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RESEARCH ARTICLE

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Understory effect on tree and cork growth in cork oak woodlands

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Abstract

Aim of study: Cork oak is one of the main forest tree species in Portugal that typically occurs in *montado*, where operational practices oriented to the tree, crop or animal management may influence several of the ecosystem components. This study aimed at contributing to fulfil the a lack of knowledge on the effect of these practices on the cork and wood growth, by comparing the wood diameter growth and the annual cork increment under two different understory management options.

Material and methods: An experimental trial implemented on an uneven-aged cork oak pure stand during a cork rotation period of 9 years, was established with the specific goal of comparing understory management options: a yellow lupine pasture *versus* spontaneous vegetation. Cork samples were taken at the beginning and end of the period and were used to measure cork thickness and annual cork rings. The differences between treatments were assessed performing a non-parametric test and a more robust approach using linear mixed model. Precipitation and treatment levels were jointly considered on the analysis.

Main results: A slight effect was found on the cork thickness regarding the treatment with lupine application. However, no distinct effect was found, regarding wood and the annual cork increment pattern. Additionally, annual cork ring width showed a positive correlation with precipitation and a negative correlation with ring age.

Research highlights: The results of this study indicate no distinct pattern regarding the annual cork and wood increment when comparing the understory effect of yellow lupine pasture *versus* spontaneous vegetation.

Additional keywords: *Quercus suber*, cork thickness; cork ring; lupine; shrubs; linear mixed model.

Abbreviations used: AIC (Akaike information criterion); Cc (crown cover percentage); du (diameter at breast height under cork); dug (quadratic diameter at breast height under cork); idu (wood diameter increment); KW (Krushal-Wallis); M (percentage of dead trees); MSE (mean square error); N (number of trees per hectare); NUR (no understory removal); OM (organic matter); RUL (understory removal with lupine seeding); *rw* (annual cork ring width).

Authors' contributions: Conception, design and implementation of the trial: MT and JAP. Data collection and analysis: SPF and JAP. Drafting of the paper: SPF and JAP. Revision of the intellectual content: MT and JHNP. All authors read and approved the final manuscript.

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Introduction

Cork oak (*Quercus suber*) is a Mediterranean species covering a worldwide area of 2,139,942 ha (APCOR, 2016), from which the tree bark (cork) is extracted and used as raw material of an industry that is responsible for a total value of exportations of 1,430 million € (APCOR, 2016). In Portugal, a country responsible for supplying 49.6% of the world cork production (APCOR, 2016), this tree plays a key role mostly in the southern rural areas. It is the main forest species present in the traditional silvopastoral system called *montado*, which is characterized by tree densities around 66 trees/ha, according to the last published official data (AFN, 2010).

In *montado*, management practices are oriented not only for cork extraction purposes, but also for grazing or crop production, which may have influence on several ecosystem components (*e.g.* Pinto-Correia *et al.*, 2011; Paulo *et al.*, 2016a). Under a silvopastoral management, it is a common practice to periodically install a legume rich pasture in the understory, such as *Lupinus luteus*, with the expectation of improving soil fertility and decrease the need of external input for animal forrage (*e.g.* Callaway, 1995; Teixeira *et al.*, 2011). When animals are not present, the spontaneous vegetation is periodically mechanically removed, reducing the fuel component to avoid fire hazard. These mechanization processes, have been refered to have a negative impact on soil compactation and affect the tree roots development contributing to the tree decline (*e.g.* Dinis *et al.*, 2015).

It is expected that interspecific competition between the trees and the understory influences tree growth patterns, along with intraspecific competition and stand structure, depending on the species, environment and management conditions. In Mediterranean cork oak stands, Sánchez-González *et al.* (2006) found out that tree diameter growth is negatively influenced by increasing stand density, however Paulo *et al.* (2016b) did not find the same pattern. Regarding the competition between trees and the understory species in the neighbourhood, diverse relationships should be considered. The presence of understory may be positive for some soil functions as it contributes to the nutrient content (Moreno & Obrador, 2007), and may influence tree natural regeneration (Pulido & Díaz, 2005). The *Cistus* species is a common spontaneous species in the cork oak woodland understory, that is reported to promote different soil C/N ratios (Gómez-Rey *et al.*, 2013). According to Correia *et al.* (2014), the *Cistus salviifolius* species success relates to a high shadow tolerance and a fast water uptake in short precipitation events. Caldeira *et al.* (2015) experimental results with *Cistus ladanifer* indicate that this species is more tolerant to low soil water potential and dry soil conditions than cork oak trees.

Several studies focus on the prediction of cork growth evolution (*e.g.* Sánchez-González *et al.*, 2007; Almeida *et al.*, 2010; Paulo *et al.*, 2016b); however, few studies are available when focusing the effect of competition between trees and understory species. This is even more evident when considering the cork oak species, where both the effect on tree wood growth and on cork growth are of interest. Caritat *et al.* (1999) indicated that there is no significant effect of shrubs presence on cork tree radial growth, although apical elongation was higher in the absence of shrubs. Similar results were found by Martín *et al.* (2015) for the holm oak species, since no significant effects were found on tree growth when comparing understory and soil management practices. Thus, no results were found when considering cork and wood differentiation growth.

To increase our understanding on the effects of the understory on the cork and tree growth, this study focuses not only in wood diameter growth, but also in the cork annual growth. The research addresses the following question: do trees have a similar increment pattern regarding wood and cork, when growing under two different understory management options?

Material and methods

Trial description

The experimental trial was located in Portugal Center, near the Montargil village (39°3.242'N, 8°10.588'W) and implemented in 2003, in an uneven-aged mature cork oak stand. The stand was characterized by an average of 101 trees/ha, where the major percentage of trees have already been debarked. There were two different cork rotation cycles within the stand: from 2003 to 2012 and from 2006 to 2015, the years in which cork stripping was performed. The understory layer, composed by spontaneous vegetation dominated by the *Cistus salvifolius,* alongside with sparsely distributed *Rosmarinus officinalis* and *Ulex airensis*, was characterized by a phytomass of 0.35 kg/m^3 at the age of 4 years. From 1994 to 2003 the understory was mechanically removed with an interval of 3 to 4 years. Accessing the digital cartography available at the Portuguese Agency for the Environment website (http://sniamb.apambiente.pt/webatlas/) soils were classified as Podzols, according to the IUSS Working Group WRB (2006). Plot determination of pH and organic matter percentage (OM) was done in 2009 (Table 1).

The trial focused on the comparison of two different understory management options, from now on designated as treatments, implemented as a complete randomized block design. Each block consisted of two quadrangular plots with 2 ha, allowing the delimitation of a 20 m border to ensure no impact of non-treated areas on the trees used for the experiment. The first treatment consisted in the maintenance of spontaneous understory vegetation during the complete cork debarking rotation period (NUR, no understory removal). The second treatment consisted on the periodical removal of the understory with incorporation of organic matter into the soil, followed by the seeding of *Lupinus luteus* (RUL, understory removal with lupine seeding). This treatment was repeated along the cork debarking rotation period in 2003, 2007 and 2009. After each application, visual assessment on the success of the lupine germination rate was made in the field.

Tree measurements

Measurements of tree diameter at breast height after debarking (*du*) were carried out at each debarking year, in 2003 and 2012, for all the trees inside the plots after being debarked. The wood diameter increment (*idu*) was computed as the difference between the diameter at breast height under cork (*du*) from the debarked trees measured in 2012 and 2003 (n_{block1}= 302; n_{block2}= 229). The stand characteristics were computed at the beginning and at the end of the period, namely: number of trees per hectare (N); the quadratic diameter at breast height under cork (dug) and crown cover percentage (Cc) (Table 1).

Cork samples collected

In 2003 and 2012, cork samples with approximately 20 cm × 20 cm, were taken at breast height from the debarked trees. Samples from 2003 cover the cork growth period between 1994 and 2003, when the understory was mechanically removed with an interval of 3 to 4 years. Samples from 2012 cover the cork growth period between 2003 and 2012, when the understory management was differentiated by the treatments implementation. All samples were boiled during 1 hour in water at 100ºC and atmospheric pressure, and left to air-dry in well ventilated conditions until equilibrium. The aim is to decrease internal tensions, caused by the cellular corrugation during cork growth, that are particularly important in the radial direction where cork thickness is measured (Pereira, 2007). Cork thickness before and after boiling was measured on each cork sample using a digital caliper (n_{block1}= 94; n_{block2}= 57). Annual cork growth rings, a total of 8 complete rings, were measured, after been visually identified on at least two positions, using the image analysis software *ImageJ* (Ferreira & Rasband, 2010; Schneider *et al.*, 2012). This procedure was carried out only in the trees having the cork samples in both debarking years where the rings were unmistakable marked (n_{Block1}= 75; n_{Block2}=51).

Climate data

According to the known relationship between annual cork growth and precipitation (*e.g.* Caritat *et al.*, 2000; Paulo *et al.*, 2016b), values of monthly precipitation for the 1994 to 2012 period were gathered from the nearest meteorological station in Montargil, available at the network SNIRH - Sistema Nacional de Informação de Recursos Hídricos (www.snirh.pt).

Data analysis

As a first step, the cork thickness, the annual cork ring width and the wood diameter increment measurements were used for a preliminary graphical analysis. The empirical distributions of the cork thickness and of the annual cork ring width were compared among treatments and separately for each block. The hypotheses to test were: 1) the distributions were not significantly different in 2003; 2) the distributions became significantly different in 2012, after the treatments application. The hypotheses were tested using the non-parametric statistical test of Kruskal-Wallis (McDonald, 2014), separately for the cork samples of 2003 (previous to the trial establishment) and for the cork samples of 2012 (subject to the trial treatments: RUL and NUR). The annual cork ring width was tested for each ring year. These analyses were evaluated (α = 0.05), with the PROC NPAR1WAY procedure of the SAS 9.3 (SAS Inst., 2011).

Modelling approach

Although the trial was established following a complete randomized block design, due to the nested structure of the data, trees inside plots and plots inside blocks, the data analysis was carried out using a mixed modelling approach. This parametric approach is particularly suitable for data referring to growth curves since it considers not only the nested structure of the data, but also the correlation from the repeated measures taken on the same individuals (*e.g.* Pinheiro

Table 1. Plot characterization by block, inventory year and treatment, where RUL is the treatment with understory removal and lupine pasture and NUR is the treatment with spontaneous understory vegetation maintenance.

Block	Treatment	Year	dug	N	Cc (%)	M (%)	pH	OM (%)
1	RUL	2003	27.5	132	55	1	5.5	1.82
		2012	28.6	131	58			
	NUR	2003	27.9	127	53	12	6.1	1.47
		2012	28.1	114	49			
2	RUL	2003	36.1	86	53	22	5.6	1.45
		2012	37.6	71	46			
	NUR	2003	33.6	100	55	11	5.7	1.37
		2012	35.7	91	56			

dug, quadratic diameter at breast height under cork (cm); N, number of trees/ha; Cc, crown cover percentage; M, percentage of dead trees; OM, organic matter percentage.

& Bates, 2000), specifically the eight complete rings of each cork sample.

For the cork annual growth, a linear mixed model was developed using the samples from 2012. The development of this model was preceded by the selection of the precipitation variable that was best related to the variable cork annual growth. The potential variables were retrieved from the list presented by Caritat *et al.* (2000) and were computed between October 1st of the year before the growth period and September 30th of the growth period year. This process was performed by fitting the following fixed base model:

$$rw_i = \beta_0 + \beta_1 t_i + \beta_2 P_i + \varepsilon_i , \quad [1]$$

where *rw* is annual cork ring width (mm) of the tree *i*; *t* is the cork age; *P* is the volume of precipitation for a specific period; β_0, β_1, β_2 are the fixed effects parameters and ε_i is the error term.

The selected precipitation variable was the one that resulted in the lower value of the mean square error (MSE) and Akaike information criterion (AIC). The fitting of the linear mixed model was then carried out by adding to the base model (Eq. [1]), a dummy variable concerning the treatment with lupine (RUL), a variable regarding the interaction between the cork age and the treatment, and the plot's random effects.

Additionally, a linear mixed model was developed for the tree wood diameter increment that included variables of the initial tree diameter, the dummy variable concerning the treatment with lupine (RUL), and the plot's random effects. The tree wood diameter increment, was assessed between the two consecutive cork extractions, performing 9 years growth. The dataset considered for fitting included all the debarked trees measured in 2003 and 2012.

All models were fitted using the procedure PROC MIXED of the software SAS 9.3 (SAS Inst., 2011). The variance components were used for the covariance structure. The RANDOM statement was applied to specify the random effects associated to the plot levels The random effect parameter was tested in all the fixed parameters, and the selection criteria for its inclusion in the model was the lowest AIC value. For each developed model, the significance of the parameters estimates were evaluated considering $\alpha = 0.05$.

Results

Treatment effect in cork growth

There was a clear decrease in the cork thickness measured after boiling, assessing the 2003 and 2012 subset samples observed in both blocks (Fig. 1). The Krushal-Wallis (KW) results performed for the cork thickness empirical distribution for the 2003 samples presented no significant difference between treatments in both blocks (*p*=0.2246 in block 1; *p*=0.5388 in block 2). This confirms that at the beginning of the trial the plots were similar. The KW test results obtained for the cork thickness, using the 2012 samples, indicate a significant difference between NUR and RUL treatments in block 1 (*p*=0.0007, mean RUL = 27.62, mean NUR = 23.15), but no significant difference in block 2 (*p*=0.2995, mean RUL = 24.45, mean NUR = 26.37).

When visualizing the annual cork ring width of each treatment (Fig. 2), no similar pattern was found in either blocks, for each subset of cork samples, 2003 and 2012. Regarding the KW test results for the annual cork ring width using the 2003 samples, no significant difference was found between the two blocks (results not presented), confirming once more that both blocks were similar before the trial establishment. While, the KW test results for the annual cork ring mean width using the 2012 samples showed significant differences between NUR and RUL treatments on block 1 for the years: 2004, 2005 and 2009, all corresponding to the year of lupine seeding or the following year (Table 2). The only exception in block 1 was the year 2007 (Table 2), however the lupine seeding in this year was applied under unsuitable precipitation and soil humidity conditions, resulting in a low germination rate of the lupine during the following year. The KW test results or the annual cork ring width of block 2 were not the same when comparing NUR and RUL treatments, only in 2010 the annual cork ring distribution was different between the treatments (Table 2).

Regarding the annual cork ring width model, the precipitation variable included was the one selected according to the MSE and AIC lower values: the annual precipitation for the period between October 1st of the year before the growth period and September 30th of the growth period year (Table 3). For this model, the random effect was more significant when added only to the intercept parameter, since it was not possible to obtain convergence with more than one random effect. Thus, the full random effect model defined was:

$$rw_{2012\,ij} = (\beta_0 + \mu_{0j}) + \beta_1 t_i + \beta_2 P_i + \\ + \beta_3\ RUL_j + \beta_4 \left(t_i\, x\, RUL_j\right) + \varepsilon_{ij} , \quad [2]$$

where *rw* is the annual cork ring width of the tree *i*; *t* is the cork age; *P* is the volume of precipitation for a given period; *RUL* is the variable regarding the treatment with lupine; β_0, β_1, β_2, β_3 are the fixed effects parameters; μ_{0j} is the random effect associated to plot *j* and ε_{ij} is the error term.

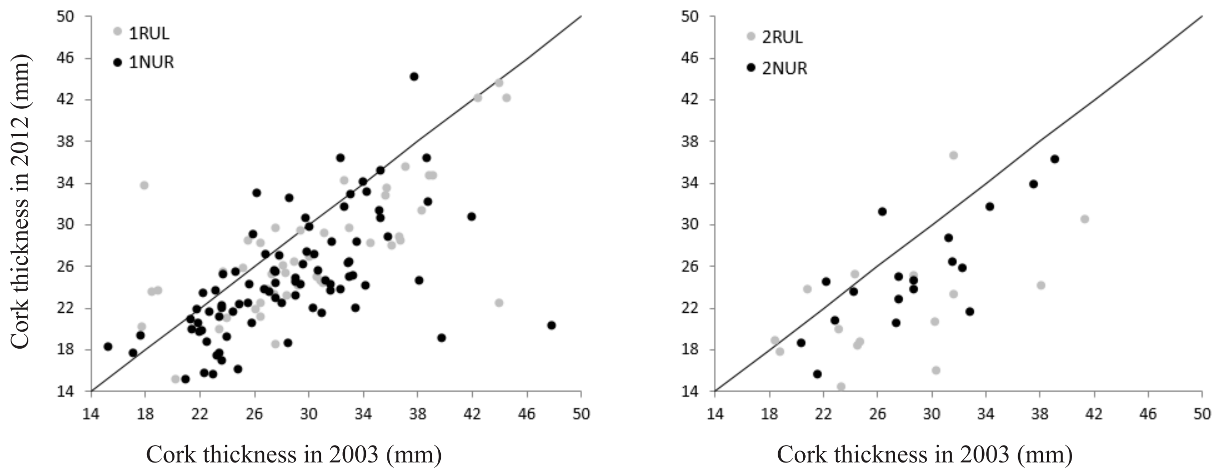

Figure 1. Relationship between the cork thickness in both debarking years, 2012 and 2003. Block 1 on the left and block 2 on the right. RUL is for the treatment with understory removal and lupine pasture; NUR is for the treatment with spontaneous understory vegetation maintenance.

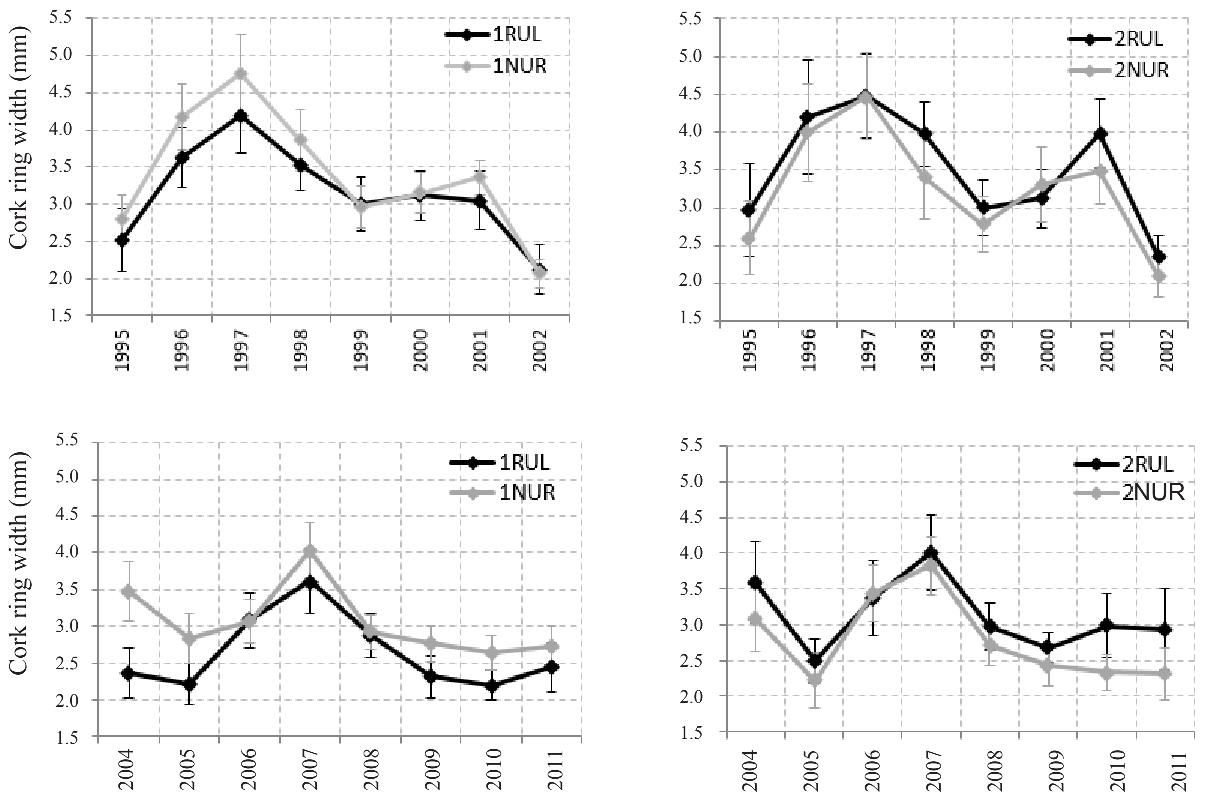

Figure 2. Annual cork ring mean width during 8 complete years of cork production for each subset of cork samples, 2003 (top) and 2012 (bottom), by treatment for each block. Block 1 on the left and block 2 on the right. RUL is for the treatment with understory removal and lupine pasture; NUR is for the treatment with spontaneous understory vegetation maintenance.

For the full fitted model (Eq. 2), the parameters estimates for *P* and *t* were statistical significant and showing a positive correlation with precipitation and a negative correlation with ring age (Table 4). The treatment with lupine (RUL) was not significant, while the interaction between the cork age and the RUL treatment was significant. However, when excluding the RUL variable, this interaction was also not statistical significant. The random effects term were not significantly different from zero for any of the plots. Thus, the final random effect model only included precipitation and cork ring age (Table 4),

Table 2. Comparison of the annual cork ring width (mm) distribution using the Kruskal-Wallis test (KW) for the 2012 sample.

Year	Lupine seeding	Rain (mm)	1st Block			2nd Block		
			RUL mean	NUR Mean	*p*-value	RUL mean	NUR mean	*p*-value
2003	Yes	614.8	2.12	1.68	–	1.83	2.19	–
2004	No	449.1	3.31	2.31	0.0006	3.04	3.24	0.7345
2005	No	251.1	2.79	2.20	0.0154	2.25	2.72	0.0705
2006	No	500.8	3.11	3.02	0.7405	3.47	3.25	0.3965
2007	Yes	844.9	4.03	3.56	0.1023	3.81	3.79	0.7919
2008	No	427.5	2.96	2.79	0.4629	2.73	2.98	0.3758
2009	Yes	396.9	2.75	2.25	0.0081	2.45	2.77	0.3707
2010	No	623.6	2.55	2.23	0.1059	2.35	2.89	0.0288
2011	No	587.3	2.73	2.37	0.0562	2.25	2.68	0.2870
2012	No	806.5	1.08	1.01	–	1.11	1.00	–

RUL= understory removal with lupine seeding. NUR= no understory removal.

which is an indication that the treatments are not different concerning their influence in annual cork ring increment.

Treatment effect in tree wood diameter increment

The wood mean diameter increment plot with diameter classes showed no similar pattern on the treatments by block (Fig. 3). For the wood mean diameter increment model, the random effect was also more significant when added to the intercept parameter. The full random effect model defined was:

$$idu_{ij} = (\beta_0 + \mu_{0j}) + \beta_1\, du_{2003\,i} + \beta_2\, RUL_j + \varepsilon_{ij}, \qquad [3]$$

where *idu* is the wood diameter increment (mm) for the debarking period of tree *i*; du_{2003} is the tree diameter under cork measured in 2003; *RUL* is the variable regarding the treatment with lupine; β_0, β_1, β_2 are the fixed parameters; μ_0 is the random effect associated to plot *j* and ε_{ij} is the error term.

For the full fitted model (Eq. [3]), the tree diameter under cork measured in 2003 was statistical significant showing a positive correlation. However, the RUL treatment was not significant, but also the intercept parameter was not significantly different from zero (Table 5). Thus, the final random effect model only included the tree diameter under cork (Table 5), indicating also that the treatments are not different concerning their influence in wood diameter increment.

Discussion

This work was the first specifically dedicated to the purpose of evaluating the influence of different understory management options on cork annual growth and tree wood growth, a research question already refered by Oliveira & Costa (2012) and Paulo *et al.* (2016b). For this purpose, the trial allowed to obtain two subsets of cork samples that were used for the analysis

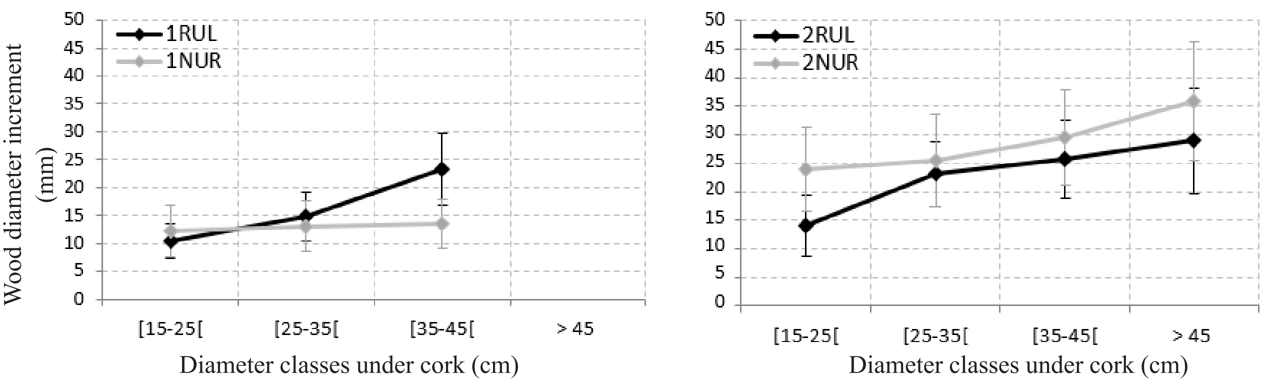

Figure 3. Wood diameter mean increment (mm), between 2003 and 2012, by diameter at breast height class (under cork) for each treatment. Block 1 on the left and block 2 on the right. RUL is for the treatment with understory removal and lupine pasture; NUR is for the treatment with spontaneous understory vegetation maintenance.

Table 3. Selection of the period of precipitation to be considered in the model, its respective mean square error (MSE) and Akaike information criterion (AIC) for the cork growth models fitted with fixed effects.

Precipitation variable (defined by the period considered)	Model	
	MSE	AIC
$March_{(t)}$ to $June_{(t)}$	1.9712	5422.8
$March_{(t)}$ to $May_{(t)}$	2.5306	5806.0
$March_{(t)}$ to $September_{(t)}$	1.8495	5326.2
$January_{(t)}$ to $June_{(t)}$	2.0706	5500.0
$January_{(t)}$ to $September_{(t)}$	2.0444	5480.5
$June_{(t)}$ to $September_{(t)}$	2.3202	5673.4
$October_{(t-1)}$ to $September_{(t)}$	1.7569	5249.6
$October_{(t-1)}$ to $June_{(t)}$	1.8590	5336.1
$October_{(t-1)}$ to $December_{(t-1)}$	2.1945	5589.8

t: year of the growth period

of cork thickness and cork ring width under two distinct understory management regimes. This is one of the study main features, since it allowed to characterize the annual cork growth rates and distributions previous to the treatments application, demonstrating that not only management was similar along the four different plots, but also that the cork annual growth presented equal distributions among the four plots.

Cork thickness decreased from the 2003 to the 2012 samples, irrespective of the treatment, which may be the result of a decrease of total precipitation within the second debarking period, and in line with the existing literature on the relationship between annual cork growth and climate conditions (*e.g.* Caritat *et al.*, 2000). The fitted model for the annual cork ring width showed a positive correlation with precipitation, as shown in several other studies (*e.g.* Paulo *et al.*, 2016b; Oliveira *et al.*, 2016). Regarding the cork ring age, a negative correlation was obtained, as expected from known studies (*e.g.* Costa *et al.*, 2002; Pereira, 2007; Oliveira *et al.*, 2016), that showed a decrease of the annual cork width trend along the cork debarking period. The inclusion of precipitation and cork age variables in the fitted baseline model for annual cork growth, allowed to isolate the treatment effect, as well as, the plot and block random effects.

No difference was found between the two understory treatments regarding their influence in annual cork width or wood diameter increment, in line with Caritat *et al.* (1999) related study, in which the results for a sample of 10 trees by treatment did not show significant differences between the treatments. Nevertheless, it was also observed that plots in both blocks did not present a similar response to the treatments. One block presented a small positive effect of the understory removal treatment, with an increase of less than 1 mm on the mean annual cork growth, when the lupine was applied or in the following year, whereas in the other block a small effect was detected only in one year. Looking at the annual response of the tree to the treatments, it was observed that although the lupine installation may favour cork increment one or two years after application, this effect could also be inexistent in years when unfavourable conditions prevailed. The increments lower than 1 mm are not expected to have an impact in the cork price and the resulting farm income (Paulo & Tomé, 2017). This varying effect suggests that site characteristics, such as soil and stand structure, may influence the impact of different management options, but that these may also be related to annual climate conditions (Sánchez-González *et al.*, 2007).

Mechanical operations such as the ones carried out for understory removal, may affect the tree roots development, contribute to the tree decline (*e.g.* David *et al.*, 2013), or limit cork oak regeneration (*e.g.* Arosa *et al.*, 2017). These operations being frequently performed may slow the full recovery of understory composition and structure as evidence in Santana *et al.* (2011). We recommend that management plans should be frequently reviewed, at the stand scale, regarding the conditions, the management goals such as the cork and cattle production, the tree regeneration, the fire hazard reduction and the biodiversity conservation, following an adaptive management strategy (*e.g.* Aronson *et al.*, 2009).

Conclusion

The data used for this study, were collected from a trial established with the specific goal to contribute for understanding the effects of the understory on the cork and tree growth. The study outcome indicates no effect, for this site, regarding cork or wood increment pattern, when comparing the understory effect of yellow lupine pasture *versus* spontaneous vegetation. The cork thickness variability between trees and the individual tree response to annual climate conditions is more determinant to the final cork thickness than the management alternatives considered in this research. Nevertheless, the differences found across the two blocks suggest that site characteristics should be explored in further research. The follow-up monitoring of this trial and the establishment of

Table 4. Parameters estimates for the annual cork ring width (*rw*) random fitted models from Eq. [2] (AIC_{Full} = 2184; AIC_{Final} = 2182).

	Full model				**Final model**			
	Estimate	***p*-value**	**Lower**	**Upper**	**Estimate**	***p*-value**	**Lower**	**Upper**
Fixed								
β_0	2.1913	0.0119	1.1518	3.2308	2.3635	0.0007	1.8358	2.8911
$\beta_{1\ tc}$	-0.1016	<0.0001	-0.1434	-0.0598	-0.1290	<0.0001	-0.1613	-0.0967
$\beta_{2\ Pr}$	0.0024	<0.0001	0.0019	0.0028	0.0024	<0.0001	0.0019	0.0028
$\beta_{3\ RUL}$	0.3915	0.2306	-0.2491	1.0321	–	–	–	–
$\beta_{4\ tc\ x\ RUL}$	-0.0625	0.0443	-0.1235	-0.0016	–	–	–	–
Random								
$\mu_{0\ 11}$	0.1229	0.5316	-0.2627	0.5086	0.1403	0.2668	-0.1076	0.3882
$\mu_{0\ 12}$	-0.1229	0.5316	-0.5086	0.2627	-0.0955	0.4402	-0.3382	0.1472
$\mu_{0\ 21}$	-0.227	0.2469	-0.6115	0.1576	-0.2424	0.0447	-0.4790	-0.0058
$\mu_{0\ 22}$	0.227	0.2469	-0.1576	0.6115	0.1975	0.1220	-0.0529	0.4479
Cov. Parm								
intercept μ_0	0.0718	–	0.01827	4.6625	0.04713	–	0.01389	1.0591
Residual	0.9566	–	0.8673	1.0604	0.9604	–	0.8708	1.0646

Table 5. Parameters estimates for the wood diameter increment (*idu*) linear mixed fitted models from Eq. [3] (AIC_{Full} = 1884; AIC_{Final} =1892).

	Full model				**Final model**			
	Estimate	***p*-value**	**Lower**	**Upper**	**Estimate**	***p*-value**	**Lower**	**Upper**
Fixed								
β_0	1.1489	0.1476	-0.9956	3.2933	–	–	–	–
$\beta_{1\ du\_2003}$	0.0207	0.0185	0.0035	0.0379	0.0287	0.007	0.01	0.0438
$\beta_{2\ RUL}$	0.0274	0.9631	-1.1358	1.1906	–	–	–	–
Random								
$\mu_{0\ 11}$	-0.3198	0.4471	-1.1456	0.5060	0.6044	0.016	0.1131	1.0957
$\mu_{0\ 12}$	0.3198	0.4471	-0.5060	1.1456	1.2090	<0.0001	0.6107	1.8074
$\mu_{0\ 21}$	-0.4662	0.2643	-1.2857	0.3534	0.4248	0.0917	-0.0691	0.9186
$\mu_{0\ 22}$	0.4662	0.2643	-0.3534	1.2857	1.3574	<0.0001	0.8178	1.8970
Cov. Parm								
intercept μ_0	0.3352	–	0.0872	18.019	1.0354	–	0.3004	25.716
Residual	1.9551	–	1.7388	2.2147	1.9580	–	1.741	2.2185

similar trials is needed in order to clarify the long-term tree response in consecutive cork debarking periods and in different environmental and structural stand characteristics.

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References

AFN, 2010. Inventário Florestal Nacional Portugal Continental IFN5, 2005-2006. Autoridade Florestal Nacional, Lisboa, 209 pp. [in Portuguese].

Almeida AM, Tome J, Tome M, 2010. Development of a system to predict the evolution of individual tree mature cork caliber over time. Forest Ecol Manage 260 (8): 1303-1314. https://doi.org/10.1016/j.foreco.2010.07.017

APCOR, 2016. O anuário de cortiça 2016. Associação Portuguesa da Cortiça, Santa Maria de Lamas, Portugal, 59 pp.

Arosa ML, Bastos R, Cabral JA, Freitas H, Costa SR, Santos M, 2017. Long-term sustainability of cork oak agro-forests in the Iberian Peninsula: A model-based approach aimed at supporting the best management options for the montado conservation. Ecol Model 343: 68-79. https://doi.org/10.1016/j.ecolmodel.2016.10.008

Aronson J, Pereira JS, Pausas JG, 2009. Cork oak woodlands on the edge. Ecology, adaptive management, and restoration, 1st edn. Soc Ecol Rest Int, Island Press, Washington D.C, pp: 129-137.

Caldeira MC, Lecomte X, David TS, Pinto JG, Bugalho MN, Werner C, 2015. Synergy of extreme drought and shrub invasion reduce ecosystem functioning and resilience in water-limited climates. Scientific Reports 5:15110. https://doi.org/10.1038/srep15110

Callaway R, 1995. Positive interactions among plants. The Botanical Review 61: 306-349. https://doi.org/10.1007/BF02912621

Caritat A, Molinas M, Vilar L, Masson P, 1999. Efecto de los tratamientos silvopastorales en el crecimiento del alcornoque. Scientia gerundesis 24: 27-35.

Caritat A, Gutierrez E, Molinas M, 2000. Influence of weather on cork-ring width. Tree Physiol 20: 893-900. https://doi.org/10.1093/treephys/20.13.893

Correia AC, Costa e Silva F, Correia AV, Hussain MZ, Rodrigues AD, David JS, Pereira JS, 2014. Carbon sink strength of a Mediterranean cork oak understorey: how do semi-deciduous and evergreen shrubs face summer drought? J Veg Sci 25 (2): 411-426. https://doi.org/10.1111/jvs.12102

Costa A, Pereira H, Oliveira A, 2002. Influence of climate on the seasonality of radial growth of cork oak during a cork production cycle. Ann For Sci 59: 429−437. https://doi.org/10.1051/forest:2002017

David TS, Pinto CA, Nadezhdina N, Kurz-Besson C, Henriques MO, Quilhó T, Cermak J, Chaves MM, Pereira JS, David JS, 2013. Root functioning, tree water use and hydraulic redistribution in Quercus suber trees: A modeling approach based on root sap flow. Forest Ecol Manage 307: 136-146. https://doi.org/10.1016/j.foreco.2013.07.012

Dinis C, Surový P, Ribeiro N, Oliveira MC, 2015. Effect of soil compaction at different depths on cork oak seedling growth. New Forests 46: 235-246. https://doi.org/10.1007/s11056-014-9458-0

Ferreira T, Rasband WS, 2010. ImageJ User Guide, IJ 1.46. http://imagej.nih.gov/ij/docs/guide/

Gómez-Rey MX, Madeira M, Gonzalez-Prieto SJ, Coutinho J, 2013. Soil C and N dynamics in a Mediterranean oak woodland with shrub encroachment. Plant Soil 371: 339-354. https://doi.org/10.1007/s11104-013-1695-z

IUSS Working Group WRB, 2006. World reference base for soil resources 2006, 2nd ed. World Soil Resources Reports No. 103, FAO, Rome, 133 pp.

Martín D, Vázquez-Piqué J, Alejano R. 2015. Effect of pruning and soil treatments on stem growth of holm oak in open woodland forests. Agrofor Syst 89: 599–609 . https://doi.org/10.1007/s10457-015-9794-x

McDonald JH, 2014. Handbook of Biological Statistics, 3rd ed. Sparky House Publishing, Baltimore, MD, USA.

Moreno G, Obrador JJ, 2007. Effects of trees and understory management on soil fertility and nutrient status of holm oaks in Spanish dehesas. Nutr Cycl Agroecosyst 78: 253-264. https://doi.org/10.1007/s10705-007-9089-3

Oliveira G, Costa A, 2012. How resilient is Quercus suber L. to cork harvesting? A review and identification of knowledge gaps. Forest Ecol Manage 270: 257-272. https://doi.org/10.1016/j.foreco.2012.01.025

Oliveira V, Lauw A, Pereira H, 2016. Sensitivity of cork growth to drought events: insights from a 24-year chronology. Climatic Change 137: 261-274. https://doi.org/10.1007/s10584-016-1680-7

Paulo JA, Crous-Duran J, Firmino PN, Faias SP; Palma JHN, 2016a. D2.4 Report describing the components, structure, ecosystem services, and economic value of selected HNCV agroforestry systems. Deliverable report 2.4 for EU FP7 Research Project AGFORWARD (613520). 29 pp. http://www.agforward.eu/index.php/pt/montado-portugal-843.html

Paulo JA, Pereira H, Tomé M, 2016b. Analysis of variables influencing tree cork caliper in two consecutive cork extractions using cork growth index modelling. Agrofor Syst 91: 221 -237. https://doi.org/10.1007/s10457-016-9922-2

Paulo JA, Tomé M, 2017. Does debarking intensity during the first cork extraction affect future cork thickness? Ann For Sci 74: 66. https://doi.org/10.1007/s13595-017-0662-x

Pereira H, 2007. Cork: Biology, Production and Uses. Elsevier Publ, Amsterdam, 336 pp.

Pinheiro JC, Bates DM, 2000. Mixed-effects models in S and S-Plus. Statistics and computing series, Springer, NY, 528 pp.

Pinto-Correia T, Ribeiro N, Sá-Sousa P, 2011. Introducing the montado, the cork and holm oak agroforestry system of Southern Portugal. Agrofor Syst 82: 99-104. https://doi.org/10.1007/s10457-011-9388-1

Pulido FJ, Díaz M, 2005. Regeneration of a Mediterranean oak: A whole-cycle approach. Ecoscience 12: 92-102. https://doi.org/10.2980/i1195-6860-12-1-92.1

Sánchez-González M, Río M, Cañellas I, Montero G, 2006. Distance independent tree diameter growth model for cork oak stands. Forest Ecol Manage 225 (1-3): 262-270. https://doi.org/10.1016/j.foreco.2006.01.002

Sánchez-González M, Calama R, Cañellas I, Montero G, 2007. Variables influencing cork thickness in Spanish cork oak forests: A modelling approach. Ann Forest Sci 64 (3): 301-312. https://doi.org/10.1051/forest:2007007

Santana J, Porto M, Reino L, Beja P, 2011. Long-term understory recovery after mechanical fuel reduction in Mediterranean cork oak forests. Forest Ecol Manage 261 (3): 447-459. https://doi.org/10.1016/j.foreco.2010.10.030

SAS INSTITUTE INC, 2011. SAS/STAT 9.4 User's Guide, SAS Institute Inc. Cary, NC, USA.

Schneider CA, Rasband WS, Eliceiri KW, 2012. NIH Image to ImageJ: 25 years of image analysis. Nature Methods 9: 671-675. https://doi.org/10.1038/nmeth.2089

Teixeira RFM, Domingos T, Costa APSV, Oliveira R, Farropas L, Calouro F, Barradas AM, Carneiro JPBG, 2011. Soil organic matter dynamics in Portuguese natural and sown rainfed grasslands. Ecol Model 222: 993-1001. https://doi.org/10.1016/j.ecolmodel.2010.11.013