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ORIGINAL PAPER

Characterization of Douglas-fir grown in Portugal: heartwood, sapwood, bark, ring width and taper

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Abstract Douglas-fir (*Pseudotsuga menziesii*) is one of the best timber conifers providing long sawnwood components. Original from North America, it has been planted in Europe on approximately 550 thousand ha. Twenty Douglas-fir trees growing in two sites in Portugal were studied regarding ring analysis, heartwood, sapwood and bark development, and taper. The radial growth rate was 7.1 and 6.6 mm year^{-1} at stem base for 45- and 50-year-old trees, respectively, in the two sites. Initial growth rate was slower, increasing until about 20 years and decreasing afterwards. Heartwood proportion represented on average 49% of the cross section in the lower part of the stem and decreased upwards. Heartwood formation was estimated to start at a cambial age of 8–9 years and increasing by 0.7–0.9 rings year^{-1}. Sapwood width was on average 75 mm at stem base, decreasing upwards. Bark was 26–27 mm thick at stem base, where it represented 15% of the cross-sectional area and decreased to 3–5 mm at the top. Stemwood and heartwood tapers were on average 15 mm m^{-1} in the lower stem part and 21 and 18 mm m^{-1}, respectively, in the upper part. Douglas-fir showed a good potential for the mountain areas of Portugal, and under the silvicultural conditions of both stands the trees presented ring homogeneity, small conicity and low taper suitable for long wood components.

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Keywords Douglas-fir · Heartwood · Sapwood · Bark · Ring width · Taper

Introduction

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), a species native to North America where it has a wide distribution, was introduced outside its natural range in various regions, namely in Europe nearly 200 years ago, where it is now the most widely distributed North American conifer (Lavender and Hermann 2014). Douglas-fir occupies approximately 19 million ha in the USA and Canada (Weiskittel et al. 2012) and over 550 thousand ha in Europe. Most timber comes from plantation forests in North America and Europe that provide sawn timber of great length and quality due to the large stem size and excellent wood properties (Ross and Krahmer 1971). Douglas-fir is now the economically most important exotic timber tree species in European forests (Schmid et al. 2014). In Portugal, Douglas-fir covers about 4200 ha (Martins 1999), but the potential area where this species could be planted is estimated at 250,000 ha (Fontes 2002).

The stem quality is a determining factor for the economic and technological performance of trees when they are intended for high-value timber. Stem quality parameters such as the radial and axial development of ring width, tree taper values, as well as heartwood proportion and its development in height, are usually considered. Heartwood is generally preferred for most timber applications because of its higher natural durability, darker colour and aesthetic value (Pereira et al. 2003; Sousa et al. 2013). Heartwood formation and development vary between species and within a species with growth rate, stand and tree biometric features, site conditions and genetics, while sapwood radial width is associated with heartwood formation and accumulation (Bamber and Fukazawa 1985; Hillis 1987; Taylor et al. 2002). Knowledge on heartwood and sapwood development over time at different heights of the trees is therefore a reference information for establishing the technological quality of a timber species, as studied for several species, e.g. *Pinus pinaster* (Pinto et al. 2004; Knapic and Pereira 2005), *Tectona grandis* (Miranda et al. 2011), *Quercus faginea* (Sousa et al. 2013), *Acacia melanoxylon* (Knapic et al. 2006).

Despite the economic importance of Douglas-fir, little information exists on its heartwood development as a technological stem quality parameter, and more information is available on sapwood development (Gartner 2002; Hein et al. 2008; Domec et al. 2012). This is addressed in the present study that analyses the within-tree development of heartwood and sapwood in relation to tree and cambial ages.

Bark proportion was also analysed since large quantities of Douglas-fir bark will be available as a residue from the primary processing of logs at sawmills or other processing mills. Douglas-fir bark is an interesting biomass component, namely because it contains a substantial proportion of cork. This potential was recognized in early studies (Kurth 1950; Hall 1971; Krahmer and Wellons 1973; Patel 1975), and recent work further investigated Douglas-fir bark as a chemical source for biorefineries (Ferreira et al. 2015, 2016).

This paper reports on the stem quality of mature Douglas-fir trees at the time of harvest in two plantations in Portugal. It is our objective to analyse their technological quality regarding ring analysis, heartwood, sapwood and bark development from a sawmilling targeted perspective. The aim is also to contribute for an integrated valuation of this timber species that is considered to have a good potential for the mountain areas of the country.

Materials and methods

The study was based on 20 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees sampled from two state-owned stands in northern and central Portugal. The stands resulted from the afforestation carried out by the state in the mid of the last century. Although the seed origin is not known, isozyme analysis suggested that the plantations are originated from seed from Oregon, west of the Cascade Range, therefore of the coastal variety *Pseudotsuga menziesii* var. *menziesii* (Fontes 2002). The afforestation was made using the forest services practices at the time for these conditions, namely targeting dense forests with densities around 1000–1200 trees ha^{-1}. There are no records of silvicultural management.

One stand (here named Cabreira), located in the Forest Perimeter of Serra da Cabreira, Cabeceiras de Basto (40°21′28.5″N, 07°27′07.2″W, 850 m of altitude, 7.5–10.0 °C annual mean temperature, 1600–2000 mm annual precipitation and Rankers soils), is a mixed stand with Douglas-fir as the dominant species but including also the softwoods *Pinus pinaster, Pinus sylvestris, Cupressus lusitana* and *Chamaecyparis* spp., and the hardwood *Betula pendula* with an average 1100 trees ha^{-1}. The other stand (named Estrela), located in the Forest Perimeter of Sarzedo, in the region of Serra da Estrela, Covilhã (41°35′18.0″N, 8°01′00.6″W, 930 m of altitude, 7.5–10.0 °C annual mean temperature, 1400–1600 mm annual precipitation and Cambisols soils), is a pure and regular stand with an average 1200 trees ha^{-1}.

Both stands were harvested to produce logs for the sawmilling industry. At the time of felling, ten trees were randomly selected in each stand and characterized by measuring total height, crown base height and diameter at 1.3 m above ground (d.b.h., as the mean of two crossed diameters). Tree age ranged from 43 to 50 years and 39 to 64 years, respectively, at Cabreira and Estrela, as given by ring counting at the stump cut at ground level (here called stem base), tree height averaged 29 m and 35 m, overbark diameter at breast height (d.b.h) ranged between 54 and 74 cm and the crown base of height to the first branch (c.b.h.) ranged between 1 and 6 m (Table 1). Measurement of the living crown height was not taken.

The trees were bucked into 2.5-m-long logs in accordance with the sawmill's demands. Stem discs (10 cm thick) were taken at the bottom end of each log, totalling 212 stem discs. The stem discs were air-dried in-doors and under well-ventilated conditions. The surface of the stem discs was smoothed by sanding. In all the cases, the annual rings were distinct and the heartwood was clearly recognizable by an orange/reddish colour that contrasted to the pale sapwood.

Eight radial directions approximately evenly spaced were randomly marked on the cross section for measurement of heartwood, sapwood and bark radial widths. The average value of these measurements was used for

Table 1 Tree age (as the number of rings at stem base), overbark diameter at 1.3 m (d.b.h.), total height and crown base height (c.b.h.) of the Douglas-fir trees sampled in the two sites of Cabreira and Estrela

	Cabreira	Estrela
Age (years)	45 ± 2 (43–50)	50 ± 7 (39–64)
d.b.h. (cm)	60.8 ± 5.8 (54.1–73.6)	60.9 ± 6.3 (53.8–73.9)
Height (m)	29.1 ± 3.3 (23.7–35.7)	34.9 ± 4.4 (30.4–46.1)
c.b.h. (m)	4.6 ± 1.3 (2.7–6.3)	2.7 ± 1.3 (1.0–5.0)

Mean of 10 trees ± SD and in parentheses interval of variation calculation of their corresponding areas considering a circular stem disc. The total number of annual rings and the number of rings included in the heartwood and sapwood were also determined.

The following variables were calculated for each stem disc:

(a) for bark: thickness (mm), area (cm^2) and proportion of the stem disc (bark area in per cent of total stem disc area);
(b) for heartwood: radius and diameter (cm), area (cm^2), proportion of the wood disc (heartwood area in per cent of total wood disc area) and number of rings;
(c) for sapwood: radial width (cm), area (cm^2), proportion of the wood disc (sapwood area in per cent of total wood disc area) and number of rings.

Volumes of tree (outside bark), stemwood (inside bark) and heartwood up to the commercial height were calculated using sections corresponding to the different heights of sampling as conical sections, and a cone (top above the last commercial log), using the following equations (Gominho and Pereira 2000):

$$V = \frac{h}{3}\left(\mathrm{Sa} + \mathrm{Sb} + \sqrt{\mathrm{Sa} \times \mathrm{Sb}}\right)$$

where Sa is the area at the lower height level; Sb is the area at the higher level; h is the length of the section. Sapwood volume was calculated as the difference of stemwood and heartwood volumes. Bark volume was calculated as the difference of tree and stemwood volumes.

The width of annual rings was measured from pith to bark along two opposite radii using Analysis software (version 3.2, AnalySIS Soft Imaging System GmbH, Munster, Germany). The arithmetic mean of the measurements was used in the calculations of tree growth. Latewood width in each ring was also measured, and its proportion in the ring was calculated.

Tree growth at the base and at the 5 m height level was characterized by the mean annual ring width (RW), the mean annual ring for the initial growth corresponding to the first 20 years from pith (IRW) and the mean annual ring for the final growth in the last 10 years before felling (FRW). Two relative growth factors were calculated: relative initial growth (IG) and relative final growth (FG) by dividing the corresponding mean initial and final annual ring width by the mean annual ring (IRW/RW and FRW/RW, respectively).

Statistical and correlation analysis was performed using Microsoft EXCEL 2013 procedures. Regression analysis was characterized by means of the Pearson correlation and coefficient of determination.

Results

Tree radial growth and ring width

The radial growth measured at stem base in trees from Cabreira showed that for approximately the same tree age of 45 years, the mean wood diameter ranged from 95.0 to 58.4 cm, corresponding to an average radial growth rate of 7.1 ± 2.0 mm $year^{-1}$. The trees from Estrela for an approximate tree age of 50 years had a wood diameter at stem base ranging from 95.4 to 55.4 cm, corresponding to an average radial growth rate of 6.6 ± 1.8 mm $year^{-1}$.

The mean growth rates and the initial (first 20 rings from pith) and final (last 10 rings) growth rates measured at stem base and at 5 m height are reported in Table 2. In both sites, the initial growth rate was similar and also at both height levels, but final growth was considerably higher at Cabreira than at Estrela (8.5 vs 3.7 mm $year^{-1}$ at stem base). The mean growth rate was higher for the trees from Cabreira at the stem base (8.1 vs 5.8 mm $year^{-1}$, respectively). For the trees from Cabreira, the growth rate was more homogeneous at the stem base, i.e. initial and final growth showed similar values relatively to the mean while at 5 m of height the relative initial growth was higher than final growth (1.2 vs 0.8) (Table 2). The growth rates at Estrela were less homogeneous over time, although the absolute and relative growth rates were very similar between the stem base and the 5 m height level. The latewood proportion in the ring was similar at both sites and without differences between base and 5 m of height (Table 2).

In general, the mean ring width profile at the stem base showed an initial slow growth rate up to 5 years of age (mean of 3.9 and 4.5 mm $year^{-1}$, respectively, at Cabreira and Estrela), after which the growth rate increased until about 17 years of age (9.0 and 7.8 mm $year^{-1}$, respectively), decreasing to 7.3 and 5.8 mm $year^{-1}$, respectively, to 45 years of age (Fig. 1).

Heartwood development

Heartwood was present in all the trees up to 25 m of stem height; at the height level of 27.5 m, only two trees from Cabreira contained heartwood.

The vertical development of heartwood was similar in all the trees: the heartwood area decreased from the tree base upwards, and the heartwood diameter followed closely that of the stemwood, also accompanying the butt swelling (Fig. 2).

The proportion of heartwood in the total stem cross section remained stable in the lower part of the stem until 5 m of tree height, after which it decreased steadily to the

Table 2 Tree growth variables and percentage of latewood for Douglas-fir trees (mean of 10 trees ± SD) from two sites (Cabreira and Estrela) measured at stem base and at 5 m of height: RW, mean annual ring width; IRW, mean annual ring for the initial growth in the first 20 years from pith; FRW, mean annual ring for the final growth in the last 10 years before felling; IG, relative initial growth and FG, relative final growth

	Cabreira		Estrela	
	Base	5 m	Base	5 m
Ring width (mm)				
Mean(RW)	8.07 ± 4.04	7.20 ± 2.49	5.75 ± 2.94	5.68 ± 2.67
Initial (IRW)	7.79 ± 4.33	8.51 ± 2.26	7.75 ± 2.85	7.78 ± 2.28
Final (FRW)	8.48 ± 4.78	5.46 ± 1.32	3.74 ± 1.93	3.38 ± 1.30
Relative growth				
Initial (IG)	0.97 ± 0.16	1.18 ± 0.07	1.34 ± 0.18	1.36 ± 0.10
Final (FG)	1.07 ± 0.24	0.76 ± 0.09	0.61 ± 0.13	0.58 ± 0.09
Latewood (%)	30.3 ± 4.7	30.6 ± 8.6	32.1 ± 8.7	29.3 ± 9.9

Tree age (as the number of rings at stem base), overbark diameter at 1.3 m (d.b.h.) and height of the Douglas-fir trees sampled in the two sites of Cabreira and Estrela

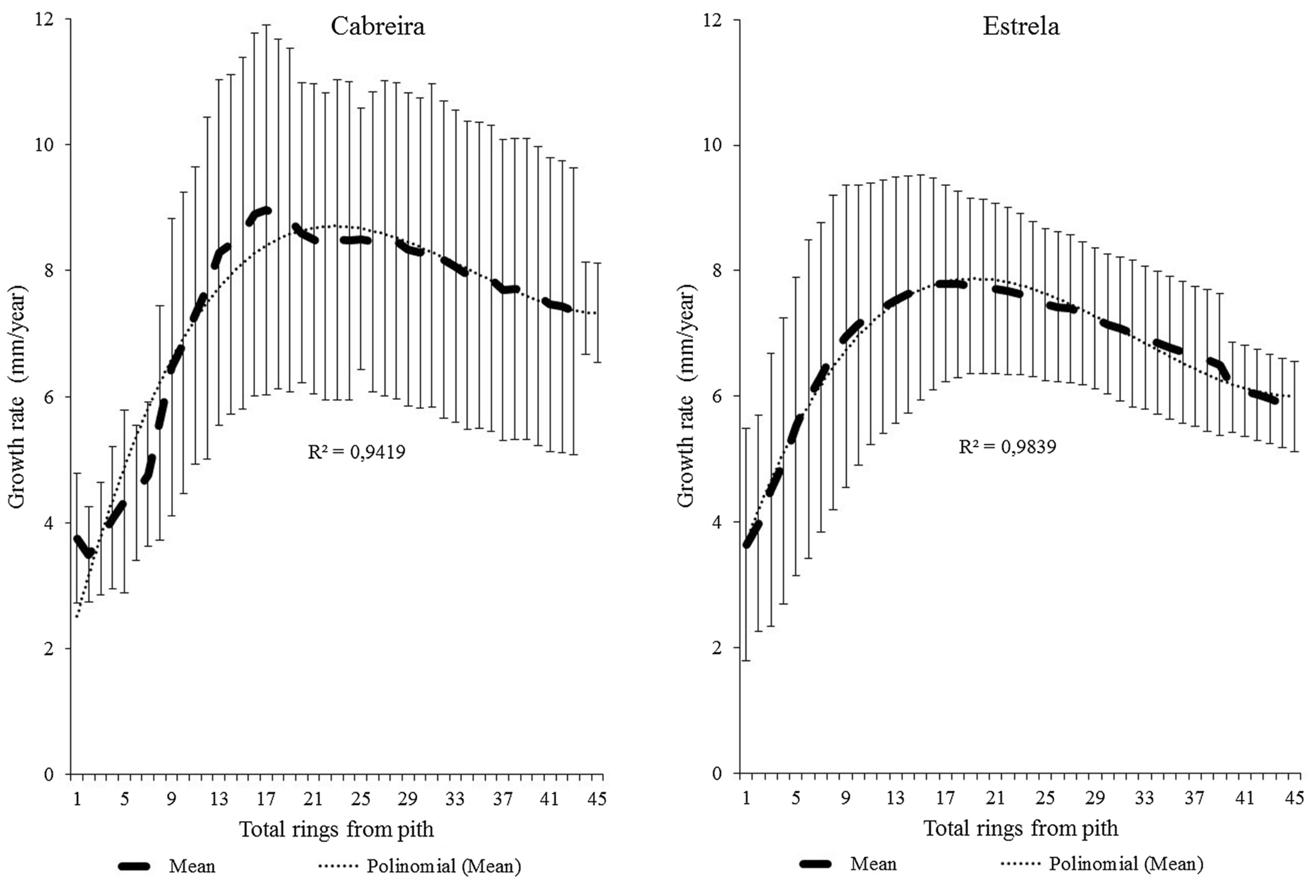

Fig. 1 Mean growth rate (and SD as *bar*) and adjusted polynomial curve, at the stem base level of ten trees from the two sites of Cabreira and Estrela

upper part (Table 3). On average, heartwood in trees from Cabreira and Estrela represented 49% at the base and 5 m height level, 45 and 46%, respectively, between 5 and 10 m of height and decreased to 38 and 40%, and to 25 and 33% for the upper height levels. The heartwood proportion was similar in both sites (Table 3).

The number of growth rings in the heartwood decreased along the stem height with a trend that was similar in all the

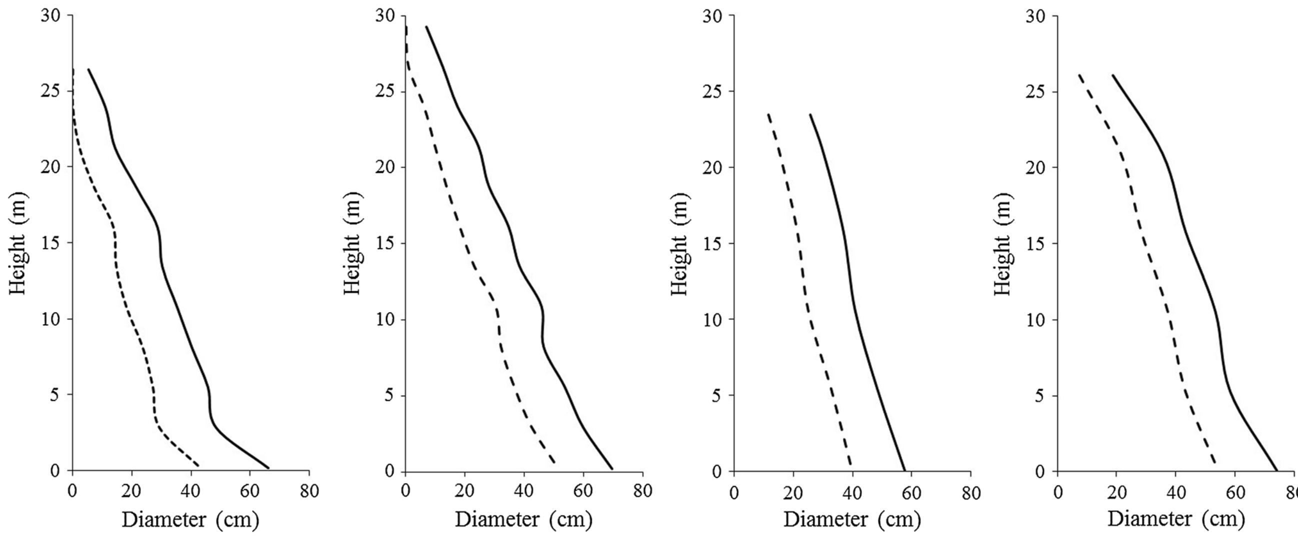

Fig. 2 Vertical profiles of heartwood (*dashed line*) and stem inside bark (*full line*) diameters for four Douglas-fir trees with different butt swelling magnitude (**a**, **b** Cabreira; **c**, **d** Estrela)

Table 3 Variation of heartwood, sapwood and bark proportion (% of the stem cross-sectional area), and of total stem cross-sectional area (cm^2) along the stem for Douglas-fir trees at two sites (Cabreira and Estrela)

Tree height level (m)	Base	5	10	15	20	25
Cabreira						
Stem cross section (cm^2)	3783.4 ± 1250.2	1892.6 ± 287.5	1313.8 ± 338.6	703.6 ± 260.4	288.8 ± 202.3	167.6 ± 104.2
Heartwood (%)	50.4 ± 7.4	48.4 ± 5.2	43.1 ± 6.8	32.6 ± 6.8	17.6 ± 10.6	12.2 ± 4.8
Sapwood (%)	34.9 ± 7.5	43.1 ± 4.9	48.3 ± 6.2	58.7 ± 6.3	73.1 ± 11.4	78.9 ± 5.3
Bark (%)	14.7 ± 3.6	8.4 ± 1.0	8.6 ± 1.3	8.7 ± 1.7	9.3 ± 3.4	10.4 ± 1.4
Estrela						
Stem cross section (cm^2)	3716.6 ± 1334.2	2203.9 ± 422.3	1271.5 ± 360.5	1288.3 ± 383.0	827.2 ± 354.2	555.6 ± 420.7
Heartwood (%)	49.6 ± 5.0	48.1 ± 8.6	42.8 ± 8.0	36.7 ± 8.8	29.2 ± 10.4	18.8 ± 7.1
Sapwood (%)	35.2 ± 5.9	41.8 ± 8.5	48.1 ± 8.0	54.4 ± 8.4	62.9 ± 11.0	73.5 ± 7.3
Bark (%)	15.2 ± 2.1	10.0 ± 1.2	9.0 ± 1.3	8.9 ± 1.4	7.9 ± 0.9	7.7 ± 0.9

Mean of 10 trees ± SD

trees. For example, the 45-year-old tree had 28 heartwood rings at the stem base, 18 at 5 m and 13 at 10 m of height; at the top level, with 6 wood rings, there was no heartwood.

Heartwood formation in relation to age was investigated by considering the variation of the number of heartwood rings (HW) with cambial age (CA) (Fig. 3), and a linear regression could be adjusted with an excellent coefficient of correlation: $HW = 0.8846\ CA - 7.3568$ ($R^2 = 0.991$) for Cabreira and $HW = 0.7280\ CA - 6.7368$ ($R^2 = 0.958$) for Estrela. The slope of the regression line indicated a rate of heartwood formation of an average of 0.9 and 0.7 rings $year^{-1}$, respectively, in Cabreira and Estrela, and heartwood formation was estimated to start at a cambial age of 8 years in Cabreira and 9 years in Estrela. The proportion of heartwood in the stemwood section varied with cambial age, increasing from approximately 12 and 19% for a cambial age of 11 and 21 years, respectively, to 50% for 46 and 50 years for Cabreira and Estrela (Fig. 4).

The average tree (outside bark) and stemwood (inside bark) volumes up to the commercial height level were 2.9 and 2.6 m^3, respectively, for the trees from Cabreira, and 4.2 and 3.7 m^3, respectively, for trees from Estrela. The heartwood volume was 1.3 m^3, corresponding to 44% of the average stemwood volume for the trees from Cabreira and 1.7 m^3, corresponding to 42% of the average stemwood volume for the trees from Estrela.

Sapwood variation

The sapwood cone started above the 25 m height level, thereby representing a length to the top of the tree under

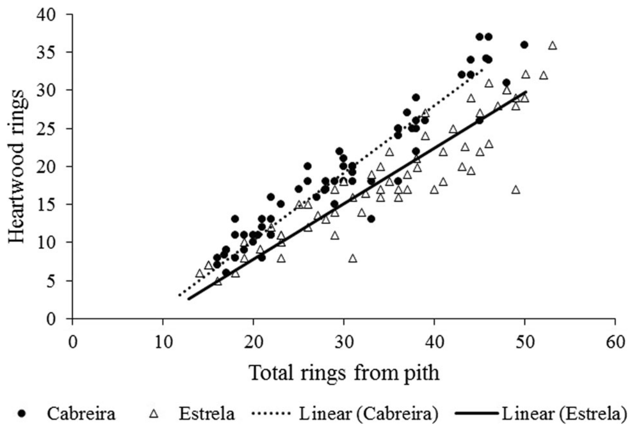

Fig. 3 Variation of the number of heartwood rings as a function of total rings from pith and fitted linear regression curve (Cabreira: HW = 0.8846 CA − 7.3568, $R^2 = 0.991$, and Estrela: HW = 0.7280 CA − 6.7368, $R^2 = 0.958$, with *HW* heartwood rings, *CA* cambial age)

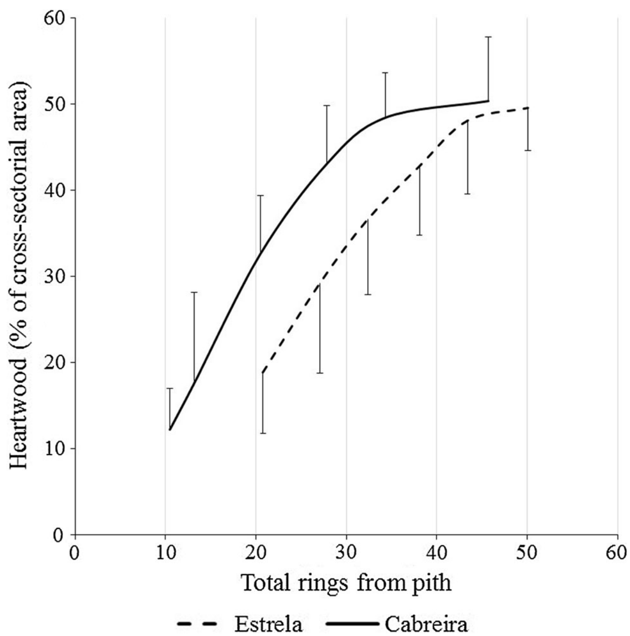

Fig. 4 Variation of heartwood proportion in the stem cross section with total rings from pith for 10 trees from Cabreira and Estrela

approximately 4 and 9 m, respectively, for Cabreira and Estrela. The radial width of sapwood was higher at the base in the region of butt swelling, where it represented on average 75 and 74 mm for Cabreira and Estrela, respectively. Between 5 and 10 m, sapwood width was approximately constant at 62 mm and decreased upwards to 44 mm at 25 m for the trees from Cabreira; for the trees from Estrela, the axial decrease in sapwood width was less pronounced and was 61 mm at 25 m of height (Fig. 5). The proportion of sapwood in the cross section increased to the upper part of the stem (Table 3).

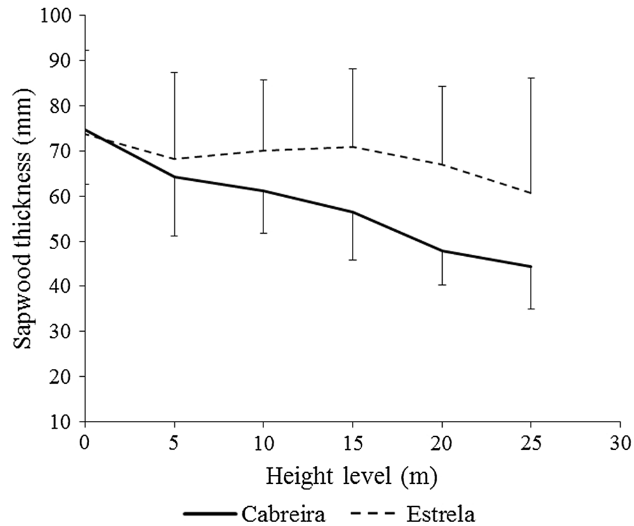

Fig. 5 Variation of sapwood radial width along the tree height in Douglas-fir trees in two locations (Cabreira and Estrela). Mean of 10 trees and SD

Bark development

Within the tree, the mean bark thickness decreased from 26.4 and 26.9 mm at the base to 3.3 and 4.7 mm at the top of the trees, respectively, for Cabreira and Estrela (Fig. 6). Bark thickness could be modelled for these 45- and 50-year-old trees (Cabreira and Estrela) as a function of the tree height level, or of the tree diameter or cambial age with high coefficients of determination:

- Cabreira:
  BT = −4.35 ln(TH) + 18.444 ($R^2 = 0.987$, R^2 adj = 0.984);
  BT = 0.0001 D^2 − 0.0664 D + 15.34 ($R^2 = 0.992$, R^2

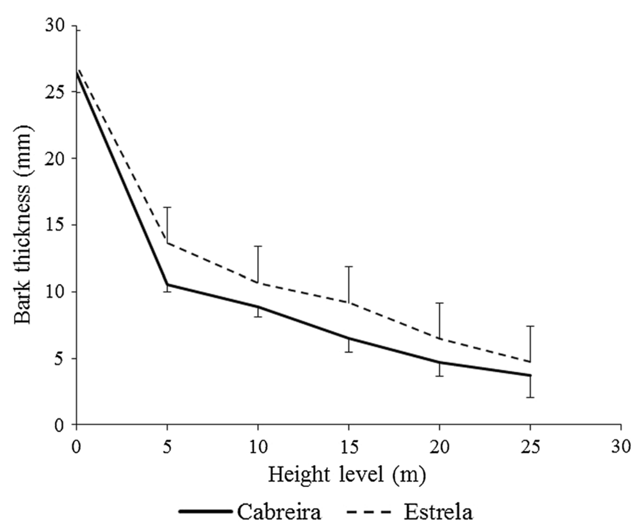

Fig. 6 Axial variation of bark thickness for Douglas-fir trees in two sites (Cabreira and Estrela). Mean of ten trees and SD (as *bar*)

adj = 0.986);
BT = 0.0022 CA^3 − 0.176 CA^2 + 4.7654 CA − 35.546 (R^2 = 0.996, R^2 adj = 0.986).

- Estrela:
  BT = −3.77 ln(TH) + 18.61 (R^2 = 0.975, R^2 adj = 0.968);
  BT = 0.0001 D^2 − 0.0514 D + 11.305 (R^2 = 0.992, R^2 adj = 0.987);
  BT = 0.0021 CA^3 − 0.1972 CA^2 + 6.2184 CA − 58.821 (R^2 = 0.992, R^2 adj = 0.983).

where BT is bark thickness (mm), TH the tree height level (m), D the diameter (cm) and CA the cambial age.

Bark proportion varied along the tree with height (Table 3). The pattern was similar for all the trees, with a higher content in the lower part of the stem (15% at base level) decreasing and stabilizing at 9.0 and 8.0% up to 25 m of height, respectively, for Cabreira and Estrela.

The average bark volume was 0.33 and 0.52 m^3 corresponding to 11 and 12% of the total tree stem volume for Cabreira and Estrela.

Taper

Stemwood taper and heartwood taper for the different logs are summarized in Table 4. At Cabreira, the taper was highest for the butt log reflecting the butt swelling. For the 5–10 m height section, stemwood and heartwood tapers were smaller and similar at an average of 14.9 mm m^{-1}; from 10 m to the upper part of the tree, the stemwood and heartwood tapers were constant at 20.5 and 18.2 mm m^{-1}, respectively (Table 4). For the trees at Estrela, the stemwood taper and heartwood tapers were smaller than for the trees at Cabreira (Table 4).

Discussion

Radial growth and ring analysis

The Douglas-fir trees showed a high radial growth in the two stands in northern and central Portugal, with an average of 6.9 mm $year^{-1}$ (Table 2) and a decreasing pattern with cambial age (Fig. 1). These results are similar to the 7.2 mm $year^{-1}$ of Douglas-fir trees growing in the coastal range of western Oregon (USA) that also showed a rapid early growth and then a gradual growth rate decline (Tappeiner et al. 1997). For Douglas-fir stands with a similar initial tree density of 1200 trees ha^{-1}, Hein et al. (2008) showed that the mean radial increment was below 8 mm decreasing steadily between the start of the experiment until the end of observation.

Growth in the juvenile phase was higher than in mature periods (Table 2), and the difference was more accentuated in the slower growth stand of Estrela; the maximum growth rate was attained at approximately 20 years (Fig. 1), in accordance with previous observations (Louro and Cabrita 1989).

Growth was somewhat higher at Cabreira than at Estrela (Fig. 1), which may be caused by the different site elevations (850 vs 930 m) since growth rate generally slows down with increasing elevation (Lassen and Okkonen 1969). Climate effects of temperature and rainfall were considered in the analysis of ring width of the trees in Cabreira and Estrela, but no significant signals were found (data not shown). Since tree competition is a factor influencing diameter growth (Kohnle et al. 2012), the fact that between-tree competition was probably higher in the regular and pure stand of Estrela may also account for this difference in growth, especially regarding the late growth in the mature trees (Table 2). On the contrary, tree height is only marginally affected by inter-tree competition and may be used as a stand-level indicator for the growth potential of a specific site (Kohnle et al. 2012); in the present context, the tree height was in fact similar for both sites.

This high radial growth in conjunction with tree height (on average 32 m, Table 1) allows a harvest age for the sawmilling industry in the range of 45–60 years (Fontes et al. 2003a), thereby confirming the good potential of Douglas-fir as a timber species for the mountain areas of Portugal, as also previously suggested (Fontes 2002; Fontes et al. 2003b), namely for afforestations directed towards increasing timber production (Diniz 1969; Fontes 1989, 2002; Freitas 1989; Louro and Cabrita 1989). It is interesting to notice that the radial growth rate of Douglas-fir is substantially higher than that reported for *Pinus*

Table 4 Stemwood and heartwood taper, in mm/m, between different stem height levels (mean of 10 trees ± SD) of Douglas-fir trees in two locations (Cabreira and Estrela)

Height levels (m)	Cabreira		Estrela	
	Stemwood	Heartwood	Stemwood	Heartwood
Base-5	31.2 ± 13.2	28.4 ± 9.8	24.0 ± 13.7	21.8 ± 9.7
5–10	15.3 ± 5.5	14.5 ± 3.7	10.8 ± 2.5	11.6 ± 2.6
10–15	20.3 ± 7.0	18.6 ± 5.9	11.8 ± 6.7	12.1 ± 6.3
15–20	20.6 ± 4.1	18.0 ± 4.5	18.2 ± 8.4	15.1 ± 5.1
20–25	20.7 ± 3.9	18.1 ± 5.2	15.5 ± 12.0	15.7 ± 5.4

pinaster that is the most common timber conifer in Portugal, e.g. in mature trees 1.8 and 2.6 mm year^{-1} (Knapic and Pereira 2005; Vieira et al. 2009) or 4.2 mm year^{-1} in 17-year-old trees (Gaspar et al. 2008).

The fact that ring width pattern was similar at different height levels along the stem, i.e. growth rate at the same cambial age was similar for the different tree ages, contributes to stemwood homogeneity which is an advantage when similar mechanical performance of long wood structural elements is desired. Exceptions were found only in some trees at the stem base where higher heterogeneity was found derived from the presence of butt swelling. The similar ring structure, i.e. latewood proportion was similar (Table 2), also gives a considerable homogeneity to the wood.

Heartwood development

Very few references are found in the literature regarding the heartwood content in Douglas-fir and its within-tree development. The trees sampled here in both sites contained a substantial proportion of heartwood that decreased from tree base upwards (Fig. 2). This axial variation pattern was already observed for 34-year-old Douglas-fir trees (Gartner 2002) and follows the general trend described for all species (Hillis 1987), namely for pines such as *Pinus pinaster* (Pinto et al. 2004; Knapic and Pereira 2005; Esteves et al. 2005), *P. sylvestris* (Bjorklund 1999; Morling and Valinger 1999), *P. canariensis* (Climent et al. 2003), *P. contorta* (Yang and Murchison 1992), *P. banksiana* (Yang et al. 1985) and *P. radiata* (Wilkes 1991). Long and Scott (1981) observed that most of the increase in total cross-sectorial area of the stem below the crown is attributable at the non-conducting heartwood.

The heartwood content increases with tree age, and various authors found evidence that, after a certain initiation age, heartwood is formed at a constant annual ring rate (Hazenberg and Yang 1991; Wilkes 1991; Sellin 1994; Bjorklund 1999; Gjerdrum 2003). This was also found here for Douglas-fir with the number of heartwood rings strongly correlated with cambial age. The rate of heartwood formation of 0.9 and 0.7 rings year^{-1} increased with cambial age, and the values were similar to those registered for other softwoods, e.g. for *Pinus pinaster* 0.5 rings year^{-1} (<55 years) and 0.7 rings year^{-1} (>55 years) (Knapic and Pereira 2005), *P. sylvestris* 0.5, 0.7 and 0.9 rings year^{-1} (<45, 90 and 115 years, respectively) (Bjorklund 1999), and 0.6 and 0.8 rings year^{-1} for cambial ages of 60 years and 220 years, respectively (Gjerdrum 2003) and *Picea mariana* 0.79 rings year^{-1} (50 years) and 0.98 rings year^{-1} (90 years) (Hazenberg and Yang 1991).

Heartwood formation was estimated to start at a cambial age of 8 and 9 years in accordance with works of Smith et al. (1966) who indicated an early formation of heartwood in Douglas-fir. Other species show different ages for heartwood initiation: for *Pinus pinaster* 13 or 18 years (Knapic and Pereira 2005; Esteves et al. 2005), *P. sylvestris* 15–25 years (Bjorklund 1999; Morling and Valinger 1999), *P. canariensis* 30 years (Climent et al. 2003) and *Picea abies* 18–20 years (Munster-Swendsen 1987). These results indicate that heartwood initiation age and formation rate are species specific.

Heartwood formation may also be more dependent on tree diameter than on age, as reported for several species, e.g. *Tectona grandis* (Kokutse et al. 2004), *Acacia melanoxylon* (Knapic et al. 2006), *Eucalyptus globulus* (Gominho and Pereira 2000, 2005) and *Pinus sylvestris* (Bjorklund 1999). In fact, heartwood dimensions have positive variations with tree growth, e.g. *Larix decidua* (Leibundgut 1983) and *Eucalyptus globulus* (Gominho and Pereira 2000), and stem diameter was a good predictor of heartwood diameter in *Pinus pinaster* (Pinto et al. 2004) and *P. canariensis* (Climent et al. 2003).

Sapwood variation

The mean sapwood width of 75 mm was in accordance with Domec et al. (2012) who reported 72 mm of sapwood width for Douglas-fir trees with 61–63 cm d.b.h (100–102 years old). The axial variation of sapwood width was of small magnitude with a decrease from stem base to the top which was more accentuated in Cabreira than in Estrela where it showed an almost constant value of 70 mm (Fig. 5), also reported by Long and Scott (1981) for 45-year-old Douglas-fir trees. This vertical distribution of sapwood supports the pipe model described by Shinozaki et al. (1964) by which the sapwood cross-sectorial area remains more or less constant below the live crown. The near constancy of sapwood width with height in Douglas-fir after initial higher values at stem base was also described for trees of different ages, e.g. 22 years old (Bancalari et al. 1987), 34 years old (Gartner 2002), 55 years old (Megraw 1986) and 59 to 78 years old (Wellwood 1955). This pattern of sapwood width variation along the Douglas-fir trees (Fig. 5) is also in accordance with that reported for other conifers, e.g. *Pinus pinaster* (Stokes and Berthier 2000; Knapic and Pereira 2005; Pinto et al. 2005), *P. sylvestris* (Bjorklund 1999), *P. banksiana* (Yang et al. 1985) and *P. contorta* (Yang and Murchison 1992). Sapwood width generally increases with tree diameter, rate of growth and relative crown size (Lassen and Okkonen 1969).

The most rapidly growing Douglas-fir trees have the widest sapwood (Wellwood 1955; Smith et al. 1966), and sapwood area is positively correlated with tree growth, largely due to its correlation with tree foliage area or mass (Grier and Waring 1974). The live crown height or diameter was not measured in this present work, and therefore, no further relation to sapwood development may be made. However, in the observed Douglas-fir trees, the radial growth rate was only weakly related to sapwood amount (data not show), and these results agree with others reported previously for Douglas-fir (Lassen and Okkonen 1969).

The number of sapwood rings at stem base (on average 10 rings) is approximately the same reported for 34-year-old Douglas-fir trees but smaller than the 30 and 40 rings observed for 100-year-old trees (Domec et al. 2012). The number of sapwood rings showed a small increase with cambial age up to a maximum at about 35–40 years followed by a decline after this age, therefore corresponding to a within-tree variation with height, in accordance with Bancalari et al. (1987) and Brix and Mitchell (1983). The small within-tree variation of sapwood width results in an increasing sapwood area proportion from stem base (on average 35% of the cross section) to the top (e.g. 57% at 15 m of height) (Table 3), as also observed by Hein et al. (2008). Domec et al. (2012) also documented a sapwood proportion increase from 30 to 53% corresponding to 100 and 34 years, respectively. Hein et al. (2008) also reported that stand density did not have effect on the cross-sectorial sapwood proportion along the stem, with sapwood extent appearing to mirror stem taper quite well.

Taper

In the sampled Douglas-fir trees, the stemwood and the heartwood showed a similar vertical profile (Fig. 2), as already described (Long and Scott 1981), and therefore, the wood and heartwood taper values were similar (Table 4). Taper was higher in the trees from Cabreira in relation to Estrela, e.g. the average taper of the trees from 5 to 25 m of stem was, respectively, 19.2 and 14.1 mm m^{-1}; this may be explained by a stronger tree competition in the pure Estrela stand. Overall, the stems were more cylindrical than would be implied by conformity to a cone, and the taper values were low which stresses the stem quality of Douglas-fir for long wood components.

Bark development

Bark thickness is a phenotypic characteristic important for forest management, the development of underbark timber volume equations, and may be associated with fire resistance (Kohnle et al. 2012). The latter aspect is particular important for Portugal where forest fires are frequent summer occurrences, and the high cork content in Douglas-fir bark confers an added insulation potential (Ferreira et al. 2015, 2016). Bark represented on average 12% of the stem volume, as also observed by McConnon (2004) and lower than the 18% referred by Maguire and Hann (1990). Bark showed, however, a significant thickness variation from the tree base upwards (Table 3; Fig. 6), as also reported by Gartner (2002). Bark thickness of Douglas-fir trees at any point above breast height can be estimated by a segmented polynomial taper equation given total height and breast height diameter (Maguire and Hann 1990).

Bark development in trees is a cumulative process, and therefore, the decrease in bark thickness with tree height is a common feature on several species (Trockenbrodt 1994), e.g. *Eucalyptus grandis* (Wilkins 1991) and *E. globulus* (Quilhó et al. 2000). Since bark of Douglas-fir may be a significant raw material if addressing a full resource use and a biorefinery approach (Ferreira et al. 2015, 2016), the results suggest that the debarking of the butt logs up to 5 m of height (where bark thickness is highest) would be the most efficient.

Conclusion

Douglas-fir showed good potential as a timber species for the mountain areas of Portugal with high radial growth that increased with age to a maximum growth rate at approximately 20 years.

The Douglas-fir trees contain a substantial proportion of heartwood estimated to start early at 8–9 years of cambial age and increasing by 0.7–0.9 rings $year^{-1}$. Sapwood width was on average 75 mm with small axial variation. The bark content is high especially in the lower part of the stem.

The stems showed a high axial homogeneity as regards ring development and low taper confirming their aptitude for long wood components for structural construction applications.

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References

Bamber RK, Fukazawa K (1985) Sapwood and heartwood: a review. For Abstr 46:567–580

Bancalari MAE, Perry DA, Marshall JD (1987) Leaf area—sapwood area relationships in adjacent young Douglas-fir stands with different early growth rates. Can J For Res 17:174–180. doi:10.1139/x87-030

Bjorklund L (1999) Identifying heartwood-rich stands or stems of *Pinus sylvestris* by using inventory data. Silva Fenn 33:119–129

Brix H, Mitchell AK (1983) Thinning and nitrogen fertilization effects on sapwood development and relationships of foliage quantity to sapwood area and basal area in Douglas-fir. Can J For Res 13:384–389. doi:10.1139/x83-057

Climent J, Chambel MR, Gil L, Pardos JA (2003) Vertical heartwood variation patterns and prediction of heartwood volume in *Pinus canariensis* Sm. For Ecol Manag 174:203–211. doi:10.1016/S0378-1127(02)00023-3

Diniz DMAM (1969) Estudo do crescimento da *Pseudotsuga menziesii* (Mirb.) Franco no Norte de Portugal. Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisboa

Domec JC, Lachenbruch B, Pruyn M, Spicer R (2012) Effects of age-related increases in sapwood area, leaf area, and xylem conductivity on height-related hydraulic costs in two contrasting coniferous species. Ann For Sci 69:17–27. doi:10.1007/s13595-011-0154-3

Esteves B, Gominho J, Rodrigues JC, Miranda I, Pereira H (2005) Pulping yield and delignification kinetics of heartwood and sapwood of Maritime Pine. J Wood Chem Technol 25:217–230. doi:10.1080/02773810500366656

Ferreira JPA, Miranda I, Gominho J, Pereira H (2015) Selective fractioning of *Pseudotsuga menziesii* bark and chemical characterization in view of an integrated valorization. Ind Crops Prod 74:998–1007. doi:10.1016/j.indcrop.2015.05.065

Ferreira J, Isabel Miranda, Jorge Gominho, Helena Pereira (2016) Chemical characterization of cork and phloem from Douglas fir outer bark. Holzforschung 70:475–483. doi:10.1515/hf-2015-0119

Fontes L (1989) Crescimento e competição em povoamentos de Pseudotsuga menziesii (Mirb.) Franco em Portugal. Universidade de Trás-os-Montes e Alto Douro, Vila Real

Fontes L (2002) The performance, constraints and potential of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in Portugal (Thesis submitted for the degree of Doctor of Philosophy at the University of Oxford). University of Oxford, Oxford, UK

Fontes L, Tomé M, Coelho MB, Wright H, Luis JS, Savill P (2003a) Modelling dominant height growth of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in Portugal. Forestry 76:509–523. doi:10.1093/forestry/76.5.509

Fontes L, Tomé M, Thompson F, Yeomans A, Luis JS, Savill P (2003b) Modelling the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site index from site factors in Portugal. Forestry 76:491–507. doi:10.1093/forestry/76.5.491

Freitas SA (1989) Perímetro Florestal de Manteigas, Direcção– Geral das Florestas

Gartner BL (2002) Sapwood and inner bark quantities in relation to leaf area and wood density in Douglas-fir. IAWA J 23:267–285. doi:10.1163/22941932-90000303

Gaspar MJ, Louzada JL, Aguiar A, Almeida MH (2008) Genetic correlations between wood quality traits of *Pinus pinaster* Ait. Ann For Sci 65:703. doi:10.1051/forest:2008054

Gjerdrum P (2003) Heartwood in relation to age and growth rate in *Pinus sylvestris* L. in Scandinavia. Forestry 76:413–424. doi:10.1093/forestry/76.4.413

Gominho J, Pereira H (2000) Variability of heartwood content in plantation-grown *Eucalyptus globulus* Labill. Wood Fiber Sci 32:189–195

Gominho J, Pereira H (2005) The influence of tree spacing in heartwood content in *Eucalyptus globulus* labill. Wood Fiber Sci 37:582–590

Grier CC, Waring RH (1974) Conifer foliage mass related to sapwood area. For Sci 20:205–206

Hall JA (1971) Utilization of Douglas-fir bark. Pacific Northwest Forest and Range Experiment Station, Portland

Hazenberg G, Yang KC (1991) The relationship of tree age with sapwood and heartwood width in black spruce, *Picea mariana* (Mill) B.S.P. Holzforsch. Int J Biol Chem Phys Technol Wood 45:320–417. doi:10.1515/hfsg.1991.45.5.317

Hein S, Weiskittel AR, Kohnle U (2008) Effect of wide spacing on tree growth, branch and sapwood properties of young Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in south-western Germany. Eur J For Res 127:481–493. doi:10.1007/s10342-008-0231-9

Hillis WE (1987) Heartwood and tree exudates. Springer, Berlin

Knapic S, Pereira H (2005) Within-tree variation of heartwood and ring width in maritime pine (*Pinus pinaster* Ait.). For Ecol Manag 210:81–89. doi:10.1016/j.foreco.2005.02.017

Knapic S, Tavares F, Pereira H (2006) Heartwood and sapwood variation in *Acacia melanoxylon* R. Br. trees in Portugal. Forestry 79:371–380. doi:10.1093/forestry/cpl010

Kohnle U, Hein S, Sorensen FC, Weiskittel AR (2012) Effects of seed source origin on bark thickness of Douglas-fir (*Pseudotsuga menziesii*) growing in southwestern Germany. Can J For Res 42:382–399. doi:10.1139/x11-191

Kokutse AD, Baillères H, Stokes A, Kokou K (2004) Proportion and quality of heartwood in Togolese teak (*Tectona grandis* L.f.). For Ecol Manag 189:37–48. doi:10.1016/j.foreco.2003.07.041

Krahmer R, Wellons J (1973) Some anatomical and chemical characteristics of Douglas-fir cork. Wood Sci 6:97–105

Kurth EF (1950) Wax from Douglas-fir bark. J Am Chem Soc 72:1685–1686

Lassen LE, Okkonen EA (1969) Sapwood thickness of Douglas-fir and five other western softwoods. USDA Forest Service Research Paper, Madison

Lavender D, Hermann RK (2014) Douglas-fir: the genus Pseudotsuga. Oregon Forest Research Laboratory, Oregon State University, Corvallis

Leibundgut H (1983) Untersuchungen verschiedener Provenanzen von Larix decidua. Schweiz Z Forstwes 134:61–62

Long JN, Scott DRM (1981) The role of Douglas-fir stem sapwood and heartwood in the mechanical and physiological support of crowns and development of stem form. Can J For Res 11:459–464. doi:10.1139/x81-063

Louro V, Cabrita P (1989) Pseudotsuga, Contribuição para o conhecimento da sua cultura em Portugal. (Estudos e Informação No. Nº 298). Direcção Geral das Florestas, Lisboa

Maguire DA, Hann DW (1990) Bark thickness and bark volume in southwestern Oregon Douglas-fir. West J Appl For 5:5–8

Martins L (1999) Área de distribuição da Pseudotsuga em Portugal. Direcção Geral das Florestas, Lisboa

McConnon H (2004) Provenance affects bark thickness in Douglas-fir. N Z J For Sci 34:77–86

Megraw RA (1986) Douglas-fir wood properties. In: Douglas-fir: stand management for the future, pp 91–96. Institute of Forest Resources Contribution 55. College of Forest Resources, University of Washington, Seattle, Washington

Miranda I, Sousa V, Pereira H (2011) Wood properties of teak (*Tectona grandis*) from a mature unmanaged stand in East Timor. J Wood Sci 57:171–178. doi:10.1007/s10086-010-1164-8

Morling T, Valinger E (1999) Effects of fertilization and thinning on heartwood area, sapwood area and growth in Scots pine. Scand J For Res 14:462–469. doi:10.1080/02827589950154168

Munster-Swendsen M (1987) Index of vigour in Norway spruce (*Picea abies* Karst.). J Appl Ecol 24:551–561. doi:10.2307/2403892

Patel RN (1975) Bark anatomy of radiata pine, corsican pine, and Douglas fir grown in New Zealand. N Z J Bot 13:149–167. doi:10.1080/0028825X.1975.10430317

Pereira H, Graça J, Rodrigues J (2003) Wood chemistry in relation to quality. In: Barnett JR, George J (eds) Wood quality and its biological basis. CRC Press, Oxford, pp 53–83

Pinto I, Pereira H, Usenius A (2004) Heartwood and sapwood development within maritime pine (*Pinus pinaster* Ait.) stems. Trees 18:284–294. doi:10.1007/s00468-003-0305-8

Pinto I, Usenius A, Song Tiecheng, Pereira H (2005) Sawing simulation of maritime pine (*Pinus pinaster* Ait.) stems for production of heartwood-containing components. For Prod J 55:88–96

Quilhó T, Pereira H, Richter HG (2000) Within-tree variation in phloem cell dimensions and proportions in *Eucalyptus globulus*. IAWA J 21:31–40. doi:10.1163/22941932-90000234

Ross WD, Krahmer RL (1971) Some sources of variation in structural characteristics of Douglas-fir bark. Wood Fiber 3:35–46

Schmid M, Pautasso M, Holdenrieder O (2014) Ecological consequences of Douglas fir (*Pseudotsuga menziesii*) cultivation in Europe. Eur J For Res 133:13–29. doi:10.1007/s10342-013-0745-7

Sellin A (1994) Sapwood–heartwood proportion related to tree diameter, age, and growth rate in *Picea abies*. Can J For Res 24:1022–1028. doi:10.1139/x94-133

Shinozaki K, Yoda K, Hozumi K, Kira T (1964) A quantitative analysis of plant form—the pipe model theory. I. Basic analysis. Jpn J Ecol 14:97–105

Smith JHG, Walters J, Wellwood RW (1966) Variation in sapwood thickness of Douglas-fir in relation to tree and section characteristics. For Sci 12:97–103

Sousa VB, Cardoso S, Pereira H (2013) Ring width variation and heartwood development in *Quercus faginea*. Wood Fiber Sci 45:405–414

Stokes A, Berthier S (2000) Irregular heartwood formation in *Pinus pinaster* Ait. is related to eccentric, radial, stem growth. For Ecol Manag 135:115–121. doi:10.1016/S0378-1127(00)00303-0

Tappeiner JC, Huffman D, Marshall D, Spies TA, Bailey JD (1997) Density, ages, and growth rates in old-growth and young-growth forests in coastal Oregon. Can J For Res 27:638–648. doi:10.1139/x97-015

Taylor AM, Gartner BL, Morrell JJ (2002) Heartwood formation and natural durability—a review. Wood Fiber Sci 34:587–611

Trockenbrodt M (1994) Quantitative changes of some anatomical characters during bark development in *Quercus robur*, *Ulmus glabra*, *Populus tremula* and *Betula pendula*. IAWA J 15:387–398. doi:10.1163/22941932-90001199

Vieira J, Campelo F, Nabais C (2009) Age-dependent responses of tree-ring growth and intra-annual density fluctuations of *Pinus pinaster* to Mediterranean climate. Trees 23:257–265. doi:10.1007/s00468-008-0273-0

Weiskittel AR, Crookston NL, Rehfeldt GE (2012) Projected future suitable habitat and productivity of Douglas-fir in western North America. Schweiz Z Forstwes 163:70–78. doi:10.3188/szf.2012.0070

Wellwood RW (1955) Sapwood–heartwood relationship in second-growth Douglas-fir. For Prod J 5:108–111

Wilkes J (1991) Heartwood development and its relationship to growth in *Pinus radiata*. Wood Sci Technol 25:85–90. doi:10.1007/BF00226808

Wilkins AP (1991) Sapwood, heartwood and bark thickness of silviculturally treated *Eucalyptus grandis*. Wood Sci Technol 25:415–423. doi:10.1007/BF00225234

Yang KC, Murchison HG (1992) Sapwood thickness in *Pinus contorta* var. latifolia. Can J For Res 22:2004–2006. doi:10.1139/x92-262

Yang KC, Hazenberg G, Bradfield GE, Maze JR (1985) Vertical variation of sapwood thickness in *Pinus banksiana* Lamb. and *Larix laricina* (Du Roi) K. Koch. Can J For Res 15:822–828. doi:10.1139/x85-133