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Cork extraction as a key factor determining post-fire cork oak survival in a mountain region of southern Portugal

Francisco Moreira *, Inês Duarte, Filipe Catry, Vanda Acácio

Centro de Ecologia Aplicada "Prof. Baeta Neves", Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Tapada da Ajuda, 1349-017 Lisbon, Portugal

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Abstract

Bark thickness, a key variable determining post-fire tree survival, usually increases with tree diameter. The cork oak (*Quercus suber*) is an exception to this, as it is the only European tree where the commercial exploitation of bark (cork) occurs. Human management thus becomes the most influential factor determining bark thickness. In this paper, we describe the survival rates and variables affecting cork oak survival 1.5 years after a large wildfire in southern Portugal, with a focus on the management of bark exploitation. The status of 1151 cork oaks was assessed in 40 sampling plots, and logistic regression used to explore the variables affecting survival likelihood, collected at the tree and plot levels. Survival rate was 84%. The most important factors affecting survival were those related to the management of cork extraction: stripped trees, trees with thinner bark and trees with larger diameter, correlated to the number of stripping operations, showed lower survival. Survival also decreased with increasing charring height, an indicator of fire damage. Stripped trees in unfavourable aspects (South to East) also showed lower survival. A survival model was built that can be used to identify areas vulnerable to future fires, if spatially explicit data on stand structure and cork management status are available.

Keywords: Post-fire survival; *Quercus suber*; Portugal; Tree mortality; Tree management; Stand management

1. Introduction

Post-fire tree survival is determined by factors related to both individual tree and fire characteristics. Important tree features include tree height, tree health and bark thickness (e.g. Ryan, 1990; Pausas, 1997; Miller, 2000; McHugh and Kolb, 2003). In terms of fire characteristics, intensity is a key factor (e.g. Miller, 2000; Schwilk et al., 2006), and it depends on wind, topography (in particular slope and aspect), fuel moisture and fuel load (determined by the nature and amount of understory vegetation) (e.g. Rothermel, 1983; Whelan, 1995; Schwilk et al., 2006). Other stand characteristics such as average crown base height and tree density, may determine the potential for crown fires (e.g. Van Wagner, 1977; Whelan, 1995; Cruz et al., 2006; Schwilk et al., 2006). Fire intensity will strongly influence fire damage, which can be indirectly evaluated through, e.g. bark char height or the percentage of the crown scorched or consumed (e.g. Stephens and Finney, 2002; Pausas et al., 2003; Rigolot, 2004).

Several studies carried out in coniferous species that do not have resprouting capacity have shown that percent crown volume damaged and bark thickness are key variables influencing post-fire tree survival (e.g. Ryan and Reinhardt, 1988; Dikinson and Johnson, 2001; Stephens and Finney, 2002; Rigolot, 2004). Necrosis of canopy components (foliage, buds, etc.) depends on plume temperatures created by convection heat and their impact on living tissues, and the higher the level of canopy damage the lower the carbon fixation rates and the survival probability (Dikinson and Johnson, 2001). Heat from the flames is conducted through the bark into the underlying cambium, so the thicker the bark, the less cambium damage will occur for a given flame temperature and residence time, increasing survival probability (Miller, 2000; Dikinson and Johnson, 2001).

The cork oak (*Quercus suber* L.) is an evergreen oak occurring in an area of ca. 2 million hectares around the Western Mediterranean basin, mostly the Iberian Peninsula (Portugal and Spain), holding more than 50% of the world distribution area, but also Algeria, Morocco, France, Tunisia

* Corresponding author. Tel.: +351 21 3616080; fax: +351 21 3623493.
E-mail address: fmoreira@isa.utl.pt (F. Moreira).

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and Italy (Pereira and Tomé, 2004; Silva and Catry, 2006). This species has two unique features related to post-fire crown regeneration and to bark that make it different from every other European tree. Firstly, it is able to resprout from stem (epicormic shoots), so the crown volume damage is not a key aspect influencing post-fire tree survival, as trees with 100% crown scorch may easily recover their canopy (e.g. Pausas, 1997). Thus, cambium damage seems the key variable for this species, as previous studies showed the importance of a thick bark for post-fire cork oak survival (e.g. Pausas, 1997; Amo and Chacón, 2003). Secondly, the cork oak has the unique ability, among other evergreen oaks, of having a phellogen, active across all the tree life, producing an increasingly thick layer of cork tissue in the outside. Cork is a valuable raw material for industry and during the cork oak exploitation it is periodically removed, by manually cutting with an axe along vertical and horizontal lines on the stem and thicker branches, and subsequent stripping-off of large cork planks (Pereira and Tomé, 2004). After each cork stripping, the tree has the capacity of producing a new cork bark by adding new layers of cork every year (Pereira and Tomé, 2004). After the first cork debarking (the first cork taken is called virgin cork), the minimum period between successive extractions is 9 years (Pereira and Tomé, 2004). Usually there is a legal size restriction for the first bark extraction (only trees above a given diameter at breast height can be debarked). So, because of cork extraction, the observed bark thickness is not only a function of tree size (or age) in cork oaks, in contrast with other species where bark thickness usually increases with tree age and diameter (e.g. Dikinson and Johnson, 2001).

Cork oak forests are acknowledged for their economical importance (e.g. Barberis et al., 2003; Silva and Catry, 2006). This is particularly so for Portugal, as it holds one third of the world's cork oak surface, from which more than half of the world's cork production is originated (Pereira and Tomé, 2004; Silva and Catry, 2006). Additionally, cork oak forests represent a valuable wildlife habitat, and cork oak stands are classified as protected habitats in the framework of the European Union Directive 92/43/CEE since 1993 (Silva and Catry, 2006).

The previous few studies on post-fire cork oak survival showed a reasonable discrepancy in the obtained results, although a positive relationship between cork oak survival and bark age was always present. For example, Lamey (1893) presents data on cork oak mortality as a function of bark age in Algeria, showing only 10% survival for trees with 2-year cork age when fire occurred, but Barberis et al. (2003) found a much more variable survival rate (up to 95%) for trees with the same cork age in Sardinia. Cabezudo et al. (1995) described only 46% survival in cork oak trees with 6 years of cork age, in Southern Spain, but Pausas (1997) found 99% tree survival rate in North-eastern Spain, with stem death inversely related to tree diameter and canopy height recovery also dependent on bark thickness. More recently, Catry et al. (2006) found 98% survival in adult cork oaks not stripped in the last 30 years, in central Portugal. Clearly, more research is needed to unveil the factors behind cork oak survival after fire, and including other factors besides tree size and cork age, that may influence fire intensity and tree survival.

Cork oak stands occur in a wide range of structures and densities; they can be managed as forest stands, mainly for the production of cork, or alternatively as agro-forestry systems (named ''montados'' or ''dehesas'') with lower tree density and the understory used for crops or pasture (Natividade, 1950; Pereira and Tomé, 2004). The former usually occur in more mountainous regions and are particularly fire-prone. During the summer of 2004 a large wildfire burned more than 20.000 ha in a mountain region of southern Portugal, including vast areas of cork oak stands. We carried out a study of post-fire oak survival in this region, with the objectives of: (i) evaluating cork oak survival 1.5 years after fire; (ii) exploring the tree and site factors affecting individual tree survival; (iii) building a survival model that can be used to identify areas particularly vulnerable to fire where fire prevention should be a priority.

2. Methods

2.1. Study area and plot definition

The study area is located in ''Serra do Caldeirão'', a mountain ridge in the northeastern part of the Algarve province, southern Portugal (Fig. 1). The climate is Mediterranean, with average annual temperature of 16.6 °C and average annual rainfall of 900 mm. Altitude ranges from 150 to 580 m. Soil type consists mainly of shallow schist lithosols with low

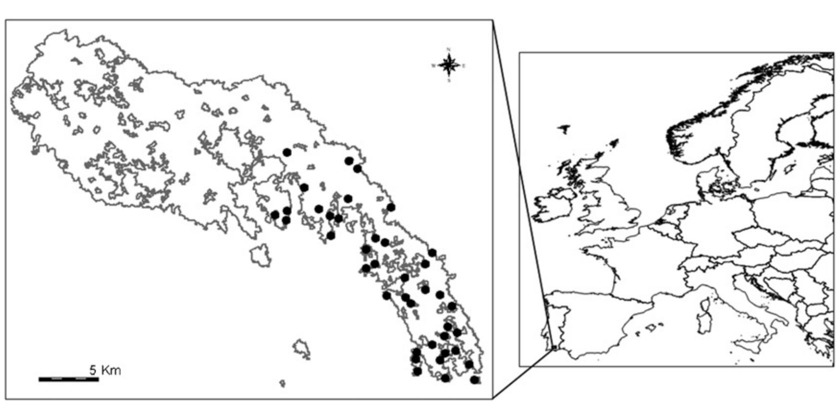

Fig. 1. Study area in the Serra do Caldeirão, showing the fire perimeter and the location of the 40 study plots.

Table 1
Descriptive statistics the variables considered in this study

Variable	Level of measurement	n	Minimum	Maximum	Mean	S.D.
Slope (%)	Transect	1151	12.3	32.4	21.2	4.25
Aspect (8 categories)	Transect	1151	–	–	–	–
Understory cover (3 categories)	Transect	992	Sparse	Dense	–	–
Estimated understory height (cm)	Transect	1052	80	350	155.2	56.21
Tree cover (proportion)	Plot	1151	0.20	0.80	0.34	0.161
Shrub cover (proportion)	Plot	1151	0.05	0.90	0.40	0.264
Tree height (m)	Tree	1151	1.8	14.7	7.1	2.17
Diameter at breast height (cm)	Tree	1151	9.0	91.0	27.1	12.18
Minimum charring height (proportion)	Tree	1151	0	1.00	0.31	0.339
Mean bark thickness (cm)	Tree	1151	0	6.65	2.53	1.21
Stripping (presence/absence)	Tree	1151	0	1	0.75	0.435

Level of measurement relates to whether the variable was measured at the plot, transect or tree level. n = sample size (number of trees); S.D. = standard deviation.

fertility and prone to erosion. The landscape is characterized by vast expanses of cork oak forests with varying tree density, ranging from areas with high tree cover to ‘‘montados’’ with scattered trees and the understory usually cleared for crops or pastures. Other land cover types include shrublands dominated by *Cistus ladanifer*, as well as a few pastures or cultivated crops. There are also scattered stands of maritime pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus* spp.). Land property is fragmented and private. Cork extraction is the main economic activity for local communities.

In the summer of 2004 (between 26 July and 4 August), a large wildfire burned 28,620 ha in this region (DGRF APIF, 2005). We used a regular 1 km × 1 km grid of points covering part of the burned area (ca. 15,000 ha; Fig. 1) and defined a 50 m-radius circle (sampling plot) around each point. Plots were checked in the field for accessibility, to confirm if they had burned, and to confirm if they were dominated by cork oak trees. Plots were discarded if these three conditions were not simultaneously met. In the end, a total of 40 plots were selected and assessed. Large within-plot variability in tree size and cork age (and, consequently, bark thickness) was common, as cork debarking was not carried out simultaneously in all individuals (uneven-aged cork).

2.2. Plot variables

For each 50-m circular plot, tree (variable *Tree cover*) and shrub (variable *Shrub cover*) cover prior to fire were visually estimated (to the nearest 5%) with aerial photographs (taken in 2002) and the help of a reference scheme (DGRF, 1999). Up to 4 strip transects were defined in each plot (see Section 2.3), and the dominant aspect (N, S, E, W, NE, NW, SE or SW) (variable *Aspect*) and slope (in percentage, measured with a hypsometer) (variable *Slope*) were registered for each one. Additionally, the understory vegetation cover prior to fire was visually estimated for each transect, and classified as sparse/nil, medium or dense, based on the amount of burned shrub remains (branches) (variable *Understory cover*). The modal vegetation height of this pre-fire situation was also estimated (to the nearest 10 cm) from the height of burned branches (variable *Estimated understory height*). In some transects not all variables were measured because post-fire management actions (such as ploughing or shrub clearing) had occurred, and so sample sizes were not the same for all variables. The values for these plot and transect variables (Table 1) were assigned to every tree in a given plot and transect.

2.3. Tree variables

Individual tree appraisal in the plots took place between December 2005 and April 2006, so roughly 1.5 years after the fire. Trees were assessed along 50-m strip transects (20-m wide) departing from the plot centre at right angles. Given the very high young-tree density in many plots, we only measured trees larger than 9 cm diameter at breast height (DBH). Trees along each transect were measured to obtain a sample of 30 trees per plot. In plots with higher tree density, one transect was enough to attain this sample size. In other plots, up to 4 transects had to be sampled. In a few plots this maximum was not achieved, thus the range was 14–30 trees per plot and the median was 30 trees. A total of 1151 individuals were measured, and five variables were measured for each (Table 1), related to: (a) tree size (tree height (m), measured with a hypsometer (variable *Tree height*), and DBH (cm), taken as the average of two perpendicular measurements (variable *Diameter at breast height*)); (b) fire damage (minimum height of charring, usually measured on the windward side of the tree, Dikinson and Johnson, 2001, expressed as proportion of tree height (variable *Minimum charring height*)); and (c) cork bark thickness (average thickness (cm) at breast height, taken from 4 measurements made with a bark gauge around the trunk (variable *Mean bark thickness*)). The latter is obviously related with time since the last stripping (cork age) in stripped trees, and we confirmed this by registering the stripping year, frequently painted on the bark for management purposes. Thus, for a sample of 259 stripped trees where the number corresponding to the stripping year was still visible in the bark, there was a significant linear relationship between bark thickness (in cm) and cork age when the fire occurred (ranging from 0, corresponding to trees stripped in the year of the fire, to 13 years) ($r = 0.78$, $P < 0.001$). Maximum height of charring is commonly used to characterize fire severity and was also estimated, but we found that in many trees this was difficult to measure due to the time passed since the fire (and the fading of charred color) and the subsequent canopy regeneration. However, there was a significant correlation between minimum and maximum charring height (both measured as a proportion of tree height) (Spearman $r = 0.55$, $P < 0.001$), so we used the former as a surrogate of the latter. The presence/absence of cork stripping was also registered for every tree (variable *Stripping*), in order to separate trees which had never been stripped, thus with virgin cork (unstripped), from trees in which cork exploitation had started and taken place at least once (hereafter named stripped or debarked). Finally, for each tree we registered the presence/absence of sprouting from canopy and trunk base.

2.4. Data analysis

We considered that a tree presented post-fire survival if it resprouted from either or both the canopy (independently of the proportion of crown recovered) and base (i.e. it produced suckers). Binary logistic regression (Hosmer and Lemeshow, 1989) was used to find which variables had an influence on post-fire tree survival (coded as 1 if tree alive, and as 0 if tree was dead). The significance of each variable was first tested through a univariate model, by using the likelihood-ratio χ^2 statistic. Variables with $P < 0.1$ were retained for the multivariate logistic model, which was built using both forward and backward stepwise selection. To check whether the obtained models could be improved, some variables were square-transformed (to allow for curvilinear or unimodal trends) and interactions between variables explored, mainly the potential interaction between stripping status, bark thickness, exposure and tree size. Different models with several combinations of variables were compared using the Aikaike Information Criterion (AIC) (Burnham and Anderson, 2003), and the one with lowest AIC considered the more parsimonious. Model performance was assessed through the likelihood ratio statistic and by calculating the area under the receiver operating characteristics (ROC) curve (Saveland and Neueschwander, 1990; Pearce and Ferrier, 2000). Understory cover, aspect and stripping status were analysed as categorical variables. Correlations between explanatory variables (Pearson correlation coefficient) were usually low. The highest values were observed for DBH and tree height ($r = 0.69$, $P < 0.001$), understory estimated height and tree cover ($r = 0.44$, $P < 0.001$), and slope and tree cover ($r = -0.32$, $P < 0.001$). All analyses were carried out using the SPSS software (SPSS, 2004). Unless otherwise stated, results are expressed as mean $\pm$ standard error.

3. Results

3.1. Plot and tree variables

A summary of the descriptive statistics for the studied variables is shown in Table 1. The average cork oak tree was 7 m tall and measured 27 cm in DBH. Average bark thickness was 2.53 cm. Mean slope was ca. 20%, and most trees were located in NE aspect (20.2% of the trees) whereas the less common orientation was SW (2.6%), with no trees located in SE aspect. The most common understory cover prior to fire was medium (64.5% of the trees), followed by sparse (21.1%) and dense vegetation (14.3%). Of the 1151 sampled trees, 292 (25.4%) had never been stripped.

Table 2
Results of univariate logistic regression to assess the effect of variables on post-fire cork oak survival

Variable	Coefficient sign	χ^2	d.f.	P
Mean bark thickness	**0.584 ± 0.075**	**67.37**	**1**	**<0.001**
Aspect	**cat**	**27.59**	**6**	**<0.001**
Minimum charring height	**−1.164 ± 0.218**	**27.52**	**1**	**<0.001**
Diameter at breast height	**−0.029 ± 0.006**	**23.47**	**1**	**<0.001**
Stripping	**−0.676 ± 0.215**	**11.04**	**1**	**0.001**
Slope	**−0.060 ± 0.019**	**10.11**	**1**	**0.001**
Tree cover	**1.661 ± 0.566**	**9.44**	**1**	**0.002**
Shrub cover	**−0.881 ± 0.320**	**7.49**	**1**	**0.006**
Tree height	0.074 ± 0.038	3.78	1	0.052
Understory cover	cat	3.44	2	0.179
Estimated understory height	−0.000 ± 0.001	0.19	1	0.890

For each variable, the coefficient (±standard error) and the value of the χ^2-test (equivalent to the change in −2 log Likelihood if the variable was removed from the model) are shown. Variables are ordered by decreasing importance. Significant variables ($P < 0.05$) are signalled in bold. cat = categorical variables.

3.2. Survival rates and variables affecting tree survival

The percentage of trees surviving 1.5 years after the fire was 84% (182 dead trees and 969 live trees). Using the univariate approach, the most important variable affecting survival was cork bark thickness, which had a positive contribution to survival (mean bark thickness of dead and alive trees, respectively, 1.86 ± 0.09 and 2.65 ± 0.04 cm) (Table 2). Aspect ranked second, and after checking survival probabilities associated with the different aspect categories, this variable was simplified and recoded into 2 classes: 1 for South or East, and 0 for the remaining categories (variable *Aspect South or East*). This recoded simpler variable was also significant ($\chi^2 = 21.27$, d.f. = 1, $P < 0.001$), showing a decreased survival probability in South to East-oriented slopes (76.8% survival against 87.7% survival in other aspect categories), and included in the multivariate analysis instead of the former (see below). The tree variables minimum charring height (mean value in dead and alive trees, respectively, 0.43 ± 0.03 and 0.28 ± 0.01), diameter at breast height (mean DBH of dead and alive trees, respectively, 31.4 ± 1.15 and 26.3 ± 0.36 cm) and stripping (proportion of stripped trees, respectively, 0.84 and 0.73 for dead and alive trees) were all negatively correlated to survival. Ranking last, shrub cover was inversely related to survival (proportional shrub cover for dead and alive trees, respectively, 0.44 ± 0.02 and 0.39 ± 0.07) whereas tree cover was positively related (proportional tree cover for dead and alive trees, respectively, 0.31 ± 0.01 and 0.35 ± 0.05). Tree height was marginally significant, with survival probability increasing in taller trees (mean height for dead and alive trees, respectively, 6.8 ± 0.17 and 7.2 ± 0.07 m).

The more parsimonious multivariate model obtained (Table 3, Fig. 2) showed that the most important variables determining cork oak survival in the study area were mean bark

Table 3
Multivariate logistic model to predict post-fire cork oak survival

Variable	Coefficient	χ^2	d.f.	*P*
Stripping × mean bark thickness	0.620 ± 0.092	53.61	1	<0.001
Stripping	−1.759 ± 0.363	24.81	1	<0.001
Diameter at breast height	−0.148 ± 0.032	22.21	1	<0.001
Tree height	1.074 ± 0.254	17.11	1	<0.001
Minimum charring height	−0.876 ± 0.257	11.26	2	0.001
Diameter at breast height^2	0.001 ± 0.000	7.43	1	0.006
Tree height^2	−0.043 ± 0.016	7.08	1	0.008
Stripping × aspect South or East	−0.526 ± 0.210	6.18	1	0.013
Constant	0.613 ± 0.840			

For each variable, the coefficient (±standard error) and the value of the χ^2 test (equivalent to the change in −2 log Likelihood if the variable was removed from the model) are shown. Variables are ordered by decreasing importance. Full model $\chi^2 = 188.4$; d.f. = 8; $p < 0.001$. Area under ROC curve = 0.78 ± 0.02; $p < 0.001$. See also Fig. 2.

thickness, stripping status and DBH. Tree height, minimum charring height and aspect were also important predictors. Stripped trees had lower survival probability than unstripped trees. Interactions between stripping status, bark thickness and aspect suggest that the effects of the two latter variables were only observed in the exploited trees, and not in unstripped ones. Thus, survival probability increased with bark thickness and decreased in unfavourable exposures, but only in stripped trees (Fig. 2a). Trees with larger DBH survived less, particularly if they had been debarked and were located in South to East exposures (Fig. 2b). Taller trees survived better, mainly if they were unstripped (Fig. 2c). The negative effect of minimum charring height was particularly visible in unfavourable exposures (Fig. 2d).

4. Discussion

Average post-fire survival probability for cork oaks in this mountain region of southern Portugal, 1.5 years after a wildfire, was ca. 84%. Factors affecting survival could be divided into the ones related to individual tree resistance to fire and the amount of fire damage. Our results showed that part of the large variability in survival estimates obtained in previous studies (e.g. Lamey, 1893; Pampiro et al., 1992; Cabezudo et al., 1995; Pausas, 1997; Barberis et al., 2003; Catry et al., 2006) may be explained by the fact that bark thickness, although important, is not the only variable affecting survival. Thus, different studies

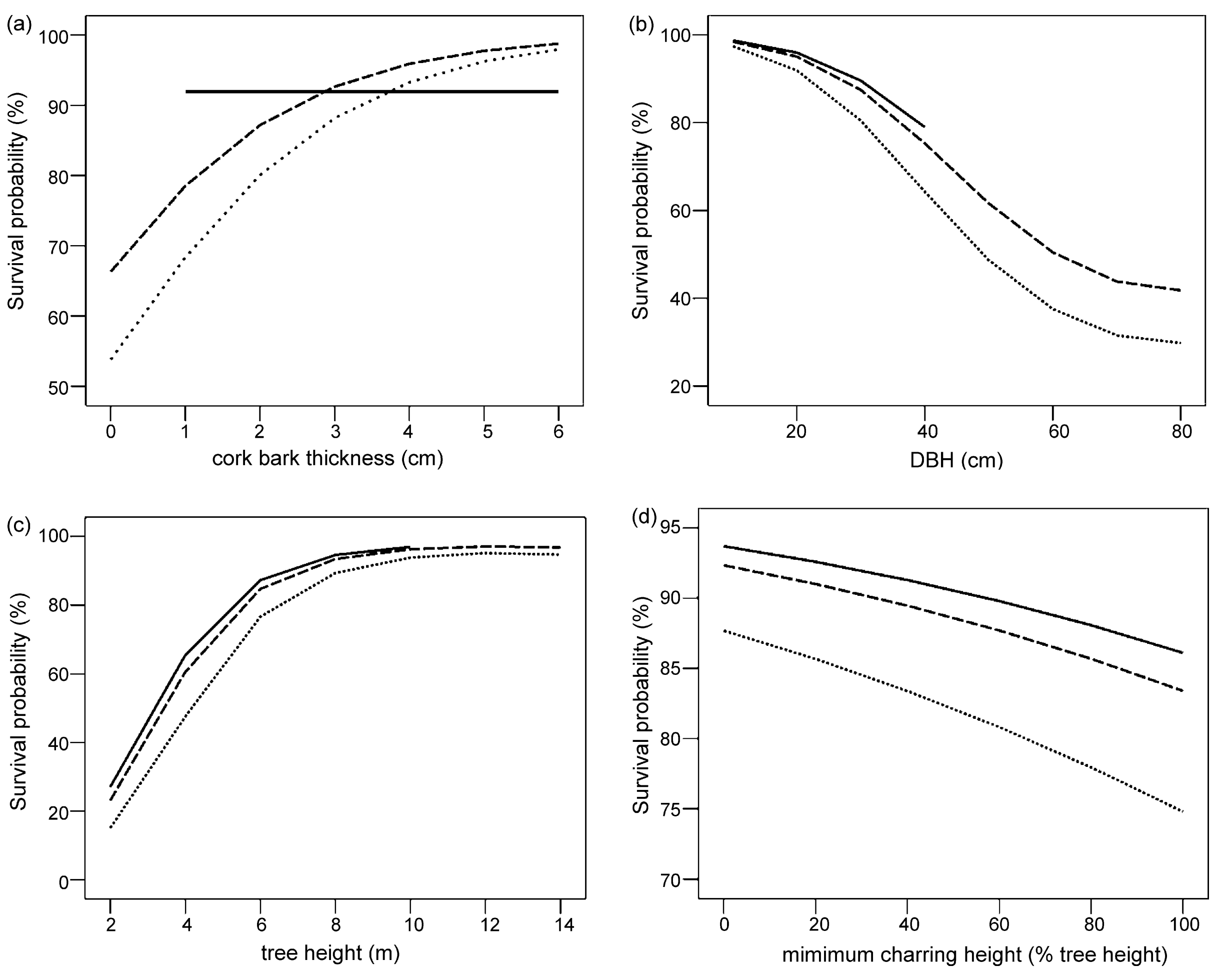

Fig. 2. Logistic model prediction of cork oak survival, based on the model in Table 3. Each figure shows survival probability in relation to (a) bark thickness; (b) DBH; (c) tree height; (d) minimum charring height. Each line represents trees with virgin cork (solid line), stripped trees in favourable exposures (dashed line) and stripped trees in unfavourable exposures (South or East) (dotted line). For each variable, the remaining variables in the model are held constant at their average values of: tree height: 7 m; DBH: 27 cm; bark thickness: 2.5 cm; minimum charring height: 30%. Only existing combinations of variables are shown.

on post-fire survival in trees having similar cork ages but widely variable tree size, understory composition, exposure, or fire intensity, may yield quite different survival rates. These latter variables were usually not taken into account previously.

Trees with virgin cork showed significantly higher survival rates (89.5%) than stripped ones (82.4%). In addition, their survival was not influenced by bark thickness or exposure, in contrast with trees being explored for bark extraction. This suggests that trees with virgin cork are more fire-resistant than stripped trees. One possible explanation for this is that the insulating properties of bark are particularly effective on unstripped cork oaks, due to a different bark structure. The cork of previously stripped trees has approximately twice the number of pores per unit of area than virgin cork, thus enabling easier heat penetration, particularly because these pores are often obstructed or surrounded by lignified walls (Calvão da Silva, 1996). It also has a higher bark density than virgin cork (Fonseca et al., 1994) and, consequently, a higher thermal conductivity that increases the rate of heat diffusion through the bark (e.g. Hengst and Dawson, 1994). A complementary explanation for the increased survival in unstripped oaks is that they do not suffer from wounding associated with cork stripping operations. Costa et al. (2004) showed that cork stripping damage (due to cuts penetrating down to the phellogen) has negative effects on tree health and growth, to which unstripped trees are not subjected.

Cork bark thickness was a key variable influencing the survival of debarked trees. In comparison with the average of 82% survival, stripped trees with bark thickness less than 1 cm ($n = 140$) had just 59% survival, and this proportion decreased to 35% for trees with bark thickness under 0.5 cm ($n = 46$). Previous studies (e.g. Lamey, 1893; Pausas, 1997; Barberis et al., 2003) showed the crucial importance of this variable in conferring a higher resistance to fire, due to the insulating properties of cork oak bark. Slight increases in thickness will largely increase survival likelihood, as heat transfer models show that the time needed to kill the cambium of a tree increases with the square of bark thickness (Dikinson and Johnson, 2001). Our models suggest that above 3–4 cm bark thickness trees are well protected from fire (Fig. 2). To find out to which cork age this thickness interval could correspond, we sought to use available models of annual cork growth (Natividade, 1950; Tomé et al., 1998). However, annual cork growth is quite variable, with estimates ranging roughly from 2 to 9 mm, and being larger for younger aged cork (Tomé et al., 1998). Furthermore, as bark thickness was measured 1.5 years after fire, we would have to correct for the potential cork growth between fire occurrence and our field measurements. To overcome these drawbacks, we preferred to use the relationship between cork thickness (measured in 2005/2006) and cork age in 2004, obtained for the measured trees (see methods). Using this relationship, 3–4 cm of cork thickness corresponded to 6–8 years of cork age. Interestingly, the obtained model suggests that stripped trees do worst than trees with virgin cork if bark thickness is less than 3 cm, but do slightly better if they have thicker bark (Fig. 2a). However, a direct comparison of survival rates as a function of bark thickness yields significant differences for the former (if thickness <3 cm, 91.4% survival for trees with virgin cork versus 77.7% survival for stripped trees; $\chi^2 = 15.1$, $P < 0.0001$) but not for the latter (if thickness ≥3 cm, 88.5% survival for trees with virgin cork versus 92.1% survival for stripped; $\chi^2 = 1.4$, $P = 0.236$).

Trees with larger stem diameter usually have thicker bark (e.g. Ryan and Reinhardt, 1988; Miller, 2000; Dikinson and Johnson, 2001) and thus higher post-fire survival. But in cork oak, trees with larger DBH had lower survival probability. First of all, there was no correlation between DBH and cork thickness ($r = 0.02$, $P = 0.487$). Additionally, larger cork oak trees correspond to older trees which were more often subjected to stripping, and thus stripping damages, as well as likely poor management practices (e.g. deep ploughing or excessive canopy pruning). Thus, they may be more susceptible to stress or diseases affecting growth and vitality (Natividade, 1950; Costa et al., 2004; Silva and Catry, 2006). Even if older trees have a thick bark, wounds and scars may be present (Natividade, 1950; Costa et al., 2004), which represent weak points in terms of fire resistance (Miller, 2000). This could explain why bigger trees may be more susceptible to fire and have lower survival probability. In Sardinia, Barberis et al. (2003) also found that cork oaks stripped more often had higher mortality after fire (40%) than trees debarked only once (17%).

Survival probability increased with tree height, although the relationship seemed to have a ceiling above 8–9 meters (Fig. 2c). Taller trees will have their canopy further away from flames during the passing fire front, and consequently will suffer less crown scorch from a surface fire (e.g. Van Wagner, 1973; Gould et al., 1997; Miller, 2000; Rigolot, 2004), and will be less prone to crown fire (Van Wagner, 1977), which probably explains their higher likelihood of survival.

Trees with a higher proportion of the bole charred had lower survival (Fig. 2d). The height of bole charring is a measure of the potential direct impact of fire in the tree, i.e. an indicator of the heat received by a tree, which is determined by the temperature reached and the duration of exposure (Miller, 2000; Rigolot, 2004). Thus, trees with larger proportion of their total height charred probably had bigger damage.

Aspect was also an important variable influencing post-fire tree survival (Table 3). In other studies, variations in fire regime with aspect have been attributed to differences in fuel accumulation, structure and moisture (e.g. Whelan, 1995; Schwilk et al., 2006). In our study area, it is likely that South to East oriented aspects, where survival was lower, have a more xerophitic character that may have caused higher tree physiological stress and thus more vulnerability to fire. In addition, South and Southeast aspects are the most exposed to the predominant hot summer winds in the region (Ribeiro et al., 1987).

Less important (only significant in univariate models) predictors of cork oak survival were slope and proportional shrub and tree cover (Table 2). Cork oak survival decreased with slope, probably because in steeper slopes water retention is lower, soils are thinner, and fire spreads faster and with higher intensity (e.g. Rothermel, 1983; Viegas, 2004), and therefore trees are more susceptible to fire. Trees located in plots with higher shrub cover experienced lower survival. Again, fire intensity is expected to be higher in these conditions of higher biomass accumulation (Rothermel, 1983). In contrast, higher tree cover in the plot increased survival probability, possibly because wind speed and fuel moisture, respectively, decrease and increase in denser stands, which mitigates fire intensity (FAO, 2001). Alternatively, this result is due to the correlation between tree density and slope (higher tree density occurred in lower slopes).

4.1. Implications for management

The present study showed that cork extraction is a key factor determining post-fire cork oak survival. Firstly, the more fire-resistant trees are the unstripped ones, and the management decision of stripping virgin cork will increase tree susceptibility throughout life. Secondly, bark extraction creates a time window of several years during which the tree is particularly fire-prone (until bark regrows to the thickness conferring higher fire protection). Thirdly, throughout a tree's life, the more stripping operations are carried out, presumably the more fire susceptible it will become. Lastly, stripping increases tree susceptibility in unfavourable exposures. Thus, in contrast to most other trees, fire resistance in cork oak is essentially determined by management decisions, namely when to start debarking and the timing of successive cork extractions, rather than by natural biological processes such as tree and bark growth. The impact of debarking has been described to be so detrimental to the extreme that trees can die just because of the occurrence of hot and dry winds immediately after cork extraction (Lamey, 1893; Natividade, 1950).

The Portuguese law establishes a minimum cycle of 9 years between successive cork extractions (Pereira and Tomé, 2004), but in some regions it is common to wait 10–12 years between two successive strippings. Longer cycles will improve tree health, resistance to fires, and in many cases cork quality (Natividade, 1950). This author suggested that in mountainous areas like in Southern Portugal, it would be possible to obtain an appreciable improvement of cork quality by increasing the debarking cycle to 12–15 years. This could be particularly important as our data suggest that trees start to be well protected from fire at a cork age of 6–8 years, almost coinciding with the 9-year debarking cycle. In addition, the cork extraction of a stand may be carried out simultaneously in all trees (even-aged cork) or only in a selection of trees, resulting in differential cork age distribution in the stand (uneven-aged cork) (Pereira and Tomé, 2004). In the former situation, the probability that all trees in the stand will die if a fire occurs after debarking is much higher in comparison with the latter, so uneven-aged cork exploitation is preferable to minimise stand-level ecological damage and economic losses from wildfires.

To minimise tree mortality in plots with higher shrub cover, understory management to reduce cover, if carried out some time before the cork striping, will reduce fire severity in case a wildfire occurs in the first years after debarking (CELIÈGE, 2005). Whenever possible, understory reduction should be done without soil mobilization to minimize erosion. Furthermore, when trees growth on thin soils, the roots are more superficial, so it is convenient to not increase tree damage by ploughing or compacting the soil (Amo and Chacón, 2003).

The obtained survival model can be used in management, as it allows the mapping of areas more vulnerable to fire (where higher post-fire mortality will be expected) based on individual tree height and diameter (or average characteristics at the stand-level), cork data (presence of virgin cork, cork thickness or cork age), and exposure. These areas should be given priority in terms of fire prevention. This vulnerability map should be updated as cork exploitation changes cork age stand-structure through time.

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