Proportion and quality of heartwood in Togolese teak (*Tectona grandis* L.f)

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ABSTRACT

Although teak (*Tectona grandis* L.f.*)* is an important indigenous timber species to south-east Asia, teak plantations have been established widely throughout the tropics and successfully in Togo since 1920. However, no studies exist concerning the quality of Togolese teak wood depending on age and stand situation. The heartwood proportion, modulus of elasticity (E_L) and wood density at 12% moisture content of 80 trees of various ages from different ecological zones in Togo were examined. Results showed that the percentage of heartwood differed significantly in trees depending on the ecological zones. Density at 12% moisture content was significantly correlated to tree age and diameter at breast height. In juvenile wood, density was highly variable, but tended to increase before stabilising with age, whereas E_L in adult wood was significantly greater than that in juvenile wood.

Key Words: *Tectona grandis* L.f, modulus of elasticity, density, juvenile wood, heartwood, wood quality.

INTRODUCTION

Teak (*Tectona grandis* L.f) is a tropical hardwood species highly prized by the wood industry due to its superior mechanical and physical properties, as well as its pleasing aesthetic appearance (Kjaer et al 1999; Sanwo 1987, 1990). Teak can be used for both interior and exterior purposes, as the heartwood is naturally durable and resistant to pathogens. The necessity over the last few years to reduce toxic preservation techniques, calls for using those woods which are naturally durable. Therefore, selection programmes or management methods which can improve heartwood quantity or quality will be of utmost importance to developing countries, where teak production is an important economic asset.

Over 10,000 hectares of teak plantations exist in Togo (Behaghel 1999). Teak wood originating from Togo is extensively used in the construction and carpentry industries and most of the timber from these plantations is exported to India, China and Japan. However no studies exist to date concerning the quality of Togolese teak wood, with regard either to its mechanical and physical properties, or to its durability. The plantations, which were first established in 1920s (Lamouroux 1957), are now practically abandoned (Souvannavong 1986) and few thinning and other sylvicultural practices are carried out (Delvaux 1973). Tree density is extremely high (1000-2000 trees ha^{-1}, Table 1) and soil is not treated or fertilised. Production tables do not exist, and rotation cycles can often be up to 70 years. No information exists concerning the proportion of heartwood in these trees and if volume or quality may differ depending on the geographic position of the stand or type of management carried out. In order to judge Togolese teak quality with regards to teak originating from other African or Asian countries, it is necessary to determine mechanical and physical properties as well as the durability (Baillères and Durand 2000, Kokutse 2002) of wood from stands throughout the country, and to compare these data with others available.

Heartwood is the non-functional central part of a tree trunk, and no living cells exist in this wood (Hillis 1987). When living parenchyma cells in the outer, functional sapwood begin to die, the substances they contain are used as energy to fuel the production of phenols and quinines, which protect the tree from pathogen and insect attack (Pahup et al 1989, Datta et al 1987). It is not known how much sapwood is transformed into heartwood per annuum, but may depend on climate and sylvicultural practices (Berthier et al 2001). Several studies on the quality of teak wood from trees of different ages have indicated that juvenile wood (wood formed by a juvenile cambium) in teak, unlike many temperate species, is not inferior to mature wood in terms of specific gravity and strength (Bhat et al 2001, Sanwo 1986, 1987, Zobel at al 1989). Bhat (1998) also showed that increased tree growth rate does not retard the formation of heartwood. However, the amount of heartwood in teak is related to tree age (Okuyama *et al* 2000, Simatupang *et al* 2000) and sylvicultural practices (Morataya et al 1999).

Heartwood proportion, elasticity and density were determined for trees of different ages and from different ecological zones in Togo. Each ecological zone has a marked climate and soil type, and is not necessarily suited for the optimal growth of teak trees. The purpose of this study was to determine the ecological zone which resulted in the best quality teak wood, with regards to the characters studied, and how these characters evolve with age. The genetic origin of the trees studied was not known and so could not be taken into account.

MATERIALS AND METHODS

Site description

Eighty trees (6-70 years old) were selected for analysis from five ecological zones in Togo. Trees of different ages were chosen in order to determine how certain characteristics evolve with age, and because material the of same age from different zones was often limited. These zones are different in both climate, soil (Lamouroux 1957) and vegetation type (Fig 1, Table 1) and are classed I -V depending on the flora present (Ern 1979; Kokou 1998):

Zone I: represents the plains in the northern part of Togo. The typical vegetation is essentially Sudanese savannah (Ern 1979). The dry season lasts from November to May, and the rainy season from June to October.

Zone II: corresponds to the northern part of Atakora Mountains in Togo and is a dry forest zone, composed of mosaic Guinean savannas and with a climate characteristic of Sudanese hills. The dry season is from October to Mars, and the rainy season from April to October.

Zone III: corresponds to the centre plains of Togo, dominated by several inselbergs (200 to 400m in height), and consists of Guinean woody savannas (Aubréville 1937).

Zone IV: constitutes the southern part of the Atakora Mountains, with ideal climatic conditions for semi-deciduous forest growth (Akpagana 1989). This area is a transitional subequatorial zone (Trochain 1957), and can be characterised by a long, rainy season lasting from March to October, and a short, dry season from November to February (Guelly 1994).

Zone V: is the coastal plain of Togo, which is considered as a dry littoral zone, with a subequatorial climate. Two rainy seasons occur per year, from March to July and September to November.

Measurement of heartwood distribution

In order to measure heartwood distribution both within a tree and between trees growing in different environmental conditions, 80 trees were chosen at random from stands in the five ecological zones described above. In zones I, II and IV, material was limited, and only 10 trees per zone could be harvested. In zones III and V, where plantations are more numerous, 27 trees were felled in zone III and 23 in zone V.

After the trees were felled, height from the tree base to the base of the crown and total height were measured, along with the diameter at breast height (BH). Discs, 5 cm thick, were then sawn and removed at BH, 5 m, and every 5 m up to the base of the crown.

Wood discs were sanded, and the distance between the pith and the heartwood boundary and the cambium along at least four radii were measured (Fig 2a). Heartwood was easily identified on the freshly cut discs, due to its deep colour. If the discs were highly irregular, as was often the case in discs taken from BH, up to eight measurements were made. The cross-sectional area of heartwood was then calculated [Equations1, 2] (Pardé et Bouchon 1988; Berthier et *al.* 2001). Heartwood as a percentage of the total cross-sectional area of the discs was then determined (n = 400 discs).

An analysis of variance was carried out to determine the difference between percentage heartwood as a function of tree age (using age classes presented in Table 2) and ecological zone.

$$S_t = \frac{\pi\left(\sum_{i=1}^{4} R_i^2\right)}{4} \qquad [1]$$

$$S_{HW} = \frac{\pi\left(\sum_{i=1}^{4} r_i^2\right)}{4} \qquad [2]$$

where: S_t = total cross-sectional area of the discs

S_{HW} = cross-sectional area of heartwood.

Density at 12% moisture content

In order to measure density at 12% moisture content in the heartwood of trees of different ages, strips (50cm longitudinal x *X*cm radial x 5cm tangential, where *X* is the stem radius) of wood were cut radially at BH from 30 trees ranging in age from 6-70 years old (Fig 2b). The strips were kept in a climatised chamber at 20°C and 65% humidity, until the moisture content of the wood samples had reached approx. 12% with a constant mass. Ten small samples (40 cm longitudinal x 1,5 cm radial x 2 cm tangential) were then cut from the strips (n = 300). Each sample was then weighed (M), and the exact dimensions measured with a pair of Vernier callipers at three points along the length of the sample.

Density at 12% moisture content D was calculated using equation [3].

$$D = M/V \qquad [3].$$

Where $V = L_e \times L \times e$

L_e = length of the sample

L = mean width of the sample

e = mean height of the sample

An analysis of variance was then carried out in order to determine the difference between density at 12% moisture content at different tree ages (using age classes presented in Table 2) and between different ecological zones.

Longitudinal Modulus of Elasticity E_L

In order to determine if E_L varies within and between trees, wood samples (dimensions as for density at 12% moisture content measurements) were cut at BH. Depending on the diameter of the trunk, 4-7 wood samples were cut in the outer heartwood, i.e. in the zone of mature wood, in 24 trees aged between 24 and 70 years old (n=130). Juvenile wood in teak is situated roughly within the first twenty growth rings closest to the pith (Kedharnadh et *al.* 1963; Bhat et *al*. 2001). Therefore, four samples of wood per tree were cut in this zone at BH from 29 trees aged between 16 and 70 years old (n= 108).

On each of these wood samples, the dynamic E_L in flexion was measured using a vibration analysis system named “Bing” described elsewhere (Bordonné 1989; Baillères et *al.*1998*;* Brancheriau and Baillères 2001, Cilas et *al.* 2002). This system is based on mechanical principles that state a relationship between the natural vibration frequencies and the elastic properties of a material. The types of stress are varied (axial and transversal) and an analysis of the natural modes of movement makes it possible to determine most of the elastic compliances. The Bing system is based on an analysis of the vibrations produced by a blow to a piece of wood of known geometry and density. Wood samples were placed on elastic supports with very low rigidity, so that interactions could be ignored (Fig 3). The wood samples were then hit perpendicular to the sample, using a small metal instrument, so as to bring into play all the natural modes of vibration at the same time. At the other end, a microphone was used to measure the vibrations emitted and transmit them via an anti-alias (low-pass) filter to an analog-digital converter (PICO ADC216), which supplied digital data to a microcomputer. The data were immediately processed by Fourier fast transformation to interpret the information in the frequency domain.

The method used to determine the E_L was based on an interpretation of the spectrum, to identify specific frequencies (associated with each mode of vibration) from the natural vibrations. Mathematical processing of the selected frequencies was carried out using software developed by Baillères et *al.* (1998), which incorporated geometrical sample characteristics and weight.

An analysis of variance was carried out in order to determine the difference between E_L at different ages (using age classes presented in Table 2) and between different ecological zones. Regressions between density, E_L and cambial age were also performed.

RESULTS

Heartwood distribution

The percentage of heartwood differed significantly in trees depending on the ecological zone in which they grew (Table 2). Heartwood proportion in old trees from zones III, IV and V was significantly different from that in zone I ($F_{4, 66} = 5.05$, $P < 0.001$). In zone I, 13-year-old trees possessed 26% heartwood at BH compared to 12-year-old trees from zone III, in which 37% heartwood was present. Eleven-year-old trees from zone V possessed 61% more heartwood than teaks from the same age from zone I (Table 2). Thirty-year-old trees from zone V possessed only 9% less heartwood than in 70-year-old trees from zone I. 64% heartwood was present in 25-year-old teaks from zone 3 compared to 72% in 70-year-old trees from zone I. The percentage of heartwood in trees from zone II did not differ significantly from trees in any other zone. At the age of 45 years in trees from zone II, almost three-quarters of the stem at BH is already transformed into heartwood.

Percentage heartwood formation was significantly correlated to tree age in trees from ecological zones I, III, IV and V (Table 3). However, when all trees were considered together, regardless of zone, the percentage of heartwood and tree diameter at BH were significantly correlated in young trees only (DBH 10-20 cm) (Fig. 4, $y = 1.95x + 4.66$, $R^2 = 0.54$, $P <0.001$). Above a DBH of 21 cm, heartwood extends slowly (Fig. 4, $y = 0.31x + 60$, $R^2 = 0.09$, $P = 0.04$). This correlation could not be carried out for trees in zone II, where all trees were over 40 years old.

Density at 12% moisture content and longitudinal modulus of elasticity (E_L)

Density at 12% moisture content at BH increased with age in teak ($R^2 = 0.46$, $P<0.001$) (Fig. 5). In young trees (11-16 years old), density was found to be significantly different (646.7 ± 54.9 kgm^{-3}) compared to trees 40-45 years old (727.7 ± 44.0 kgm^{-3}) ($F_{15,1}= 9.15$, $P=0.01$) and

67-70 years old (779.4 ± 77.3 kgm^{-3}), ($F_{9,1}$= 9.79, P=0.01). The density in young trees (11-16 years old) was only 17% lower than trees 67-70 years old. Likewise, in trees 40-45 years old, density was only 6% lower than trees 67-70 years old but density was not found to be significantly different. Density was only weakly correlated with cambial age (Fig. 6, R^2 = 0.18, P<0.001) and was highly variable between the ages of 6-23 years old (coefficient of variation = 10%), but increases and stabilises above this age (coefficient of variation = 2.7%). When density at 12% moisture content and E_L were compared in each of the ecological zones, no significant differences were found between zones.

E_L increased significantly with cambial age (Fig. 7, R^2 = 0.24, P<0.001), however, variability was high, and did not stabilise with age (coefficient of variation =23% in juvenile wood and 19% in adult wood). E_L was significantly higher (E_L=16704 ± 3158 MPa) in adult wood ($F_{201,1}$= 36,48; P<0,001) than in juvenile wood (E_L=13163 ± 2976 MPa). When density was regressed with E_L, a significant positive relationship was found in juvenile wood (R^2 = 0.40; P<0.001), but not in adult wood (Fig. 8).

DISCUSSION

The proportion of heartwood in teak trees is an important factor for wood quality. During the process of heartwood formation, certain chemical processes take place, which improve durability and change the colour of the wood (Higuchi 1997). A maximum of heartwood volume is therefore desirable to end-users. Compared to other plantation species, heartwood formation begins relatively early on in the life of teak trees, at about 7 years of age (Okuyama *et al.* 2000). At the age of 11-13 years, 30% of the wood surface is transformed into heartwood in Togolese teak, which is lower than that in teaks growing in Kerala, India, where the same volume of heartwood is already formed in 8 years old trees (Bhat 1995). However, no data are available on the plantation mode of Togolese trees. If trees originated from seeds rather than stakes, the relationship between cambial age and heartwood formation would be retarded. In the trees studied by Bhat (1995), the stand density was also lower than that typical of a Togolese stand. Therefore, it may be possible to increase the volume of heartwood in Togolese teak, by improving stand management. The teak plantations in Togo date from end of World War 1, and have apparently never, or rarely been thinned; therefore, the number of stems ha^{-1} is far too high for optimum growth (Delvaux 1973). Where thinning has been carried out, it has been done so very late compared to normal silvicultural practices. In such a case, crown development is reduced and stem secondary growth retarded (Morataya et *al.* 1999). Results showed that heartwood proportion is significantly correlated with stem diameter in Togolese teak, as well as in teak from Kerala (Bhat 1995). Therefore, if an increased volume of heartwood were desired in teak wood, it would be necessary to change management practices to ensure improved stem growth.

When comparing the results of heartwood volume in Togolese teak to that in plantation teak from Kerala, India, it was found that 77% of the stem surface at BH, was transformed into heartwood in 51 years old trees from Kerala, compared to 71% in 70 years old Togolese teaks

(Bhat et *al*.1985). These results support the findings by Kjaer et al (1998), that the volume of heartwood in teak originating from Asia, is greater than that in African teak. Heartwood volume in teak therefore appears to be influenced by tree age, silvicultural practices and genetic provenance.

The proportion of heartwood in the stem of teak tree depends not only on age, but also on the ecological zone in which the trees grow. Although the number of trees examined per zone were low, it could be seen that in zone III, 25 year old trees possess almost as much heartwood as 50 year old trees from zone II, or 70 year old trees from zone I. Thirty year old trees from zone V however, have a similar volume of heartwood at BH, when compared to 60-70 year old trees from zones I, II and III. In terms of heartwood volume, zones III, IV and V were therefore the most productive. It may be assumed that these zones are more favourable to tree growth, due to the high amount of annual rainfall (1200-1500mm year^{-1}). However, not only does rainfall differ between zone I and other zones, but also the soil in this region is much poorer. The dry season in the north of Togo can last up to five months and the soil contains fewer elements and minerals. This type of soil results in poor root growth, with consequences for tree health and vigour (Lamouroux 1957). Therefore, heartwood formation in teak may also be affected by climatic and edaphic factors, although more trees per zone should be examined to confirm this hypothesis.

Results show that the percentage of heartwood in stems did not differ in trees aged 45-60 year old. In a similar study, Bhat (2000) showed that no evolution in heartwood volume occurred in trees aged 55-65 year old. Results also support those of Okuyama *et al.* (2000) who found that the percentage of heartwood increased more rapidly with trunk diameter in young trees compared to trees aged over 30 year old. Therefore, heartwood volume seems to be more dependent on diameter than plantation age and it can be supposed that the proportion of heartwood in plantation teak does not increase significantly once the age of 45 years has been reached (Kokutse 2002). This age may therefore be a suitable age to carry out a clear felling of the stand, if shorter rotation times were desired. However, further data on tree growth rate and heartwood volume depending on age, are needed in order to determine optimum rotation periods in Togo.

Density at 12% moisture content for Togolese teak was similar to that of teak from natural forest or from other plantations in West Africa (Kokutse 2002). Mean density at 12% moisture content for teak from natural forests in Indonesia, Thailand and Myanmar was 690, 620 and 700 kgm^{-3} respectively (Baillères et Durand 2000). Plantation grown teak from Bénin, Côte d'Ivoire, Burkina Faso and Togo has a mean density at 12% moisture content of 650 kgm^{-3}. Durand (1984) even found that certain wood properties e.g. shrinkage, crushing strength, static bending, shock resistance and density in teak from the Ivory Coast, were similar to those in Togolese teak, and better than those in teak originating from Asia. Wood density in Togolese teak was found to not differ significantly in trees between the ages of 40-45 and 70 years old. In teak originating from India, Bhat (1995) found that eight-year-old trees possessed wood with a density only 5% lower than 51 years old trees from the same region. However, Sanwo (1990) found that in teaks growing in Nigeria, the density of adult wood was significantly greater than that in juvenile wood.

Several authors have shown that differences in mechanical and physical properties of juvenile and adult wood in some tropical ring-porous hardwood such as teak are negligible (Bhat et *al.* 2001; Sanwo 1987; Baillerès et *al.* 2000). In Togolese teak, density at 12% moisture content and E_L were found to increase only slightly with tree age. Even though the number of samples used to calculate E_L was higher for juvenile wood than adult wood, a significant increase in E_L with cambial age was observed. E_L was 20% greater in adult wood than in juvenile wood, which is identical to results obtained by Bhat et *al.* (2001) on 63 year old plantation teaks from India, even though a different method was used for calculating $E_{L.}$ In our study, the presence of defects in the wood were not accounted for, and juvenile wood is likely to contain more defects due to the presence of branches compared to older wood. In Togolese teak, inter-tree variability was high, even for trees from the same stand, and may well be result of a genetic effect. Such a possibility should be examined further, and could be manipulated in tree breeding programs.

The results from this study showed that teaks aged 40-45 years old possess a relatively large proportion of heartwood (70% at BH) and a mean density at 12% moisture content of 0.7 and that heartwood volume is greatest in zones III, IV and V. Kokutse (2002) also showed that DBH was significantly correlated with tree age in stands <30 years old. Above the age of 30 years, growth is slow and correlations between DBH *vs* age, and heartwood volume *vs* age are not significant. Above the age of 40 years old, the proportion of heartwood in Togolese teak does not appear to increase significantly. As foresters in Togo do not have the financial means to manage teak plantations e.g. by carrying out thinning, it could be suggested that stand rotation times be reduced to 40 years, instead of the current 60-70 years. Further studies should be carried out on the influence of stand density and thinning practices on heartwood volume and quality, as well as how durability evolves with tree age and if differences occur depending on the plantation site.

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Legends to tables

Table 1:

Environmental conditions of five study zones in Togo. Each zone is considered ecologically individual due to differences in rainfall, temperature and soil type.

Table 2:

Tree characteristics and percentage of heartwood in trees depending on age and ecological zone**.** Heartwood proportion in older trees from zones III, IV and V was significantly different to that in zone I.

Table 3:

Percentage heartwood was significantly correlated with tree age in all ecological zones except for zone II, where no trees were available under the age of 44 years old.

Table 1.

Characterisation	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Mean annual rainfall (mm)	1000	1000	1300-1500	1300-1500	1200
Temperature range (°C)	17-39	19-30	25-40	25-30	25-29
Soil type	Ferruginous soil Sandy structure/ Silty gravel structure	Ferruginous soil Gravel-sand soil structure/sandy silt structure	Ferruginous soil Clay/sandy silt structure	Ferralitic soil Sandy-silt structure	Ferruginous soil Clay/ Sandy structure

Table 2.

	Zone I		Zone II		Zone III					Zone IV		Zone V		
Age (years)	**13**	**70**	**44-48**	**67**	**12**	**24-25**	**39**	**41-46**	**57-59**	**16-18**	**43-45**	**11**	**29-32**	**45-50**
Stand Density	1700	1300	2000	1000	2500	2300	2000	2100	2200	NA[2]	NA[2]	2000	1700	2000
Mean stand DBH (cm)	12.9±2.1	32.3±5.3	35.7±8.5	27.1±8.9	11.3±4.2	26.8±3.8	21.4±4.1	22.6±3.4	26.6±2.6	21.6±3.4	29.2±3.7	19.1±4.4	31.3±3.5	24.4±8.5
Height (m)	7.4±2.7	21.1±1.9	37±6.7	19.3±3.2	8.4±1.8	22.1±1.4	16.7±2.3	21.6±2.1	23.8±3.3	16±1.4	20.3±6.4	17.9±2.0	27.5±2.2	15.3±3.8
% Hw[1] at 0.0 m	35.1±12.8	74.0±9.4	65.9±11.6	69.5±5.6	35.0±14.5	60.9±5.3	65.5±4.5	69.8±2.4	65.0±7.7	35.5±8.1	67.4±3.5	44.3±11.0	69.1±6.5	69.9±9.3
% Hw at 1.3 m	26.1±12.6	72.3±8.5	67.3±1.1	69.6±2.2	36.7±14.0	63.7±1.7	62.0±3.0	69.3±2.3	63.5±6.7	31.1±9.8	66.1±4.4	42.1±13.4	65.7±6.6	65.6±17.0
% Hw at 5.0m	NA[2]	61.0±5.4	62.8±0.2	59.5±7.4	34.5±15.8	59.5±4.9	51.9±6.1	63.4±3.4	60.7±7.8	35.4±0.5	63.5±3.9	31.5±9.9	66.5±8.4	59.5±8.3
% Hw at base of crown	NA	64.3±7.0	43.8±3.0	54.8±4.6	26.4±17.3	60.3±5.1	45.5±6.5	59.4±2.5	50.9±9.1	28.9±8.4	54.6±6.1	20.6±10.6	51.3±8.8	52.3±14.0

[1]Hw = heartwood

[2]NA= data not available

Table 3.

Regression equation	R^2	P	F
y=15.5 + 0.81age (zone I)	0.85	<0.001	45.34
y=62.7 + 0.10 age (zone II)	0.15	0.2 ns	1.63
y=24.2 + 0.93 age (zone III)	0.49	< 0.001	23.15
y=13.7 + 1.19 age (zone IV)	0.60	0.005	14.40
y=38.2 + 0.67 age (zone V)	0.50	0.001	17.18

ns- not significant at 0.05 level

Legends to Figures

Figure 1:

Togo can be divided into five ecological zones which differ with regards to climate, soil and vegetation, (zones are classed I-V). Full black circles represent the geographical position of teak stands from which samples originated.

Figure 2:

a) Schema of a cross-section of a teak stem, illustrating the eight axes along which measurements were made (R = the axis between the pith and the bark, r = the axis between the pith and the heartwood boundary). b) Schema showing the position of strips of wood removed from the tree. Each strip was cut into samples, which were used to determine density at 12% moisture content and longitudinal modulus of elasticity.

Figure 3:

The vibration analysis system used to measure dynamic E_L in bending. The wood samples were hit using a small metal hammer, so as to bring into play all the natural modes of vibration at the same time. At the other end, a microphone was used to measure the vibrations emitted and transmit them via a filter to an analog-digital converter, which supplied digital data to a microcomputer.

Figure 4:

Relationship between heartwood ratio and DBH of trees of various ages (y = 40.12 Ln(x)-71.44, $R^2 = 0.61$).

Figure 5:

Density at 12% moisture content was significantly correlated with age in 30 trees from 6-70 years old (y = 2.45x + 622.68). Each symbol represents mean density at 12% moisture content ± standard error for 10 samples taken at BH.

Figure 6:

Radial variation in density at 12% moisture content was only weakly correlated to age in heartwood from 24 trees aged 16-70 years old (y = 33.25Ln(x) + 661.52, R2 = 0.18, P<0.001), probably due to the high variability in data distribution.

Figure 7:

Radial variation in longitudinal modulus of elasticity was weakly correlated to age in heartwood from 29 trees aged 16-70 years (y = 1746.80 Ln(x) + 9728.60, R^2 = 0.24, P <0.001).

Figure 8:

Density at 12% moisture content and longitudinal modulus of elasticity were significantly correlated at BH in 29 trees aged between 16-70 years for juvenile wood only. Full symbols represent juvenile wood and empty symbols represent adult wood.

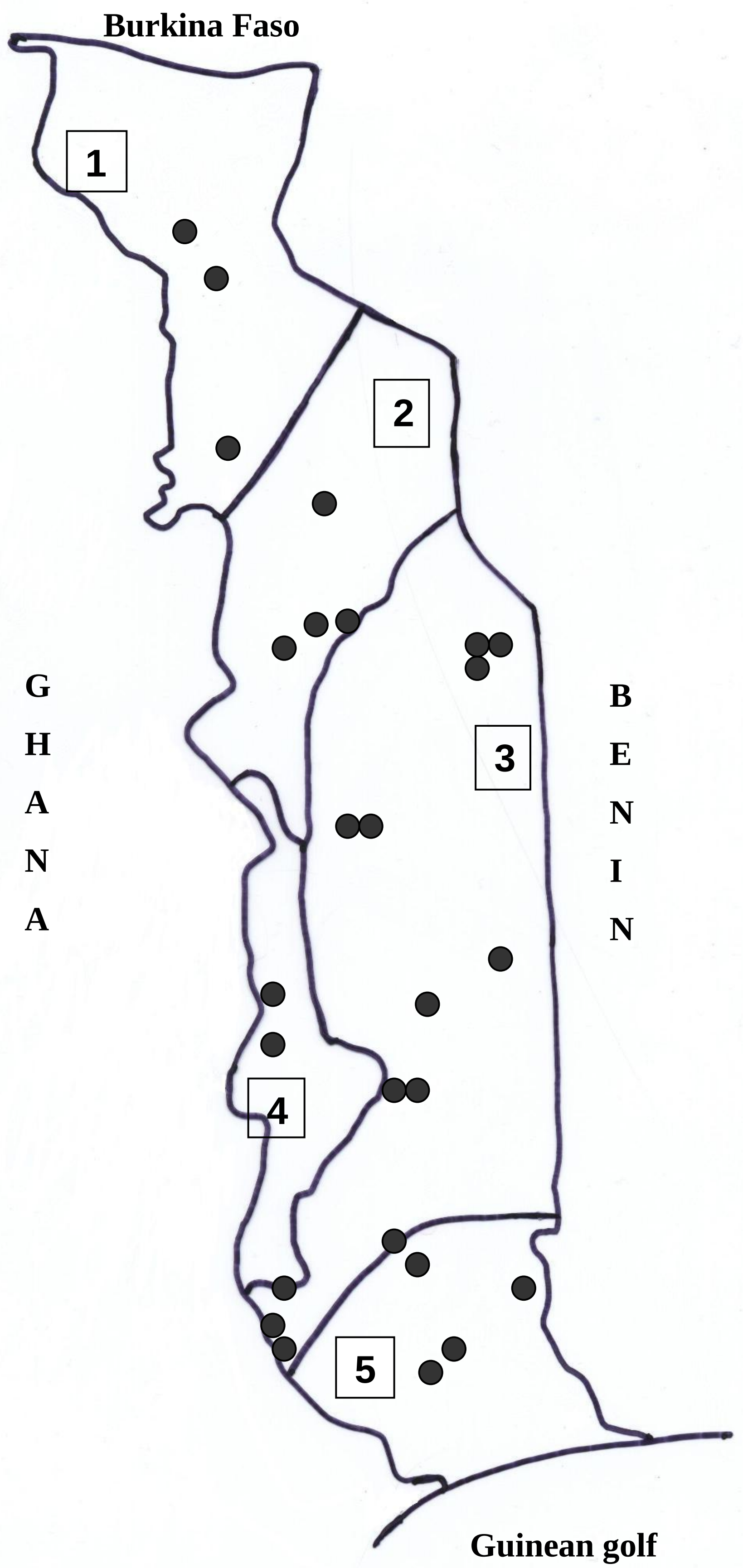


Fig. 1.

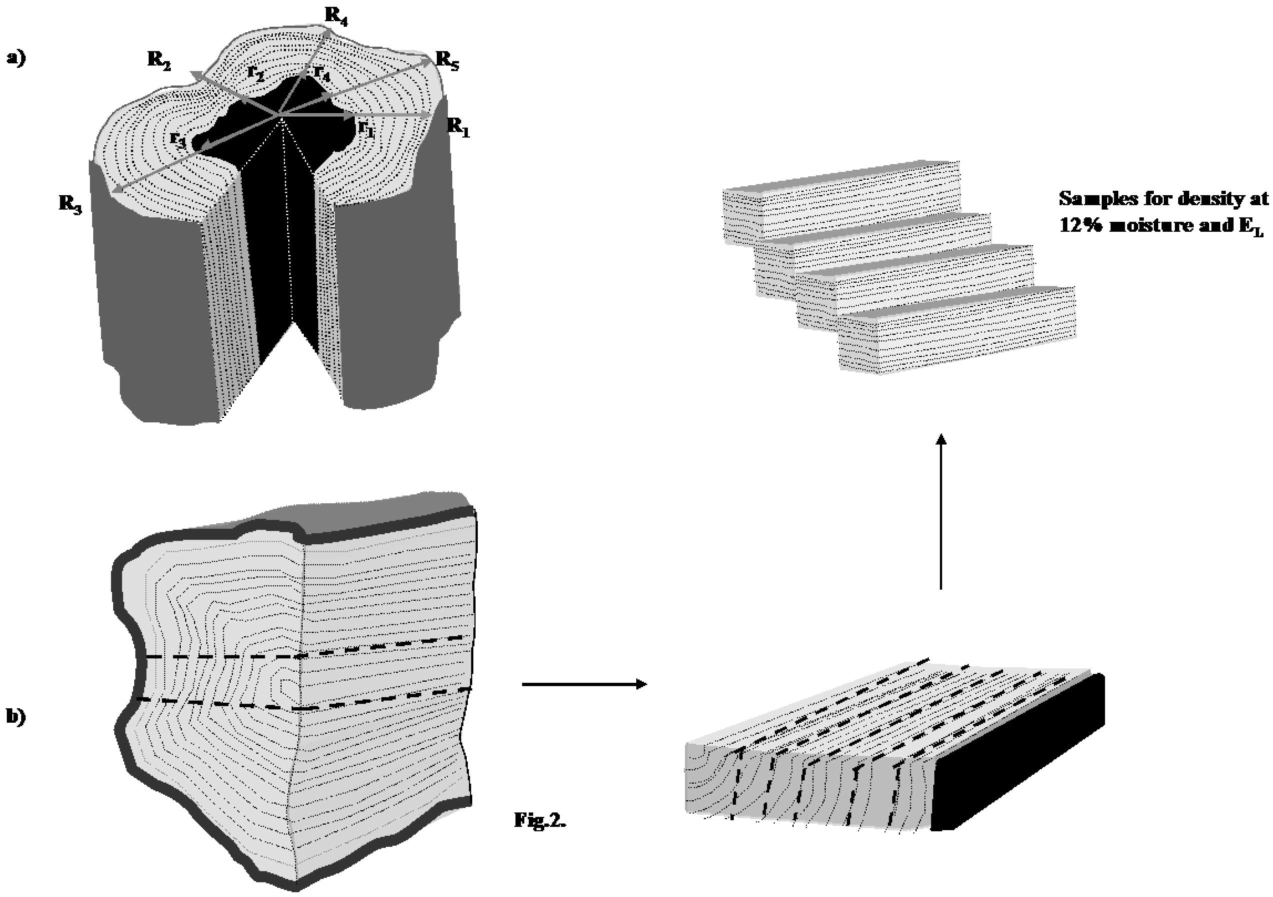

a)
R4
R2
r2
r4
R5
r1
R1
r3
R3
Samples for density at
12% moisture and E_L
b)

Fig.2.

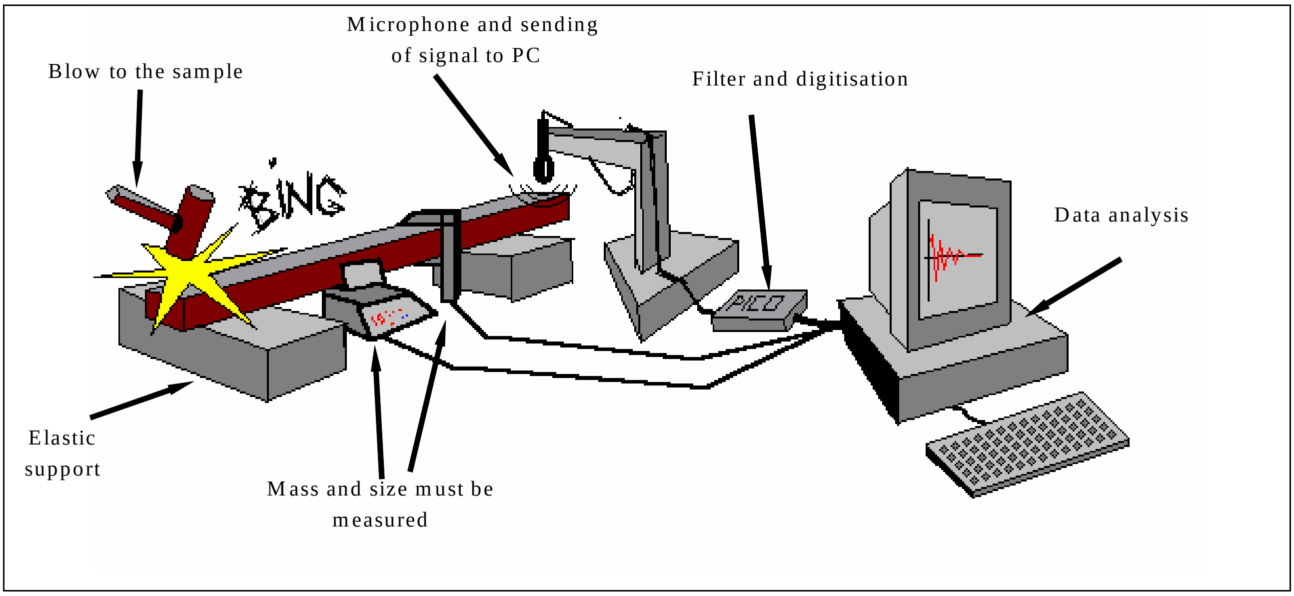
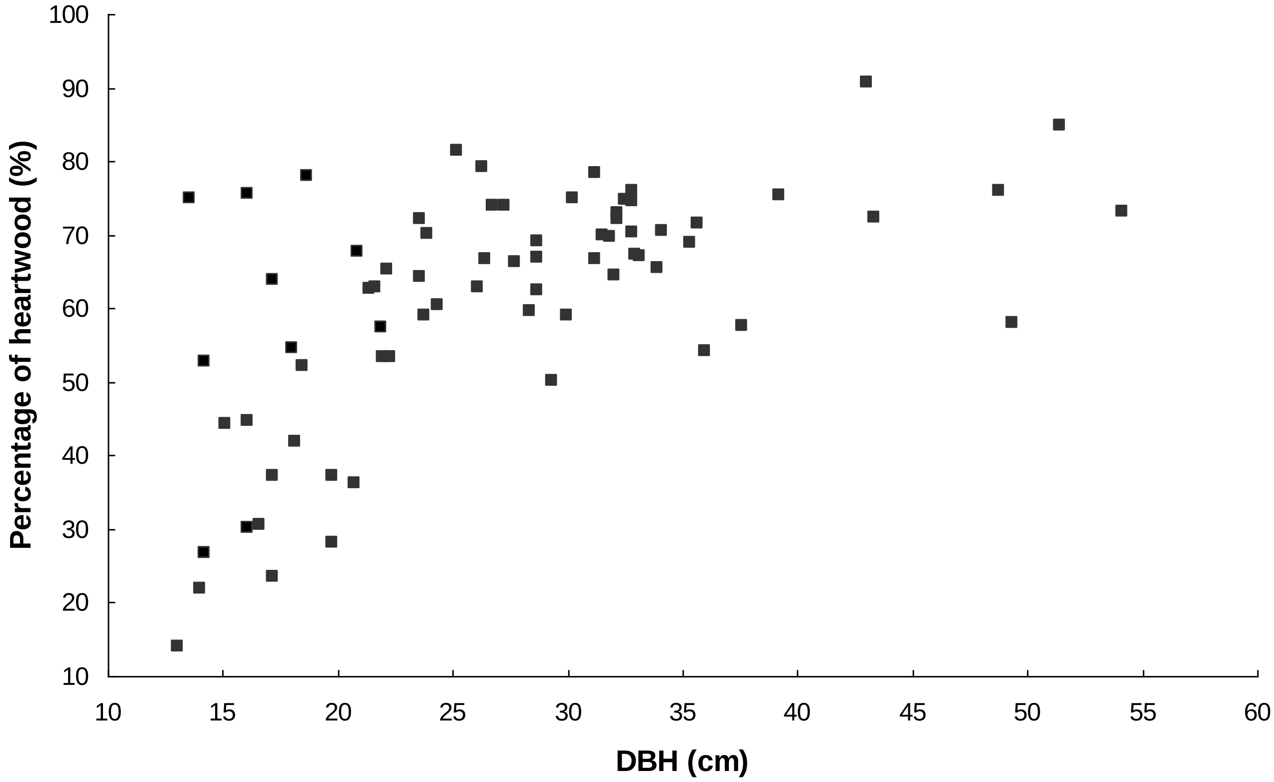

Microphone and sending
of signal to PC
Blow to the sample
Filter and digitisation
BING
PICO
Data analysis
Elastic
support
Mass and size must be
measured

Figure 3



Percentage of heartwood (%)
100
90
80
70
60
50
40
30
20
10
10
15
20
25
30
35
40
45
50
55
60
DBH (cm)

Fig 4

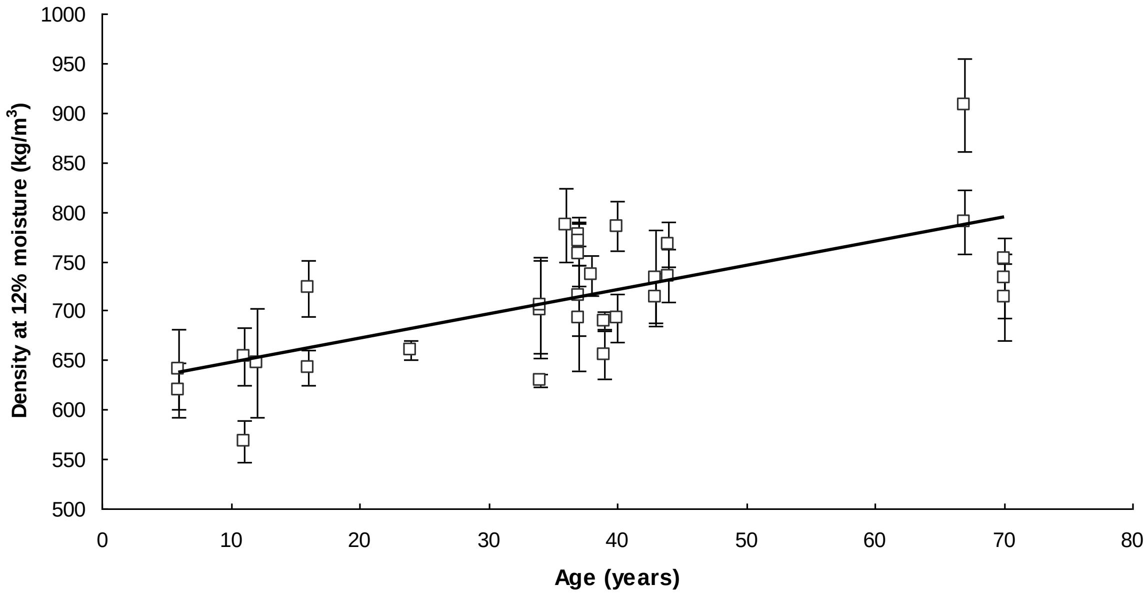

1000
950
900
850
800
750
700
650
600
550
500
Density at 12% moisture (kg/m^3)
0
10
20
30
40
50
60
70
80
Age (years)

Fig 5

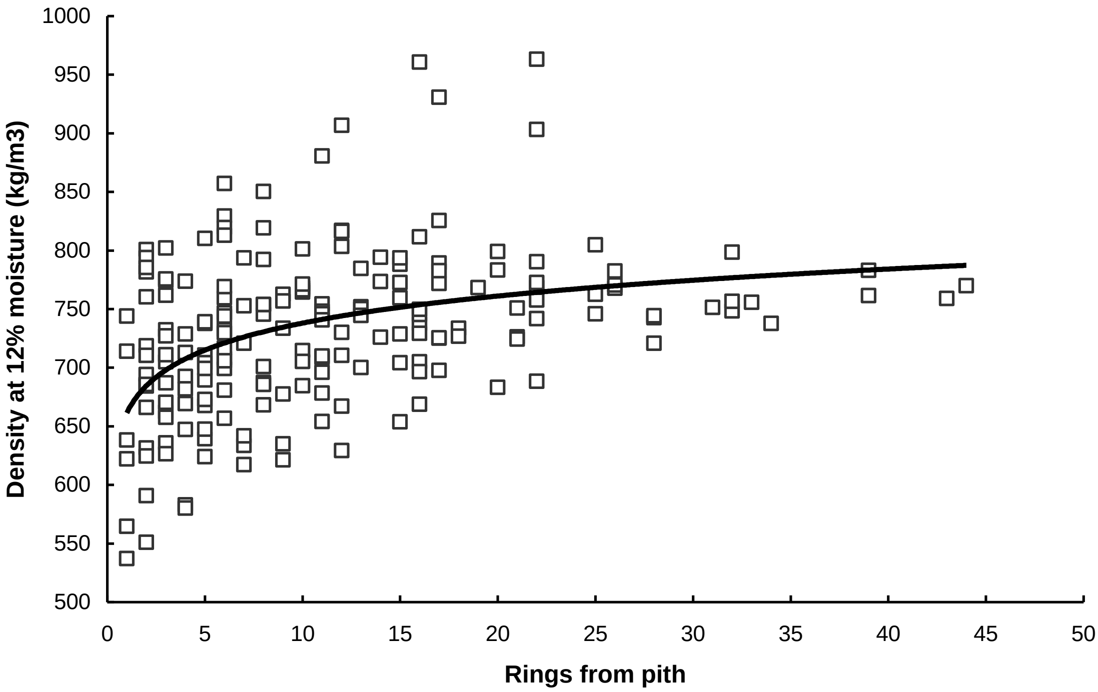

Density at 12% moisture (kg/m3)
1000
950
900
850
800
750
700
650
600
550
500
0
5
10
15
20
25
30
35
40
45
50
Rings from pith

Fig. 6

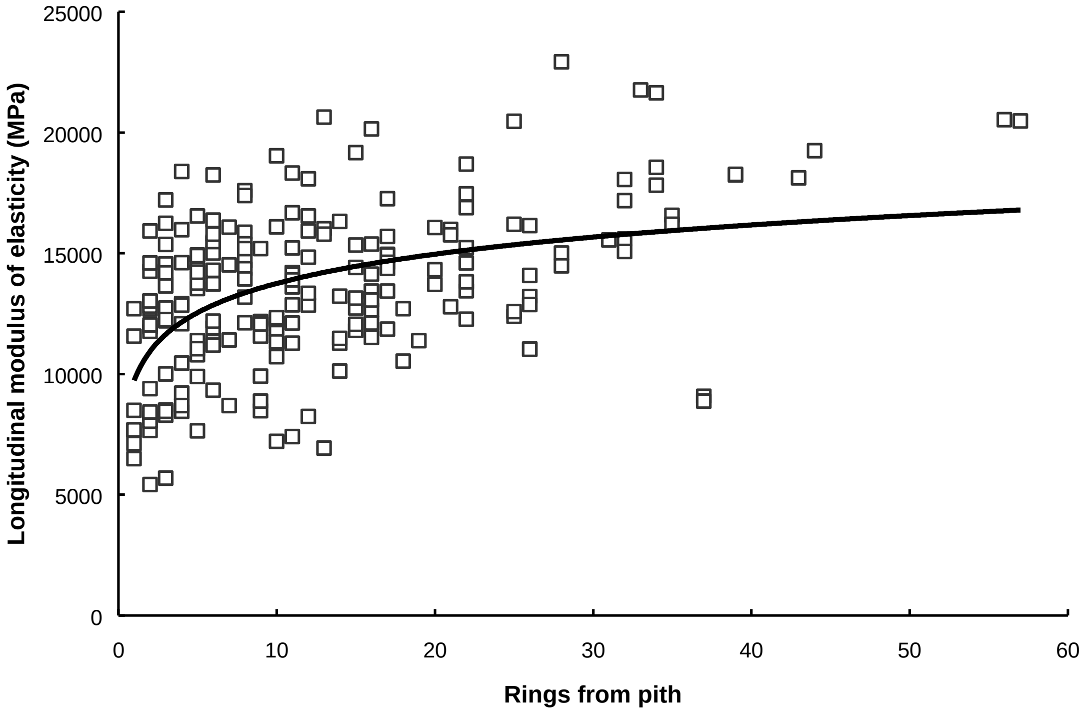
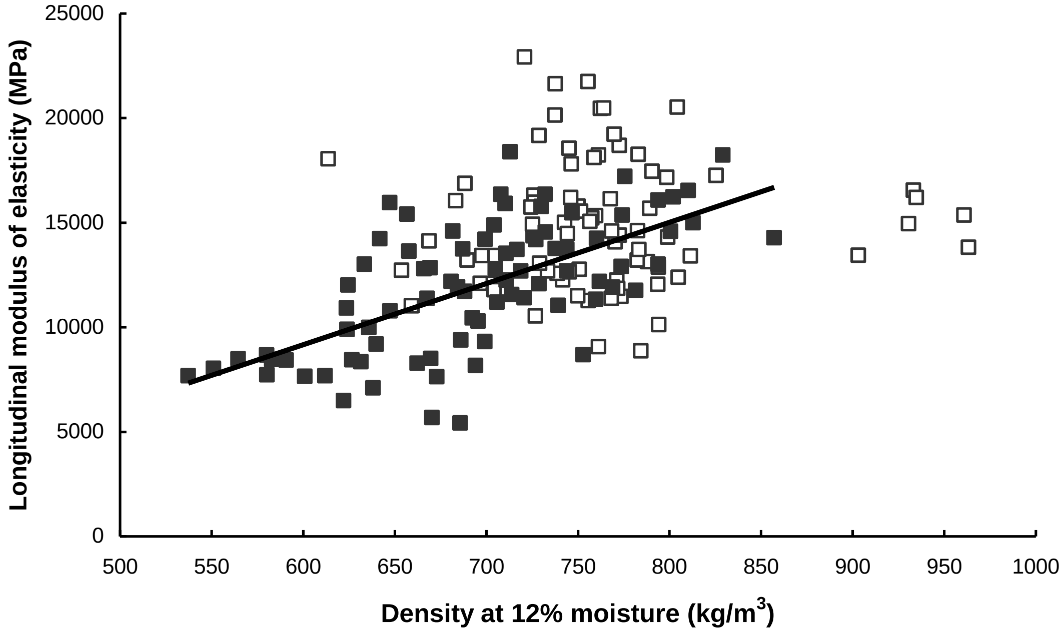

Longitudinal modulus of elasticity (MPa)
25000
20000
15000
10000
5000
0
0
10
20
30
40
50
60
Rings from pith

Fig. 7



25000
20000
15000
10000
5000
0
Longitudinal modulus of elasticity (MPa)
500
550
600
650
700
750
800
850
900
950
1000
Density at 12% moisture (kg/m3)

Fig. 8