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► To cite this version:

Joana A. Paulo, Margarida Tomé. Does debarking intensity during the first cork extraction affect future cork thickness?. *Annals of Forest Science*, 2017, 74 (4), pp.66. <10.1007/s13595-017-0662-x>. <hal-02976558>

HAL Id: hal-02976558

<https://hal.science/hal-02976558v1>

Submitted on 23 Oct 2020

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Does debarking intensity during the first cork extraction affect future cork thickness?

Joana A. Paulo¹  · Margarida Tomé¹

Received: 13 February 2017 / Accepted: 23 August 2017 / Published online: 27 September 2017
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Abstract

• **Key message** The use of increasing debarking during the first harvest of cork oak trees (*Quercus suber* L.) had no effect on the secondary cork calliper (thickness) in one of the trials and had a small negative effect in a second trial. Little evidence was found that debarking coefficient is a useful index for the management of cork oak stands.

• **Context** The Portuguese national legislation defines, without the support of scientific data or knowledge, maximum values of debarking coefficients (ratio of debarking height and perimeter at breast height measured over cork). For the first debarking, this value is limited to 2.0.

• **Aims** The aim of this study was to determine the impact of increasing cork debarking coefficient on the calliper of the secondary cork extraction.

• **Methods** Trees were located in two sites, in distinct regions characterized by low or high productivity classes. Three debarking coefficients were considered: 1.5, 2.0 and 2.5.

The debarking coefficient for the first cork extraction was randomly selected for each tree. During the second debarking, a cork sample was taken from each tree. The samples were used for assessing secondary cork calliper. Differences in cork calliper were analysed using both correlation analysis and modelling approaches.

• **Results** Debarking intensity increase had a small negative effect on secondary cork thickness in the most inland site, while no effect was detected in the more coastal site.

• **Conclusion** In our experiment, debarking intensity had a significant but small effect in one site and no effect in other sites. Debarking coefficients not only should be defined according to legal constraints but also instead should be adapted considering tree and site characteristics.

Keywords *Quercus suber* L. · Montado · Debarking coefficient · Debarking height · Secondary cork · Cork thickness · Cork calliper

Handling Editor: Andrew Merchant

Contribution of the co-authors

Joana Amaral Paulo: experimental design, data collection, data analysis and manuscript writing.

Margarida Tomé: experimental design, data analysis and manuscript revision.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s13595-017-0662-x>) contains supplementary material, which is available to authorized users.

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1 Introduction

Cork oak forests, also designated as *montados*, are one of the most extended high natural and cultural value ecosystems in the Mediterranean region (den Herder et al. 2017; Plieninger et al. 2015). These systems have been managed for centuries to engender the compatibility of cork production with agriculture and/or extensive grazing, but cork is frequently one of the most important sources of revenue for the landowners. Therefore, tree debarking is one of the most important management operations, not only because it results in the collection of the cork but also because the way the operation is carried out may affect the tree and cork growth in the following growth period (Costa et al. 2004; Costa et al. 2015; Natividade 1950; Pereira 2007).

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The immediate physiological response of the tree to the debarking operation has been researched at tree level by Correia et al. (1992), Hakam et al. (2012) and Werner and Correia (1996) and at stand level by Silva et al. (2015). Apart from for Hakam et al. (2012), no author found any relation between the tree response and the debarking intensity evaluated by debarking coefficient and by total debarked surface. Regarding a medium (annual) to long-term (period between two cork extractions) tree response, Costa et al. (2015), Fialho et al. (2001), Leal et al. (2008) and Oliveira et al. (2002) researched the effect of the debarking on radial growth and tree phenology, but none of the authors investigated the tree response to different debarking intensities.

One of the main concerns of landowners, managers and researchers regarding the management of the cork oak tree is the impact of the debarking intensity at a debarking event at tree age t , on tree and cork growth during the next cork growth period that will terminate in the debarking event at tree age $(t + 9)$ (e.g. Oliveira and Costa 2012; Paulo et al. 2016). Debarking intensity may be measured by debarking height or number of debarked branches variables or computed as debarking coefficient or debarking surface values. The Portuguese national legislation defines maximum values for the debarking coefficients, defined as the ratio between debarking height measured along the tree stem and the debarked branches and the perimeter at breast height measured over cork. It restricts to a maximum of 2.0 for the first debarking, 2.5 for the second and 3.0 for the third and following debarking operations. The established values were suggested by Natividade (1950) based on expert judgement. These limits are clearly defined as upper limits, with the objective of protecting trees from overexploitation, but questions related to the most appropriate value for particular stands or trees remain open (Paulo et al. 2016). It is expected that several variables may be related to the tree response to the debarking, for example, stand growing conditions (site productivity), management operations (e.g. understory composition and management operations for its control) or tree characteristics (e.g. sanitary conditions, cork thickness). Natividade (1950) suggested a reduction of the proposed 3.0 debarking coefficient to 2.5 for trees with more than three debarked branches, highlighting the importance of tree structure and tree debarking surface on the definition of the debarking intensity. More recent research, based on representative data sets, is scarce in the literature. The need for long-term experiments and data collection in controlled trials largely explains the current state of the art regarding this subject. Paulo et al. (2016) and Pizzurro et al. (2010) indirectly discuss the effect of the debarking intensity on cork thickness, the first suggesting that other variables such as annual precipitation and site characteristics are more influential for cork thickness, and the second supporting the conclusions of Natividade (1950) that increasing debarking heights will result

in a decrease in cork calliper. Both authors base their research on data collected from adult trees, of unknown age, and with an ‘unknown management history’, particularly in what concerns the debarking intensities that were applied in previous debarking operations. These characteristics of the data sets do not exclude a possible influence of the past debarking operations on the results.

The objective of the present research is to evaluate the effect of the debarking intensity, at the first cork extraction, on cork thickness extracted during the second debarking operation. This was carried out by the analysis of the cork thickness values, measured at tree level, in two distinct trials characterized by distinct soil and climate conditions. The trees in both sites had not been debarked prior to the treatments application, and for this reason, no co-effect of previous debarking disturbs the results.

2 Materials and methods

The research was developed on two distinct sites. The first site is located in a privately owned property called Machuqueira do Grou, located in the Ribatejo province, in the Coruche county (WGS84 coordinates: 39.132 N, – 8.343 W). The second site is located at the Perímetro Florestal of Contenda, currently a municipal property under the joint management of the Municipality of Moura and the National Forest Authority. It is located in the Baixo Alentejo province, near the city of Barrancos in Moura county (WGS84 coordinates: 38.058 N, – 7.040 W). The two sites are, from now on, referred to as MG (Machuqueira do Grou) and PFC (Perímetro Florestal de Contenda).

The stand of the MG site is characterized by an uneven-aged structure, including a considerable percentage of young undebarbed trees. It is managed as a traditional silvopastoral system: reduced number of animals per hectare (sheep) feeding on natural pasture and reduced implementation of mechanical understory control methods (one or two per cork growth rotation period made with mounted knives or chains). The average number of trees per hectare is 145, with a basal area under cork of $7.6 \text{ m}^2 \text{ ha}^{-1}$ and a crown cover percentage of 45%. The stand includes older and adult trees, mixed with young non-debarked trees. The trees considered for the trial had similar diameter and were therefore considered to have approximately uniform age. The productivity of the site, assessed by the site index model from Paulo et al. (2015), was estimated at 16 m for the total height of the dominant trees at a base age of 80 years, corresponding to a high productivity class (Paulo et al. 2015).

The stand of the PFC site is characterized by an even-aged structure stand, installed between 1958 and 1964, and managed primarily for game production (Pinheiro 1997). Forest management in PFC was limited to understory control

operations with mounted knives or chains, carried out with a reduced frequency and in order to reduce fire risk. The average number of trees per hectare was 143, with a basal area under cork of $3.1 \text{ m}^2 \text{ ha}^{-1}$ and a crown cover percentage of 24.2%. The productivity of the site, assessed by the site index model from Paulo et al. (2015), was estimated at 13 m, corresponding to a low productivity class.

In the matter of soil and climatic conditions, the two sites are also very distinct (Table 1). Since the years at which cork growth took place were not the same for both sites, a comparison of the annual precipitation distribution over the years of cork growth at the two sites is shown in the figure available as [supplementary material](#).

The selected trees were completely enclosed by virgin cork (undebarked trees) at the year of the trial installation. Due to legal constraints imposed by national legislation, only trees presenting a minimum value of 70 cm of perimeter at breast height over virgin cork were considered. All debarking operations took place in June. In the MG site, a total of 90 trees were randomly selected. These trees were debarked for the first time in 1995. The second debarking took place in 2005, on 72 trees. The remaining 18 trees were not found and presumed dead. In the PFC site, a total of 144 trees were selected among 8 existing permanent plots in the stand. These trees were debarked for the first time in 2003. The second debarking took place in 2012, on 134 trees. The ten remaining trees were dead and randomly distributed across four plots.

Table 1 Soil and climate characterization of the two sites where the trials were installed

Variable	MG	PFC
Predominant soil type ^a	Podzols	Leptosols
Lithology	Sandstone	Schist
Soil depth (cm) ^b	–	40
Parent material	Sedimentary	Metamorphic
Altitude	79 to 173 m	235 to 583 m
Slope	0 to 5%	15 to 30%
Annual precipitation ^c	642 mm	689 mm
Annual minimum temperature ^c	9.5 °C	11.1 °C
Mean annual temperature ^c	16.0 °C	16.2 °C
Annual maximum temperature ^c	22.5 °C	21.2 °C
Years of debarking	1995; 2005	2003; 2012

MG high productivity class site, PFC low productivity class site

^a FAO soil group according to the IUSS Working Group WRB (2006) classification

^b Not available for MG site

^c Average values for the 30-year period of 1961 to 1990, computed for the closest national meteorological station from the network of the Portuguese Meteorological Service

On both sites and during each measurement, the following tree measurements were carried out: diameter at breast height before (d_i where $i = 1, 2$ for representing the first and second cork debarking operations, respectively) and after debarking (du_i where $i = 1, 2$ for representing the first and second cork debarking operations respectively) and total height (h_i where $i = 1, 2$ for representing total height at the time of the first and second cork debarking operations). Virgin cork thickness (ctv) was computed as $(d_1 - du_1)/2$. In the year of the first debarking stem height (hs), vertical debarking height (hdv), debarked length in the branches (lb) and perimeter at the middle section of the debarked branches (pb) were also measured. The two last measurements were only carried out when the debarking height was higher than the stem height. These measurements allowed the computation of two additional variables that characterize debarking intensity: total debarking height (hdtot) and total debarked surface (sd). hdtot is defined as the sum of the debarking length on the stem and on the branches. Total debarked surface is computed as the sum of the surface area of cylinders associated to the stem (characterized by hs and du_1) and the branches (characterized by lb and pb).

The debarking height to apply to each tree included in the trial was computed from a debarking coefficient (dcoef) randomly selected: 1.5 (below maximum legal limit), 2.0 (maximum legal limit) and 2.5 (above maximum legal limit). Table 2 presents summary values for the hdv, hdtot, sd and du_1 variables on each site at the year of the trial installation (1995 at the MG site and 2003 at the PFC site). During the second debarking operation, a cork sample was collected in every tree at breast height. This sample was used for cork quality and cork thickness assessment. Cork thickness was measured before and after boiling. Cork boiling is an industrial standard post-harvest operation made for all raw cork-boards, but not carried out on virgin or secondary cork (Pereira 2007). For this reason, cork thickness previous to the boiling operation (ct) was used as a response variable.

The analysis of the effect of the debarking intensity was carried out at two levels: individual tree and stand level. Distinct statistical approaches were considered for each level.

The analysis at the individual tree level consisted of the following:

- Graphical and correlation analysis of the relationship between the response variable secondary cork thickness (ct) and the following independent variables: diameter before and after debarking (d_1 , du_1 , du_2), virgin cork thickness (ctv), vertical debarking height (hdv), total debarking height (hdtot), debarked surface (sd) and debarking coefficient (dcoef). Graphical analysis was made by means of scatter and box plots observation. Correlation analysis was carried out by the computation of the Pearson r and Spearman ρ correlation coefficients, for assessing linear and monotonic relationships respectively (McDonald

Table 2 Summary statistics of tree variables at the establishment of the trials

Variable		MG (<i>n</i> = 90)			PFC (<i>n</i> = 144)		
		1.5	2.0	2.5	1.5	2.0	2.5
hdv (cm)	min	102	136	170	80	125	165
	avg	110	148	179	130	157	195
	max	131	180	193	169	215	256
hdtot (cm)	min	102	136	170	80	125	165
	avg	110	150	182	130	158	197
	max	131	200	215	169	224	287
sd (m ²)	min	0.452	0.637	0.865	0.500	0.638	0.823
	avg	0.594	0.827	0.978	0.923	0.985	1.175
	max	0.943	1.186	1.153	1.562	1.786	1.863
du (cm)	min	16.9	16.6	18.1	15.0	15.3	15.6
	avg	21.1	21.1	21.6	22.2	19.6	19.1
	max	27.7	29.2	24.8	31.2	27.7	28.6

MG high productivity class site, PFC low productivity class site, *hdv* vertical debarking height, *hdtot* total debarking height (stem + branches), *sd* total debarked surface (including branches), *du*- diameter at breast height (cm), 1.5, 2.0 and 2.5 debarking coefficient values

2014). This analysis was carried out with the PROC CORR procedure of the SAS 9.4 software.

- Linear modelling of the secondary cork thickness (*ct*) value as a function of tree variables (*d*₁, *du*₁, *du*₂, *ctv*) and variables related to debarking height and intensity (*hdv*, *hdtot*, *sd* and *dcoef*). Due to the categorical feature of the debarking coefficient variable (*dcoef*), dummy variables associated to each category were created as suggested by Myers (1990): *dcoef1.5* (assumes a value of 1 for trees debarked for a 1.5 *dcoef* and 0 for other trees) and *dcoef2.5* (assumes a value of 1 for trees debarked for a 2.5 *dcoef* and 0 for other trees). Trees debarked for a 2.0 *dcoef* present values of *dcoef1.5* and *dcoef2.5* equal to zero. While for the MG site a fixed effect model was suitable due to the non-existence of any grouping structure of the tree data, for the PFC site, a mixed model approach was considered due to the nested structure of the data that presents trees inside plots (Pinheiro and Bates 2000). The modelling procedure was carried out with the PROC MODEL and PROC MIXED procedures of the SAS 9.4 software.

The general expressions of the fitted models are as follows:

$$ct_i = \alpha_0 + \alpha_1 X_i + \alpha_2 Y_i + e_i,$$

for MG site, where α_0 , α_1 and α_2 are fixed parameters, *ct_i* is cork thickness of tree *i*, *X_i* is one of the tree variables, *Y_i* is a tree level variable related to debarking height or intensity and *e_i* is the model error associated to tree *i*.

$$ct_{i,j} = \alpha_0 + \alpha_1 X_{i,j} + \alpha_2 Y_{i,j} + u_j + e_{i,j},$$

for the PFC site, where α_0 , α_1 and α_2 are fixed parameters, *ct_i* is cork thickness of tree *i*, *X_i* is one of the tree size variables, *Y_i* is a tree level variable related to debarking height or intensity, *u_j* is the *j* plot random effect, and *e_i* is the model error associated to tree *i* in *j* plot.

All variables were tested separately for significance ($\alpha = 0.05$) and biological meaning of the associated parameter. Models including more than one single variable were then tested considering the inclusion of the variables selected in the previous step. The final models were characterized and discussed in terms of mean square error (the smaller the better) and adjusted *r*² (the larger the better) for the case of linear fixed effect models and AIC (the smaller the better) for the case of linear mixed models. If the plot random effect (*u_j*) was not significant in the final model defined for the PFC site, it was removed and the model was refitted as a linear fixed effect model.

The analysis at the stand level consisted of the following:

- Comparison of the median cork thickness value by the median test (McDonald 2014)
- Comparison of the cork thickness empirical distributions values by the Kruskal-Wallis test (McDonald 2014), for each site and for each debarking coefficient value (1.5, 2.0 and 2.5). When the Kruskal-Wallis test rejected the null hypothesis of equal empirical distributions, these were again compared using the Kolmogorov-Smirnov tests for a two-sample comparison, therefore resulting in three tests: *dcoef1.5* versus *dcoef2.0*, *dcoef1.5* versus *dcoef2.5* and *dcoef2.0* versus *dcoef2.5*. This analysis was carried out with the PROC NPAR1WAY procedure of the SAS 9.4 software, by the inclusion of the EDF, median and Wilcoxon options.

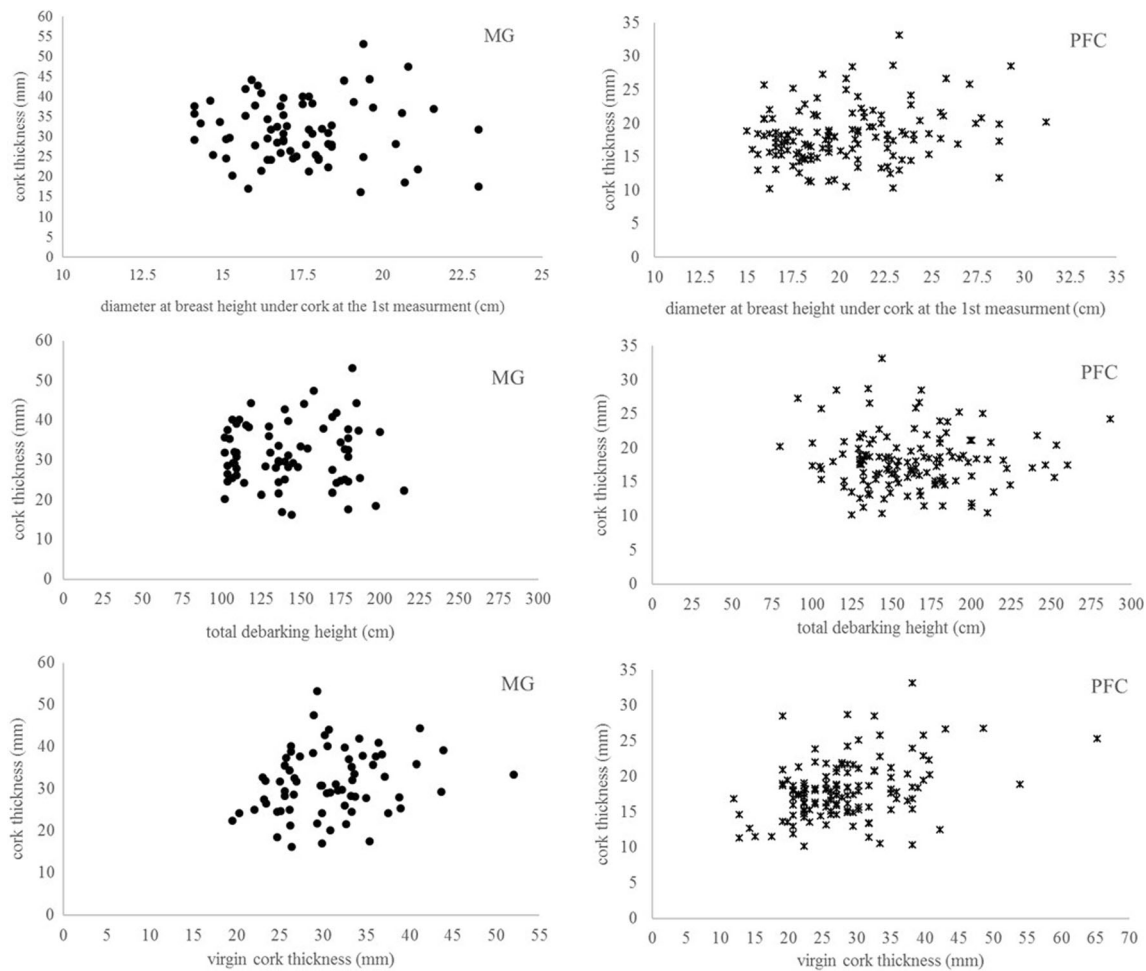


Fig. 1 Plot of cork thickness (mm) as a function of tree diameter at breast height (cm) after debarking (under cork), total debarking height (cm) and virgin cork thickness (cm). MG (left plots): high productivity class site. PFC (right plots): low productivity class site

3 Results

The graphical analysis did not evidence a relationship between secondary cork thickness (ct) and the independent variables (Fig. 1). The computation of the Pearson's and Spearman's correlation coefficients (Table 3) confirmed these results for all the variables related to debarking intensity (hdv, hdtot and sd). However, correlation coefficients showed a significant and positive relationship (both linear and monotonic relationships were significant for a 5% significance value) between secondary cork thickness (ct), tree diameter (d_1 , du_1) and virgin cork thickness (ctv), for the PFC site. A monotonic positive correlation was observed for the MG site (high productivity class) when relating secondary cork thickness (ct) with virgin cork thickness (ctv) variables.

Figure 2 shows the box plots of secondary cork thickness (ct) values grouped by site and by dcoef value. For the MG site, no difference was observed between the cork thickness (ct) among different debarking coefficient (dcoef) categories. For the PFC site, a decrease of the average and median values

of secondary cork thickness (ct) was observed with the increase of debarking coefficient (dcoef).

Fitting of the linear models confirmed the results obtained by the graphical and correlation analysis for both sites. For the MG site, no variable included in the model was significant ($\alpha = 0.05$), either related to the tree size or debarking intensity. This confirmed the difficulty of predicting cork thickness when no previous tree level cork measurement is available (Paulo et al. 2016; Sánchez-González et al. 2007). The variable virgin cork thickness (ctv) was included in the model if a 10% significance level ($\alpha = 0.10$) was considered. The estimates of the model parameters and fitting statistics are presented in Table 4, showing a positive parameter estimate associated with the ctv variable (α_1) and a p value of 0.0666.

For the models developed for the PFC site, variables d_1 , du_1 , du_2 and ctv were significant ($\alpha = 0.05$) and associated with positive values. Variables hdv, hdtot and sd were not significant in the model (not shown). Dummy variables dcoef1.5 and dcoef2.5 confirmed the differences in ct average values already suggested by the box plots of Fig. 2. The

Table 3 Pearson (r) and Spearman (ρ) correlation coefficients between secondary cork thickness (ct) and explanatory variables (d_1 , du_1 , du_2 , ctv , hdv , $hdtot$ and sd)

Site	Correlation coefficient	d_1	du_1	du_2	ctv	hdv	$hdtot$	sd
MG	r	0.0374 (0.7606)	-0.0414 (0.7357)	0.0044 (0.9715)	0.2255 (0.0666)	0.0249 (0.8392)	0.0205 (0.8676)	-0.0185 (0.8804)
	ρ	0.1235 (0.3119)	-0.0642 (0.6005)	-0.0746 0.5422	0.2502 (0.0412*)	0.0205 (0.8670)	0.0281 (0.8185)	-0.0115 (0.9252)
PFC	r	0.2951 (0.0006*)	0.2092 (0.0161*)	0.22895 (0.0083*)	0.2959 (0.0006*)	-0.0841 (0.3377)	-0.0385 (0.6615)	0.0799 (0.3628)
	ρ	0.2759 (0.0014*)	0.18001 (0.0389*)	0.2101 (0.0156*)	0.2925 (0.0007*)	-0.0439 (0.6174)	-0.0267 (0.7617)	0.0793 (0.3659)

Inside breaks the p value of the correlation coefficients determined under the null hypothesis of $H_0: r = 0$ and $H_0: \rho = 0$
 MG high productivity class site, PFC low productivity class site, d_1 and d_2 diameter at breast height before debarking measured at the first and second stand measurements (cm), du_2 diameter at breast height after debarking measured at the second stand measurement (cm), ctv virgin cork thickness (mm) computed as $(d_1 - du_1)/2$, hdv vertical debarking height (cm), $hdtot$ total debarking height (cm), sd total debarked surface (m²)

*Correlation coefficient is significant ($\alpha = 0.05$)

variance estimates associated with the plot random effect (u_j) in the mixed model were not significant, allowing the rejection of the hypothesis that different plot conditions had significant effect on the secondary cork thickness (ct). For the following modelling process, the fixed effect model approach was considered for the PFC site. The models presenting the lower mean square error and higher adjusted r^2 values were the ones including variables d_1 or ctv (Table 4). When combining d_1 or ctv variables with the dummy variables $dcoef1.5$ and $dcoef2.5$, two final models were obtained (Table 4). These models did not include the $dcoef2.5$ dummy variable, indicating that no significant differences exist between trees debarked with $dcoef$ of 2.0 and 2.5. Parameter estimates indicated that larger trees or trees with higher virgin cork thickness were associated with larger ct values and that the application of a $dcoef$ equal to 1.5 would result in a 2.125-mm increase of the ct value.

At the stand level, the differences were tested by the median and Kruskal-Wallis non-parametric tests, performed separately for each site (Table 5).

While no significant differences were present at the MG site, the rejection of the null hypothesis for the PFC site confirmed significant differences for the median values of ct between the three cork thickness distributions associated with different $dcoef$ s. This led to the computation of the Kolmogorov-Smirnov tests for a two-sample comparison (Table 6).

For the PFC site, the cork thickness empirical distribution from trees debarked with a lower debarking coefficient ($dcoef = 1.5$) was significantly different from the ones debarked with a debarking coefficient of 2.0 or 2.5. The average value of cork thickness decreased from 19.9 mm (median 19.0 mm) to 16.9 mm (median 17.1) going from $dcoef$ of 1.5 to 2.5. Instead, no significant differences were found between the empirical distributions resulting from trees debarked with debarking coefficient of 2.0 and 2.5 (Table 6).

4 Discussion

The relationship between mature cork thickness and tree diameter after debarking has been researched by Pizzurro et al. (2010) and Sánchez-González et al. (2007) considering cork thickness before boiling and by Paulo et al. (2016) considering cork thickness after boiling. Despite this difference of the cork response variable, results suggest a positive (Paulo et al. 2016 and Sánchez-González et al. 2007) or null relationship (Pizzurro et al. 2010) between the two variables. Our results agree in suggesting a small and positive relationship between these variables, but only at the site located in an inland region, characterized by Leptosols and drier climate. Since none of the available and published data sets addressed the relationship of cork thickness and tree diameter for

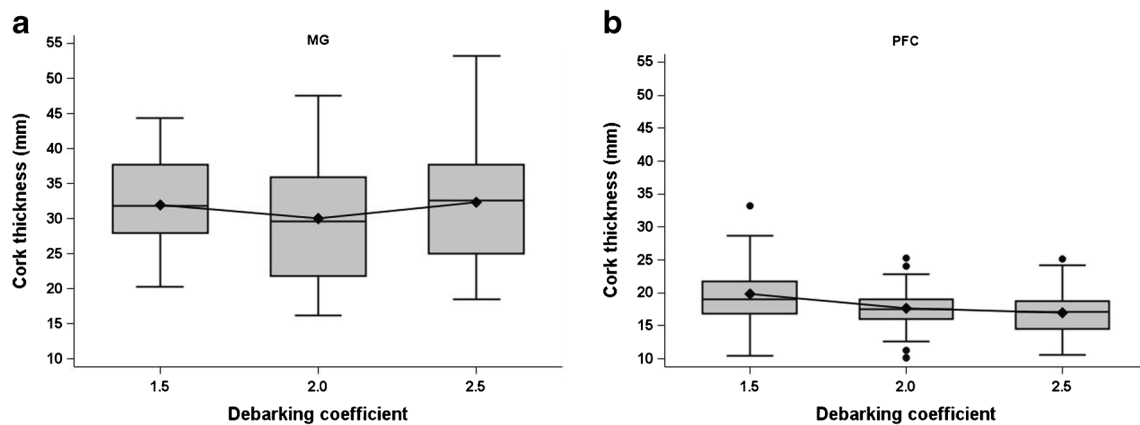


Fig. 2 Box plots for the values of secondary cork thickness, grouped by debarking coefficient value (1.5, 2.0 and 2.5). MG (left): high productivity class site. PFC (right): low productivity class site. Lines connect average values of secondary cork thickness

different site conditions (Paulo et al. 2015), open questions remain to be addressed regarding the different patterns of relationship of between these variables.

An additional and relevant characteristic of the data sets, used by Paulo et al. (2016), Pizzurro et al. (2010) and Sánchez-González et al. (2007), is the lack of information about the management of the sampled trees or stands (number of previous debarkings, previous debarking intensities, etc.), since this could help to understand the differences in the results when researching the relationship between cork thickness and debarking intensity. Pizzurro et al. (2010) reported a negative effect of the debarking intensity (assessed by total debarking height, debarking coefficient and debarking surface) while Paulo et al. (2016) concluded on a null relationship (assessed by vertical and total debarking heights and debarking coefficient). Our results suggest that the effect of distinct debarking intensity may be different according to the soil and climate conditions of the site, with limiting sites being associated with a significant and negative effect of increasing debarking intensities on secondary cork thickness.

Considering the impact of debarking coefficients in the revenue resulting from the debarking operation, one may

observe that, for average values, the differences encountered in the two sites varied from 0 to 2 mm. The largest differences were encountered in the PFC site, with Podzols and dry climate conditions, between the trees debarked with a debarking coefficient of 1.5 and others debarked with 2.0 or 2.5 coefficients. Looking at current cork price structures, it may be expected that these differences, although significant from a statistical point of view, will not have a large impact in the price of the resulting cork (Paulo and Tomé 2017).

Present results are restricted to the impact of the debarking intensity from the first cork extraction on secondary cork thickness, and no extrapolation should be made for cork extracted in following debarking operations and/or in adult trees. Research on the effect of long-term under- or over-exploitation of cork requires the maintenance of the trials presented in this manuscript, the replication of the trials, and the inclusion of additional independent variables in the analysis, such as microsite soil chemical and physical properties (Corona et al. 2005). Meanwhile, the present results are key for the management of new cork oak plantations in Portugal and for other species able to be considered for bark extraction (Leite and Pereira 2017) such as the *Quercus variabilis*, a

Table 4 Parameter estimates in the models for cork thickness estimation

Site	model	α_0		α_1		α_2		MSE	Adj- r^2
		Estimate	Pr > t	Estimate	Pr > t	Estimate	Pr > t		
MG	$ct_i = \alpha_0 + \alpha_1 \text{ctv}_i$	22.425	< 0.0001	0.287	0.0666			57.185	0.036
PFC	$ct_i = \alpha_0 + \alpha_1 d_{1,i}$	10.404	< 0.0001	0.298	0.0006			15.755	0.080
	$ct_i = \alpha_0 + \alpha_1 \text{ctv}_i$	13.964	< 0.0001	0.149	0.0006			15.746	0.081
	$ct_i = \alpha_0 + \alpha_1 d_{1,i} + \alpha_2 \text{dcoef}(1.5)_i$	11.964	< 0.0001	0.215	0.0193	1.828	0.0222	15.243	0.110
	$ct_i = \alpha_0 + \alpha_1 \text{ctv}_i + \alpha_2 \text{dcoef}(1.5)_i$	13.968	< 0.0001	0.124	0.0037	2.125	0.0044	14.895	0.130

MG high productivity class site, PFC low productivity class site, ct_i cork thickness of tree i , ctv_i virgin cork thickness of tree i , $d_{1,i}$ diameter at breast height before cork debarking of tree i , $\text{dcoef}(1.5)_i$ dummy variable associated to the dcoef (1 for trees debarked with a 1.5 dcoef and 0 for other trees), α_i model parameters, MSE mean square error, Adj- r^2 adjusted r^2

Table 5 Chi-square statistics of the median and Kruskal-Wallis tests, performed for the comparison of median value and empirical distribution comparison of *ct* from the three debarking coefficient: 1.5, 2.0 and 2.5

Trial	Test	
	Median	Kruskal-Wallis
MG	0.2507 (0.8822)	0.2142 (0.8985)
PFC	6.4534 (0.0397*)	8.7571 (0.0125*)

Inside breaks the *p* value associated to the test statistic

MG high productivity class site, PFC low productivity class site, *ct* cork thickness

*The rejection of the test null hypothesis ($\alpha = 0.05$)

species relatively abundant across temperate and subtropical areas in East Asia and presently under increase interest (e.g. Du et al. 2015; Zhou et al. 2010). Portuguese plantations began to be established at the end of the 1980s with the support of the common agricultural policy measures, and now they represent an important area in the country and a potential plus for national cork production (Coelho et al. 2012) and carbon sequestration (Palma et al. 2014). Average trees from these plantations have now achieved, or are close to achieving, the minimum perimeter value of 70 cm defined in national legislation that allows the first debarking to be carried out. National legislation also defines the maximum value of 2.0 for the debarking coefficient to apply during this operation. The established values, suggested by Natividade (1950) based on expert judgement and with a clear objective of protecting trees from overexploitation, should be considered as maximum values for good to average growth conditions that are associated with high and average Portuguese productivity classes proposed by Paulo et al. (2015). Meanwhile, in sites characterized by lower productivity classes, values under 2.0 are also considered, as they may contribute to an increase in the average cork thickness produced by the tree in the growth period immediately following.

Table 6 Chi-square statistics of two samples Kolmogorov-Smirnov test for the PFC site (average low productivity)

dcoef	ct
$H_0: f_{1.5}(ct) = f_{2.0}(ct)$	1.4350 (0.0325*)
$H_0: f_{1.5}(ct) = f_{2.5}(ct)$	1.5850 (0.0132*)
$H_0: f_{2.0}(ct) = f_{2.5}(ct)$	1.0283 (0.2409)

Inside breaks the *p* value associated to the test statistic

1.5, 2.0 and 2.5 debarking coefficients (dcoef), *ct* cork thickness

*The rejection of the test null hypothesis ($\alpha = 0.05$)

5 Conclusions

Our results suggest that the impact of the increasing debarking intensity from the first debarking on cork thickness is small albeit different between sites. The debarking coefficient was significantly related to secondary cork thickness in the site characterized by Podzols, drier conditions and associated to average to a low productivity class but was not significant in the site characterized by Podzols and associated to a high productivity class. It is suggested that during the first debarking operation, the debarking coefficient values should be defined considering tree and site characteristics. The follow-up monitoring and sampling of the trials are needed in order to clarify the long-term tree response to increasing debarking intensities in consecutive cork debarking operations.

Acknowledgements The authors acknowledge Cristina Gonçalves, Sónia Pacheco Faiais, Susana Barreiro, Sofia Leal and Sofia Knapic for their collaboration during measurements and sample collection.

Funding information Present research was supported by projects: SUBERWOOD (EU LRT-200-00701), REINFORCE (INTERREG IVB), StarTree (EU Grant agreement 311919) and AgForward (EU Grant agreement 613520), under the Seventh Framework Program for Research and Technological Development and by the ReinForce project (INTERREG IVB operational programme). The first author developed this work under contract SFRH/BPD/96475/2013 established with Fundação para a Ciência e Tecnologia (Portugal). Centro de Estudos Florestais is a research unit supported by Fundação para a Ciência e Tecnologia (Portugal) under contract UID/AGR/00239/2013.

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