The impact of fire recurrence on populations of *Quercus suber* in southeastern France

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Abstract
Cork oak (*Quercus suber*) is known as one of the most fire-resistant and fire-resilient tree species in French Mediterranean ecosystems. However, the repetition of high intensity wildfires is hypothesized to entail direct or delayed mortality in the populations of the Maures massif (southern France). We have installed a network of 90 permanent plots in an area affected by the intense 2003 wildfire. The plots were sampled along a gradient of fire recurrence since 1959, with one to four fires, and unburned control plots. Trees were individually surveyed between 2004 and 2007. Field survey included tree mortality, damage intensity, and individual tree growth and allometry. Results indicate that the total tree mortality (i.e. root and stem mortality) ranged from 3% to 8% one year after the fire. This confirms the high survival ability of *Quercus suber*, especially in comparison to the other tree species of the study area. However, delayed mortality has been observed from 2004 to 2007, probably in relation to repetitive summer droughts. The mortality of cork oak did not vary linearly with fire recurrence: it was maximal after one first fire and 3-4 fires. The best-fit logistic model predicted the mortality of cork oaks as a function of their dendrometric characteristics (crown and stem diameter), which are hypothesized to express the ability of trees to escape fire and to resprout. At population scale the fires have exerted a size-dependent selection with higher mortality for small and large trees. As a consequence, the fire recurrence tends to regularize and to open the cork oak stands. Our findings suggest that the mortality rate should increase and become a major concern for forest and land managers of this area in a context of global change, with presumably increasing fire recurrence and summer droughts.

Keywords: *Quercus suber*, wildfire regime, tree mortality, mortality model, resprouting ability

1. Introduction

Cork oak (*Quercus suber* L.) populations of southeastern France are protected by the European Union (Habitat directive 92/43/EEC) due to their high ecological value. They cover ca. 56,500 ha area in the Maures massif, i.e. about 3% of the whole area of this species. *Quercus suber* is an evergreen sclerophyllous tree common on carbonate-free soils of the Mediterranean basin (Pausas, 1997). Cork oak woodlands have long been favored for cork production, but most stands have not been managed (cork extraction, shrub-clearing) since the 1960s owing to the collapse of silviculture and grazing, and the competition from Portuguese and Spanish cork industry. As a consequence, the shrublands expanded strongly within the landscape. The present cork oak habitats are a mosaic of cork oak woodlands, shrublands composed of highly flammable shrubs (*Erica*, *Cistus* and *Calycotome*), mixed oak woodlands (*Q. suber*, *Q. ilex* and *Q. pubescens*) and pines (*Pinus pinaster*, *P. halepensis*). These populations experience large and recurrent wildfires since decades (Curt et al., 2009) owing to the expansion of shrublands and the harsh summer droughts. Cork extraction has been abandoned in most cork oak forests, thus allowing the insulating cork to thicken and probably increasing the fire-resistance of trees. In the same time, most forests had not shrub cleared anymore, thus entailing the fuel accumulation in the shrubby understorey and leading to intense and large surface wildfires. These fires spread in the understorey maquis but can generate high flames reaching or surpassing the canopy of cork oaks, thus generating high damages to stems and crowns. The present mean fire interval is about 15 years in shrublands (Curt et al., 2009), and intense wildfires are hypothesized to increase owing to the climate change (Pausas, 2006). In this context, evaluating the postfire mortality and the regeneration ability of *Quercus suber* is a major issue for forest management.

Postfire mortality models for trees try to estimate the mortality (or the survival) of individuals on the basis of the intensity of stem- or crown damages due to fire (Stephens, 2002; Fowler and Sieg, 2004). A large set of variables has been tested including the percentage of crown scorched or the depth of the charred bark (Hely et al., 2003; Fowler and Sieg, 2004). As strong allometric relationships generally exist between the different tree compartments (e.g. bark thickness vs. stem height), the individual dendrometric characteristics of trees can also be efficient surrogates and predictors of tree mortality (Rigolot, 2004; Thies et al., 2006). These models aim at predicting tree mortality as soon as possible after a fire in order to apply rapidly the silvicultural options such as tree removal or coppicing (Catry et al., 2009). However, many tree species experience a delayed mortality after fire. This delayed mortality results from the fact that fire may have altered the tree cambium without killing the tree immediately (Jones et al., 2006), or that pests or diseases can emerge a few years after fire (Filip et al., 2007). In addition, resprouting species such as *Q. suber* and many oaks have the ability to develop aerial or basal resprouts that may die after some years. Resprouting is an efficient life-history trait by which woody plants can recover from disturbance (Pausas, 1997). As a consequence, building an accurate model of tree survival thus implies re-sampling trees up to three or four years after fire. In the case of recurrent fires such as in the Maures massif, one can expect that cork oak populations have been shaped through the succession of fires, and of direct and delayed mortality.

In this study we hypothesized that cork oak mortality depends upon the recurrence of historic wildfires and the intensity of damage caused to the trees. On the basis of a network of permanent plots installed in 2004 (just after the intense 2003 wildfire) we test the hypothesis that the individual tree dimensions can be efficient predictors of tree mortality as they relate to the resistance of trees to fire and to their resprouting ability. We also investigate to which extent recurrent fires along the past decades have shaped the size distribution of tree and the stand structure.

2. Materials and Methods

The study area is located in the Maures massif in southeastern France (43°3 N, 6.3° E). The Maures massif is made of granitic and metamorphic basement and covered with acidic brown soils. The climate is typically Mediterranean and classed as subhumid xerothermic with harsh summer droughts. Fire regime within the study area is known using a comprehensive and georeferenced fire database since 1959 (Schaffhauser et al., 2008; Curt et al., 2009). In the past decades, two large and very intense summer wildfires have burned about 25.000 and 13.000 ha in the Maures massif in 1990 and 2003, respectively. We have installed a network of 90 plots (20x20 meters) in an area affected by the intense 2003 summer wildfire. The plots were sampled along a gradient of fire recurrence from one fire (2003 only) up to four fires (see Curt et al., 2009 for explanations). We also selected control plots unburned since at least 1959, in similar site conditions.

All the plots were dominated by *Quercus suber*, which have not been submitted to bark extraction since at least 30 years. This allows comparisons among trees since cork extraction has been recognized as a main factor affecting tree survival after fire (Moreira et al., 2007b). Depending upon the past fire recurrence, cork oak trees were associated with a variable coverage by shrub species forming typical *Erica-Cistus* shrublands (so-called 'maquis'). The control (i.e. unburned) plots corresponded to mature oak woodlands with *Q. suber*, *Q. ilex*, and *Q. pubescens*. We checked for symptoms of tree diseases such as *Phytophtora cinnamomi* (Brasier 1996), *Platypus or Porthetria dispar* that are common in some foreign cork oak populations (Moreira and Martins, 2005). All stands were likely to be unharmed of pests and diseases that would entail an additional mortality.

All the trees were individually labelled at the end of 2003 and surveyed twice a year until 2009. Field survey included the assessment of tree damage and mortality, the intensity of resprouting, and dendrometric measurements. Crown damage was assessed using the volume of crown scorched and killed, and the minimal and maximal height of charring measured on the windward side of the tree. Stem damage included the minimal and maximal height of scorched bark, and the depth of bark charred using a gauge. Trees were noted as fully dead when their canopy and stem had been severely burned, and when they had no resprouts. Fore tree having resprouted we noted the type of resprout (basal only, crown only, and mixed). Live trees were those that had no damage, or that resprouted. For basal resprouts we assessed the number of sprouts and the number of viable sprouts (i.e. having a complete bark at the root collar), their height and basal diameter, and the crown dimensions of sprout clusters. The quality and quantity of resprouts in the crown were assessed using a visual grid, from high and total recovery to very low recovery. We also used a simple damage code to assess visually the extent of fire damages endured by each tree. This code ranged from the absence of visible damage (0), the tanning of leaves (1), the partial burning of leaves and small twigs (2), the total burning of leaves and small twigs (3), and the consumption of all branches (4), the consumption of the main stem. Dendrometric measurements included tree height, diameter at breast height (dbh), vertical and horizontal crown dimensions.

We used simple or multiple analyses of variance to compare the main variables describing tree survival and regeneration according to the modalities of fire regime. Binary logistic regression was used to compute a mortality model according to the main dendrometric variables such as dbh or crown diameter (McCullagh & Nelder 1997):

$$P(m) = \frac{1}{1+e^{-(b_0+b_1x_1+...+b_nx_n)}}$$

where x_1 to x_n are the explanative variables, and b_1 to b_n are the parameters to estimate using the method of maximum likelihood. The adjustment of the model were operated using the Akaike information criterion AIC = -2LL + 2(1 + n_{var}), with LL is the likelihood function and n_{var} is the number of explanative variables in the model. The quality of the model was estimated with a pseudo-R^2 = $(dev_{null} - dev)/dev_{null}$, with dev_{null} is the deviance of the null model, and *dev* is the deviance of the model. Logistic regression models included only predicted values of 0 (dead tree) and 1 (live tree), thus parameters estimates and significance tests did not require an assumption of normal distribution of data (see Regelbrugge and Conard, 1993).

3. Results

Our data indicate that the total tree mortality (i.e. root and stem mortality) ranged from 3% to 8% one year after the fire. However, the delayed mortality strongly increased up to 20% during the very dry 2004-2007 period. Mortality was high after a first fire, and maximal with for high fire recurrence (i.e. 3-4 fires since 1959). Overall, the cork oaks killed by fire had a lower diameter at breast height (40.0 cm vs. 67.9 cm), a lower height (4.9 m vs. 7.0 m) and a lower crown diameter (3.0 m vs. 3.8 m) than the surviving cork oaks. The Wilcoxon *pc* tests for these variables were 0.0151, 0.0456 and 0.0148, respectively. The characteristics of the cork oak stands were affected by fire (Table 1). The stands density decrease with fire recurrence but not significantly. The basal area, the cork oak height and dbh decreased significantly. It is noteworthy that the basal area decreased after one fire, and almost after three of four fires.

	No Fire	1 Fire	2 Fires	3 Fires	4 Fires	Total/Mean	Tests
Sample size	19	20	16	20	15	90	

Stand density (n.ha)	708 ± 67	455 ± 43	533 ± 102	619 ± 71	495 ± 67	546	NS
Cork oak basal area ($m^2.ha^{-1}$)	15.9 ± 1.0	14.3 ± 0.7	16.3 ± 1.3	15.2 ± 1.3	12.8 ± 0.7	140.5	P=0.0206*
Stand basal area ($m^2.ha^{-1}$)	26.3 ± 0.7	19.3 ± 1.6	17.0 ± 1.5	15.3 ± 1.2	12.9 ± 0.6	17.8	P=0.0003***
Cork oak dbh (cm)	28.2 ± 2.2	23.9 ± 2.2	21.4 ± 1.5	21.3 ± 1.7	18.9 ± 1.4	22.2	P<0.0001****
Cork oak height (m)	9.8 ± 0.4	7.1 ± 0.5	6.8 ± 0.3	5.9 ± 0.4	5.3 ± 0.5	7.0	P=0.0047**

Table 1. Stand characteristics of the plots according to the recurrence of fires (1959 to 2009). Data are means ± standard error. We used the Least Significant Difference procedure (LSD, 95% confidence interval) to test the differences between the modalities of fire recurrence. ^{NS} = statistically non-significant.

We compared different mortality (or survival) models that combined the different predictive variables, i.e. the intensity of damages caused by fire and the dendrometric characteristics of trees. A binary logistic regression indicated that the postfire survival of *Quercus suber* correlated well with tree height, diameter at breast height and crown diameter. However, the pseudo-R^2 remained low (30-40%) for all the models, thus limiting their accuracy to predict the tree survival. Among all the models, the best explanative variable was the mean crown diameter (pseudo-R^2 = 37%). The best-fit logistic model of *Quercus suber* survival after fire (variance explained = 42%) was computed as following:

$$p_{\text{survival}} = \frac{1}{1+e^{-1.0434*cd+0.018*cbh}}$$

where p_{survival} is the probability of survival of a cork oak tree, *cd* is the crown diameter (in meters) and *cbh* is the circumference at breast height (in cm). In this model, the crown diameter is the main explanative variable (χ^2 test = 0.04). The probability of survival as a function of the mean crown diameter differed significantly for trees burned only once and tree burned recurrently (Figure 1).

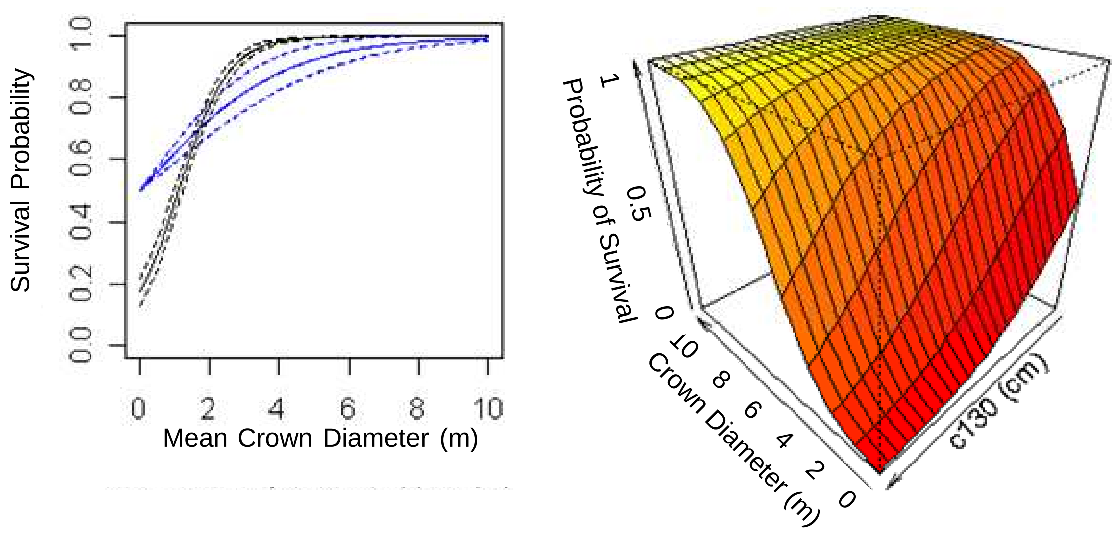

Figure 1. Left panel: Model of probability of survival for cork oak one year after the 2003 fire according to the mean crown diameter. The blue curve is for trees burned only once since 1959, and the black curve is for trees burned more than two times since 1959. Dotted lines correspond to the 95% confidence interval. Right panel: Probability of survival of cork oak one year after the 2003 fire according to the mean crown diameter and the circumference at breast height (c130, cm)

The recurrence of fire affected clearly the distribution of the tree diameters (Figure 2). The control (unburned) stands had an almost even frequency of tree diameters, including all classes from very large to very small trees. As the number of fires increased, the stands had a more uneven distribution of tree diameters, with a clear over-representation of small-to-medium trees and the progressive elimination of large and very small trees.

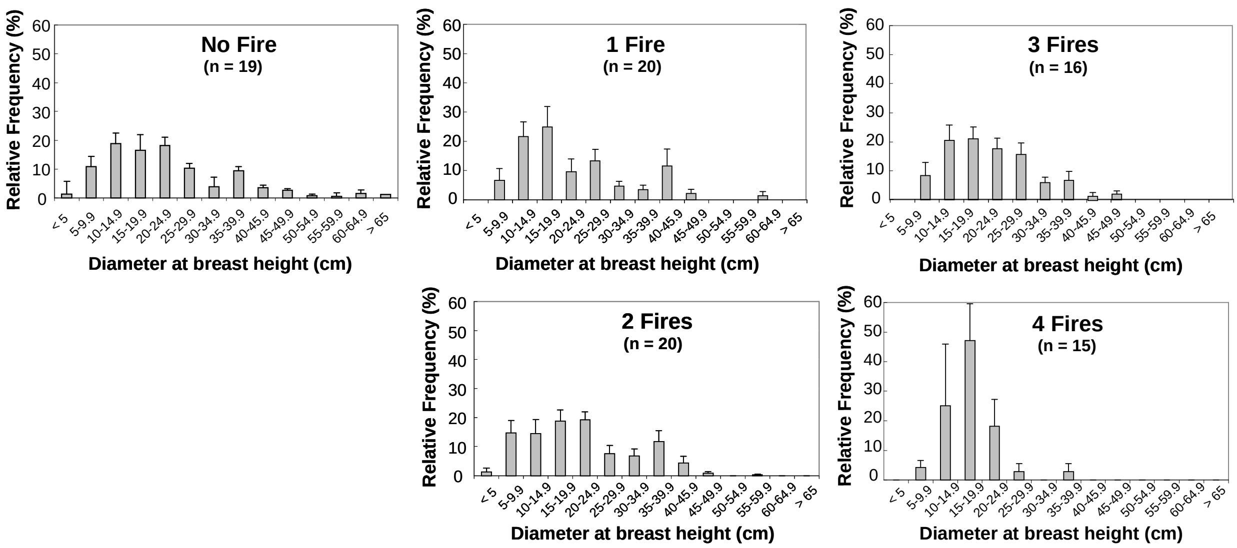

Figure 2. Distribution of the relative frequency of tree diameters (values at breast height, 1.30 m) according to the fire recurrence since 1959. Large grey bars are means, and small bars are standard errors

4. Discussion and conclusions

Our data confirm the high survival ability of *Quercus suber* after fire in the Maures massif, even after intense and recurrent wildfires. This result fits with those of previous studies in Spain (Pausas 1997; Gonzalez et al., 2007) and Portugal (Moreira et al., 2007b; Catry et al., 2009). Actually, cork oak has generally a very high survival rate in fire-prone environments, probably the highest among the Western Mediterranean trees (e.g. Gonzalez et al., 2007). In the Maures massif, cork oak is unquestionably the more fire-resistant and fire-resilient oak species. This resistance is likely due to its thick insulating bark that allows trees to resist fire, and its resilience relates to a high resprouting ability that allows trees to survive (Pausas, 1997). In contrast, most tree species have been severely damaged in 1990 and 2003, especially pines (*Pinus pinaster* and *P. halepensis*). These species have been almost eliminated from the forest overstory due to the direct effects of fires and the indirect effects, in particular the subsequent expansion of pests such as *Matsuccocus feytaudi* (Schaffhauser et al., 2008).

Even if cork oak if resistant and resilient, wildfires progressively reshaped the populations of the Maures massif. In particular, they exerted a size-dependent selection that is clearly visible through the stand structure: the cork oak stands recurrently burned are strongly regularized and sparse. This regularization to the benefit of small-to-medium trees corresponds to the postfire mortality of two cohorts. First, the smallest individuals generally died because they are less resistant to fires due to their thin bark and their low canopy that is generally strongly damaged by fires. Second, the large (= old) trees are clearly eliminated by fires, possibly due to their low ability to resprout and the repetition of stresses due to the past fires (Moreira et al., 2007b). These two processes have led up to the canopy opening and subsequently to the establishment of a dense shrubby understory. This, in turn, is hypothesized to favour fire recurrence and increase fire intensity (Curt et al., 2009).

We proposed a postfire survival model for cork oak, based on the mean crown diameter and the stem diameter at breast height. In contrast with most models proposed in the literature (see Hood et al., 2007; Ryan and Reinhardt, 1988; Rigolot, 2004) our best-fit model does not take into account the intensity of damage due to fire, but only dendrometric variables. This could result from the fact that crown and stem diameter express the vigour of cork oak individuals, and especially their resprouting ability, which is the major way to survive fire (Pausas, 1997; Moreira et al., 2007a). Second, they are strongly correlated to the variables related to fire damage, such as charred crown height or volume: in example, larger tree crowns are expected to allow trees to escape flames.

Our findings suggest that the recurrence of intense wildfires and possibly the combination with several years of harsh summer drought after fire could affect cork oak populations in the long-term, as suggested in Portugal (Acácio et al., 2009). Actually, fires could become more frequent and more intense in the context of global change. The expansion of shrublands challenges the cork oak woodlands because it favours fires and it severely limits the postfire recruitment of cork oak from seeds (Curt et al., 2009). A sustainable management of this ecosystem should focus on the dynamics of shrublands and the maintenance of mature cork oak stands that could act as seed suppliers.

Acknowledgments

We greatly acknowledge the CRPF PACA (L. Amandier) for his help and scientific advice on cork oak ecology and dynamics. This study has been funded by the French Ministry for Ecology (DEB SU0000381), the Provence Cote d’Azur Region (2008-29918) and thebVar District (2009-019).

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