average value per tree of the percentage of heartwood of each log into which the trunk was divided (volume/volume ratio),

III. as the value (%) per tree emerged from the ratio between heartwood volume (m^3) (according to section C.3) and total volume of the tree with bark (m^3) (according to section A); volume/volume ratio.

5. Sapwood thickness: The thickness of the sapwood was calculated in radial direction based on the mean diameter of each slice without bark and the mean diameter of the heartwood, according to the following expression:

$$SW = (D_{ub} - D_{HW}) / 2 \qquad [3]$$

where SW: sapwood thickness [cm]; D_{ub}: under bark mean diameter of the cross-section r [cm]; and D_{HW}: mean diameter of the heartwood [cm].

D. Statistical analysis

The analysis of variance (ANOVA) was developed under a statistical model for fixed effects, where the effects considered as fixed were: the site, the height at the stem, and the tree nested at the site [4]. The alpha probability value established to consider the differences between the sources of variation as significant was 0.05. Tukey's test (honestly significant difference -HDS) was used as a method of multiple comparisons of means. The assumptions of normality and homogeneity of variance were verified by the Shapiro-Wilk and Levene statistical tests respectively.

$$y\ ijk = \mu + \alpha\ i + \beta j + \delta k\ (i) + \alpha\beta ij + \varepsilon\ jk \qquad [4]$$
$$i = 1, 2, 3, 4 \quad j=1, 2, 3, 4 \quad k= 1, 2,\ldots 20$$

where y ijkl: estimation of the variable corresponding to the k-th tree at the j-th height of the stem at the i-th site; α i: effect of the i-th site; βj: effect of the j-th height of the stem; δk(i): effect of the k-th tree at the i-th site; αβij: effect of the interaction between the i-th site and the j-th height of the stem; ε jk(i): effect of the k-th tree at the j-th height at the i-th site

Pearson correlation analysis was used for the analysis of the linear relationships. General linear models were used to analyze the relationships between heartwood content, DBH, total height (predictor variables), site and age tree (categorical independent variables) (Statistica 7). The models whose parameters were estimated by least squares were adjusted and ANOVA was developed to test the significance. The confidence intervals of the parameters of the models were calculated. The suitability (or quality of fit) of the models was assessed by the determination coefficient.

Results

Heartwood variability

All the trees presented heartwood along the stem. The mean heartwood content (area/area and volume/volume) for the experimental material was 47.6% (±16.3) and 49.2% (±14.7) respectively. The average thickness of the sapwood was 2.18 cm (±0.75), whereas that of the bark was 0.81 cm (±0.28).

The ANOVA indicated that the site, the sampling height and the tree were significant sources of variation ($p<0.001$) for the proportion of heartwood in the cross-section of the stem (area/area), the proportion of heartwood in relation to the volume (volume/volume), and the sapwood thickness (Tables 2, 3 and 4). The site x height interaction was not significant for these variables (p values= 0.8250, 0.8488 and 0.4894, respectively).

The sites LT and MCh (the latter of which had the youngest trees of all the sites studied) did not differ in heartwood content (either as a proportion in the cross-

Table 2. Mean values of heartwood proportion and sapwood thickness according to each site

	LT [17-30 years]	LC [19-32 years]*	CC [20-31 years]	MCh [9-15 years]
Heartwood (%) in cross section (area/area)	57.34 c	35.50 a	43.78 b	54.01 c
Standard deviation	6.4	8.2	8.2	20.5
Number of observations	20	20	20	20
Heartwood (%) in the logs (volume/volume)	58.44 c	36.91 a	44.38 b	56.02 c
Standard deviation	6.9	10.1	11.3	21.6
Number of observations	15	15	15	15
Sapwood thickness (cm)	1.86 a	2.64 b	2.56 b	1.68 a
Standard deviation	0.31	0.44	0.79	0.80
Number of observations	20	20	20	20

* Range of ages of the trees at the site. Sites: LT: Los Tuelches, LC: Las Cortaderas, CC: Cinco Cerros, MCh: Mar Chiquita. The letters are read horizontally: the same letters do not differ significantly (p> 0.05), Tukey's Test.

section or as volume/volume ratio) and had the highest proportion of heartwood (Table 2).

The heartwood content in the cross-section was highest in the basal region of the stem up to breast height, and then decreased towards the apex. Sapwood thickness was highest at the upper end of the stem, although statistically, this value did not differ from that recorded at the base, and thus could be considered largely constant along the stem (Table 3). In addition, the highest percentage of heartwood (volume of heartwood in relation to the total volume of logs) was observed in the basal region (Table 4).

Based on the average data of the 20 trees studied, the heartwood radius decreased uniformly, closely following the shape of the stem. In contrast, sapwood thickness remained constant (Fig. 1). In some basal discs we observed wavy contours of the heartwood and the slice because of the presence of buttresses on the trees.

Relationship between variables and heartwood prediction

Sapwood thickness was not correlated with the height of the stem (TH, $r = 0.06$; $p = 0.57$), while the heartwood radius showed a negative and significant relationship with the height of the stem ($r = -0.46$; $p < 0.001$).

The heartwood radius and the radius of the cross-section (over and under bark, and at all sampling height) were positively and significantly correlated ($r= 0.96$; $p < 0.001$ for the section over bark and $p< 0.05$ for the section under bark). Thus, the linear models predicting the diameter of the heartwood based on

Table 3. Mean values of heartwood proportion and sapwood thickness according to the four sampling heights

	Base	BH	30%TH	50%TH
% heartwood (area/area)	53.48 c	53.52 c	47.73 b	35.91 a
Standard deviation	16.5	13.2	13.6	16.3
Number of observations	20	20	20	20
Sapwood thickness (cm)	2.23 ab	2.05 a	2.07 a	2.40 b
Standard deviation	0.9	0.6	0.5	0.8
Number of observations	20	20	20	20

Axial sampling heights: base: 0.3 m from the ground; BH: breast height (1.3m); TH: total height. The letters are read horizontally: the same letters do not differ significantly (p> 0.05), Tukey's test.

Table 4. Mean values of the heartwood content in relation to the volume of the logs, according to the sampling heights.

	Log Base-BH	Log BH-30%TH	Log 30% TH-50%TH
% heartwood (volume/volume)	53.50 c	51.08 b	43.00 a
Standard deviation	14.9	13.2	14.6
Number of observations	20	20	20

Axial sampling heights: base: 0.3 m from the ground; BH: breast height (1.3m); TH: total height. The letters are read horizontally: the same letters do not differ significantly (p> 0.05), Tukey's test.

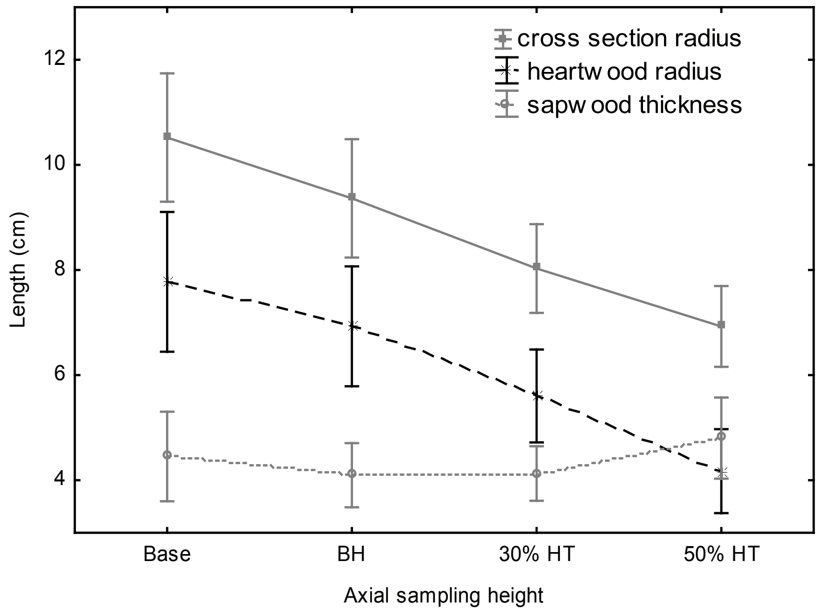

Figure 1. Radius of the heartwood, radius of the cross-section over bark, and sapwood thickness relative to the sampling heights (BH: breast height, HT: total height).

diameters of the stem over and under bark showed high fitting (R^2= 0.92 and p< 0.001 in both cases) (Fig. 2). This model estimates that heartwood started to form for stem diameters above 10 cm.

The proportion of heartwood, determined with the three calculation procedures used, was positively correlated with TH, DBH over bark and the volume of the stem. The correlation was greater when the heartwood content of the whole tree involved in the proportion was estimated as the sum of the volumes of heartwood in each log (Table 5). The age of trees was not correlated with the tree growth variables (r= 0.08 p>0.05 for DBH and r= -0.02 p>0.05 for total height) nor with the heartwood content (Table 5; Fig. 3). The youngest trees sampled from MCh site (9-15 years old) registered the highest heartwood content (higher than 50% at least in four of five trees) and very different DBH (12.5 - 23.5

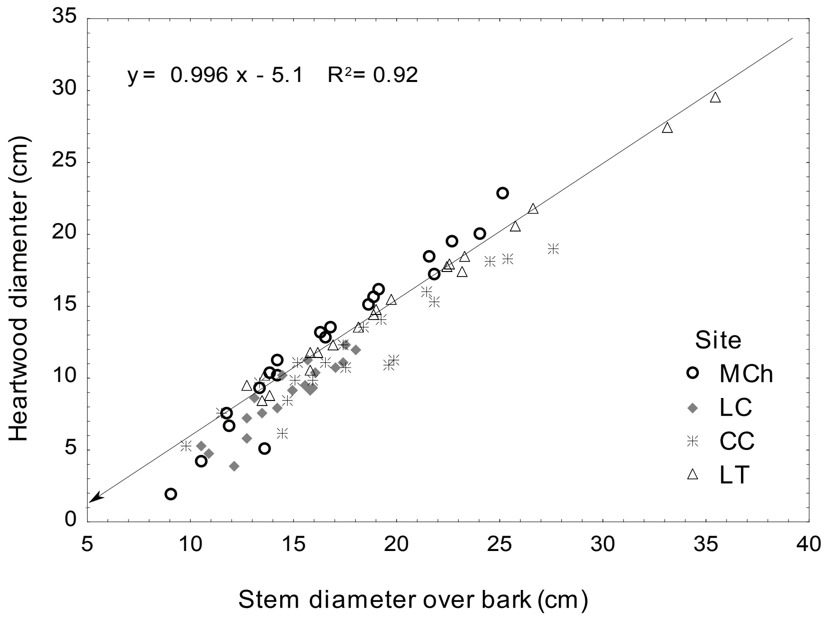

Figure 2. Variation of heartwood diameter with the diameter of the stem over bark (at all sampling height).

Table 5. Correlations (Pearson coefficient: r) between the heartwood content of the whole tree, the age, the total tree height (TH), the diameter at breast height over bark (DBH_{ob}) and the volume of the stem (n= 20)

	TH (m)	DBH_{ob} (cm)	Age (years)	Total volume of the stem ob (m^3)
	r (p value)			
% heartwood (area/area)[A]	0.65 (**)	0.64 (**)	-0.24 (ns)	0.60 (**)
% heartwood (volume/volume)[B]	0.66 (**)	0.64 (**)	-0.27 (ns)	0.60 (**)
% heartwood (volume/volume)[C]	0.74 (***)	0.72 (***)	-0.22 (ns)	0.64 (**)
heartwood volume (m^3)[D]	0.89 (***)	0.94 (***)	0.01 (ns)	0.99 (***)

A: simple average value per tree from the % of heartwood of each cross-section. B: simple average value per tree from the % of heartwood of each log into which the stem was divided. C: heartwood volume of the whole tree / total volume of the stem over bark (method 4.III). D: sum of the heartwood volume of each log into which the stem was divided. p values: *** p<0.001; ** 0.001 > p < 0.01; * 0.01>p<0.05; ns: not significant. TH: Total tree height, DBH_{ob}: diameter at breast height over bark.

cm DBH_{ob}). Eleven 19 – 27 years old trees sampled at the others three sites showed a great variation of heartwood content (33-65%) and DBH (16.6 – 32.3 cm) (Fig. 3).

Table 6 shows the general linear models between the heartwood content (in % and m^3) as dependent variable and DBH, TH, tree age and site as predictor (covariates) or categorical independent variables (factors). Heartwood content could be predicted by DBH or TH alone. The site or tree age did not affect the adjustment of the model. Trees of the LC site had the lowest DBH dispersion (15-17 cm), with large age range (19-32 years) and low heartwood content (35-40%). In contrast, LT trees showed the highest range of DAP (16.6 - 33.2 cm), with tree age like LC trees site (17-32 years) and with high heartwood content (55-65%) (Fig. 4).

Discussion

Heartwood variability

The 20 trees studied were characterized by an average height to the crown of 57% of the total height (Table S1 [supplementary]). In addition, all the trees presented heartwood along the stem, which is an important aspect for the potential use of this wood destined to sawing (Searle & Owen, 2005; Bradbury *et al*., 2011). In contrast to that reported for *A. melanoxylon* trees of higher commercial sizes (DBH 40 cm, TH 39 - 42 m), where the height reached by the heartwood was on average 81% of the total height (Knapic *et al*., 2006), we did not observe a free height level of heartwood. Similarly, in *A. melanoxylon* plantations in Portugal (DBH 39-41 cm, TH 29 - 33m),

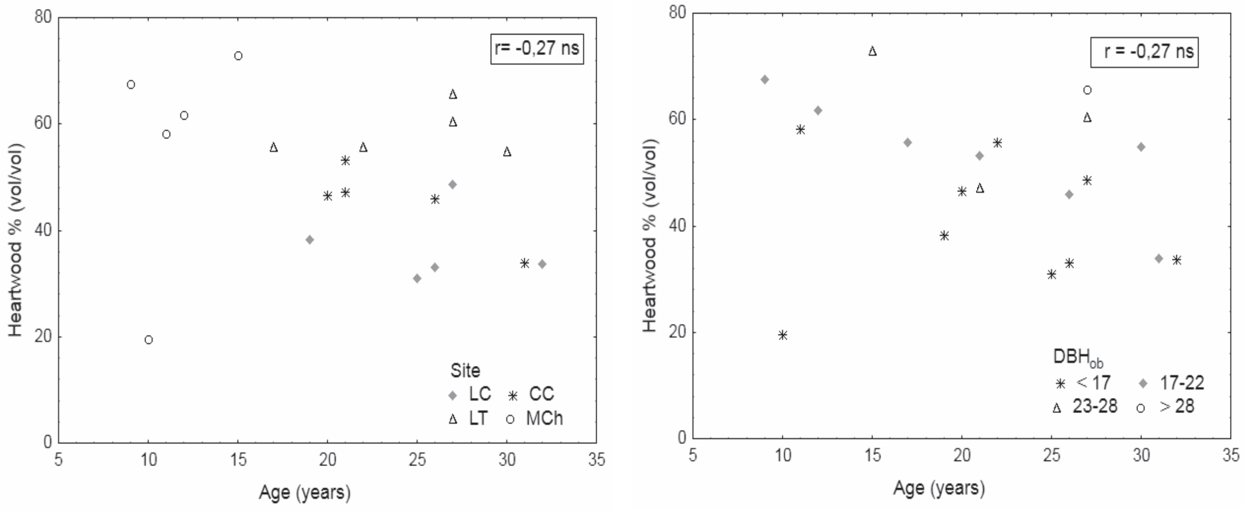

Figure 3. Variation of heartwood content with the tree age (by site, left panel; by diameter at breast height over bark – cm DBH_{ob}, right panel).

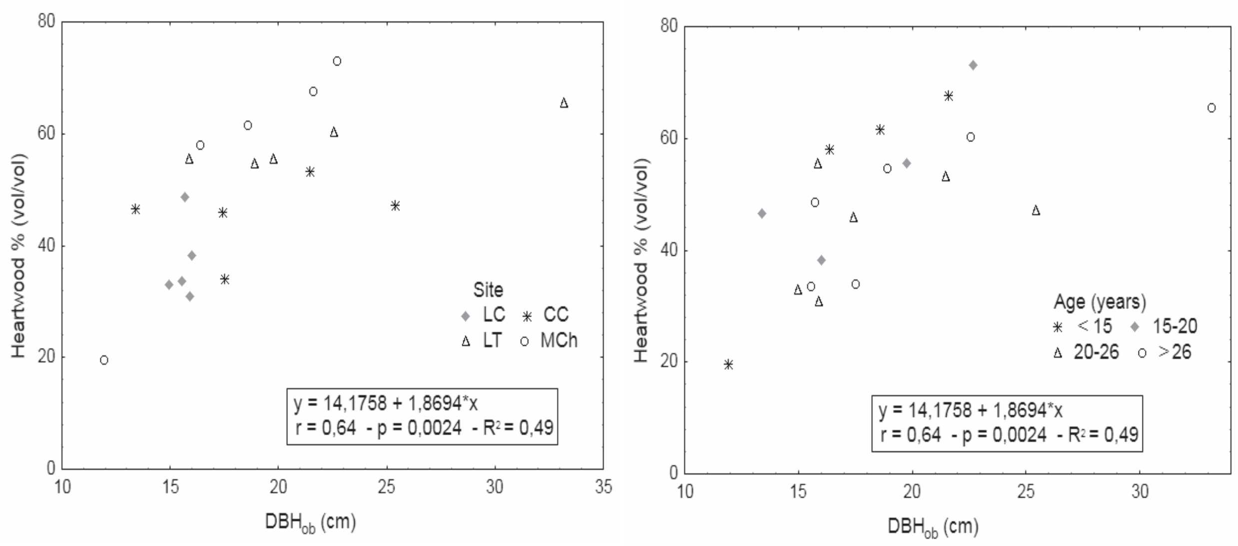

Figure 4. Variation of heartwood content with diameter at breast height over bark - DBH_{ob} (by site, left panel; by tree age, right panel).

Santos *et al*. (2013) did not find free height level of heartwood in the stem.

Our results showed that the development of the heartwood had a conical shape (correlation between heartwood radius and height r= -0.46) and closely followed the contour of the stem (correlation between radius of the heartwood and cross-section radius r= 0.96), which can be considered as a regular pattern (Climent *et al*., 2003). It is accepted that most tree species that differentiate their heartwood present regular heartwood. However, in some cases (species and trees within species), there are unknown mechanisms that lead to an irregular formation of the heartwood in both radial and axial sense, as it occurs in species of the genus *Pinus* (Stokes & Berthier, 2000; Berthier *et al.,* 2001; Climent *et al*., 2003). The regular pattern of axial development of heartwood is coincident with that reported for the species by other authors (Knapic *et al*., 2006; Santos *et al*., 2013). According to the results of our work in some discs of the basal region of the stem, the heartwood presented wavy contours (data not shown), due to the presence of buttresses, a feature also noted by Knapic *et al.* (2006).

The local plantations studied presented a proportion of heartwood which could be considered within the range of values reported in other countries for ordered plantations (Table 7).

It is accepted that the heartwood area is usually greater at the base of trees and decreases towards the apical region (Hillis, 1987; Taylor *et al.,* 2002). Particularly for *A. melanoxylon*, in plantations in

Table 6. General linear model between the heartwood content of the whole tree, total tree height (TH), the diameter at breast height over bark (DBH_{ob}), tree age and site

Dependent variable	Predictor variable	Independent variable	Model R^2_{adj}	Equation
	p value			
% heartwood (volume/volume)[A]	DBH_{ob} (ns)	Age (ns)	0.79 ns	
	TH (ns)	Age (ns)	0.80 ns	
	DBH_{ob} (**)	Site (ns)	0.38 **	y= 1.47+1.87x
	TH (**)	Site (ns)	0.41 **	y=-30.5+5.7x
% heartwood (volume/volume)[B]	DBHob (**)	Age (ns)	0.83 ns	
	TH (**)	Age (ns)	0.86 ns	
	DBHob (***)	Site (ns)	0.89***	y=-0.68+0.05x
	TH (***)	Site (ns)	0.78***	y=-1.74+0.15x

A: simple average value per tree from the % of heartwood of each log into which the stem was divided. B: heartwood volume of the whole tree / total volume of the stem over bark (method 4.III). p values: *** p<0.001; ** 0.001 > p < 0.01; * 0.01>p<0.05; ns: not significant. TH: Total tree height, DBH_{ob}: diameter at breast height over bark.

Table 7. Heartwood content reported for *Acacia melanoxylon* in New Zealand (NZL), Tasmania (TAS), South Africa (SAF), Australia (AUS), and Portugal (POR).

Reference	Heartwood	Country	Age	DBH	Nº of trees
Haslett (1986)	50%*	NZL	15	NR	NR
Nicholas *et al.* (1994)	42-52%	NZL	10	16-20	59
Bradbury (2005)	25-40%**	TAS	14-22	13-21	210
Nicholas & Brown (2002)	42-52%**	NZL	10	NR	59
Harrison (1974)	83%**	SAF	NR	40	75
Searle & Owen (2005)	2.4%**	AUS	8	8,7	17
Knapic *et al.* (2006)	61%*	POR	45	40	20
Santos *et al.* (2013)	55%**	POR	45	39-41	20
Bradbury *et al.* (2011)	38.6%**	TAS	18	11.1-19.5	192
This study	49.2%* 47.6**	ARG	9-32	13-33	20

DBH: diameter at breast height, *Average proportion in relation to the volume of the shaft, **Average proportion in the area of the cross-section, NR: information not recorded.

various sites in Portugal, Knapic *et al.* (2006) and Santos *et al*. (2013) reported the same axial patterns here described but did not observe differences in heartwood content between the different sites. In our material, the heartwood percentage was highest in the basal area of the stem up to breast height (Table 3). On the other hand, in technological and biological terms, it could be understood that the percentage of heartwood volume is 53-51% up to 30% of the total height of the tree, finally being 43% in the apical log (Table 5). This pattern of axial variation in heartwood content was similar at each site, in agreement with the negative site x height interaction found.

The sapwood thickness in our material (2.18 cm) was lower and showed greater individual variation (Tables 2 and 3) than that reported for *A. melanoxylon* by Knapic *et al.* (2006). These authors, working on 45-year-old trees (DBH= 40 cm) determined values of 3.1-3.5 cm along the tree, which, as in the present work, could be considered as an axially constant thickness. In *A. melanoxylon* plantations in New Zealand, Haslett (1986) pointed as usual a thickness of 2-5 cm, whereas in 18-year-old trees (DBH= 15.3 cm) in Tasmania, Bradbury *et al*. (2011) reported a thickness of 2.7 cm, values that are in agreement with that observed in this study. On the other hand, a constant thickness of sapwood along the stem has also been observed in other commercial genera such as *Eucalyptus* (Hillis, 1987; Taylor *et al.,* 2002; Miranda *et al.,* 2009). The amount of sapwood in a tree is related to its conductive needs that are in relation with its crown development and therefore, the formation and development of heartwood progresses within the tree to regulate the amount of sapwood (Bamber, 1976; Berthier *et al*., 2001). This explains the different distribution pattern of heartwood and sapwood within the stem and the positive relation of tree growth with heartwood content (Climent *et al*., 2002, 2003; Bradbury, 2005; Searle & Owen, 2005; Knapic *et al.,* 2006; Gominho & Pereira, 2000, 2005**;** Miranda *et al*., 2009).

Relationship between variables and heartwood prediction

The high variation of heartwood content among trees found in the present study could be related to the non-uniformity of ages and/or different growth rates that characterized the material within the sites (Fig. 3 and 4). Several authors consider the age of the trees as the main factor that control the contents of heartwood and sapwood (Harrison, 1974; Stokes & Berthier, 2000; Taylor *et al.,* 2002; Climent *et al*., 2002, 2003; Bradbury, 2005; Searle & Owen, 2005). It has also been found that the content of heartwood is related to the growth rate, the site, the silvicultural practices, and a moderate genetic control (Hillis, 1987; Zobel & Jett, 1995; Taylor *et al.,* 2002; Knapic *et al.,* 2006; Gominho & Pereira, 2000, 2005**;** Miranda *et al*., 2009; Bradbury *et al*., 2011). However, in the present study, we found no significant linear relationship between the heartwood content (both in relative and absolute terms) and the age, at least at the age ranges that characterized this material (9-32 years). In the evolution of a forest of regular structure (or uniform age), it is expected that older ages represent higher sizes/development/ vigor of the trees (Daniel *et al*., 1982), which was not the case in this work. As shown in Figs. 3 and 4, trees of similar diameters showed different ages and vice versa, the same age was found in trees of different DBH values (development), typical of forest of non-uniform age. This may have contributed to the absence of a significant linear relation between age and heartwood content. In contrast, we did find a positive relationship between heartwood content and the tree development (TH-DBH-volume of the stem), as well as a significant variation among sites.

It has been indicated that the better the conditions of the site, the greater the formation of heartwood, but it has also been mentioned that this analysis can be confusing (Taylor *et al*., 2002). In South Africa, Harrison (1975) found that the species produced higher heartwood contents at sites with higher relative humidity, good drainage and high content of organic matter in the soil. In the plantations in Portugal studied by Knapic *et al*. (2006) and Santos *et al*. (2013), these authors did not detect variation among sites, differentiated primarily by their thermal and water regimes. The size/heartwood or growth/heartwood ratios (conditioned by the site/genotype and the interaction between them) have been referred to as having a positive nature in *A. melanoxylon*, at both the phenotypic and the genetic levels (Harrison, 1974; Knapic *et al.,* 2006; Bradbury *et al*., 2011), as well as in other species (Knapic & Pereira, 2005; Gominho & Pereira, 2000, 2005). This is consistent with that found in this work: high correlation between DBH, TH and stem volume and heartwood content (Table 5), as well as higher heartwood content in the trees from LT and MCh, sites that represented the best places from the biometric point of view (Table S1 [supplementary], for more information see Igartúa, 2013).

The estimation of heartwood volume in *A. melanoxylon* is important because this feature is an important attribute of quality (Harrison, 1974; Searle, 2000; Nicholas & Brown, 2002; Bradbury *et al.,* 2011). Therefore, it is of interest to find, for specific situations (species, sites, ages), procedures that provide satisfactory estimates of the whole individual, that avoid destructive samplings, and that simplify the evaluation and comparison between trees and populations. Predictive equations based on simple and usual measurements in forestry (DBH and TH) are valuable in this regard. In the forest resource studied, the DBH with bark, total tree height and the total volume of the commercial portion of the stem were significantly correlated with the absolute amount of heartwood, and the predictive models showed high fitting (R^2 = 0.79 - 0.89). Therefore, the proposed hypothesis is accepted. The heartwood content was affected differently by the tree age and the growing site due to the forest structure of non-uniform age and without management. In our sampled trees, the absolute amount of heartwood was driven by growth rate. However, it is possible to fit a general linear model for heartwood prediction.

Conclusions

The *Acacia melanoxylon* trees growing in the southeast of Buenos Aires province (Argentina) have conical-shaped heartwood that follows the contours of the stem along all its commercial height. Within stems, the highest volume of heartwood content was that of the basal regions, up to 30% of total height, a feature observed in all the sites studied, while sapwood thickness was constant along the stem.

The age of the trees did not affect the amount of heartwood, whereas the environmental conditions of the sites did affect this parameter. These positive heartwood/size and heartwood/growth rate ratios previously reported for the species were also recorded in the local resource studied. It is then expected that a forest management aimed to achieve a structure of regular mass, with major rotations and interventions on plant density, will lead to higher and more uniform development of the trees. According to the results of this research, these better developments will be associated with higher heartwood content, which is the most important quality attribute of this wood. On the other hand, the heartwood volume in this forest resource can be estimated through linear equations whose predictive variables are DBH and TH.

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