Chapter 9
Post-Fire Management of Cork Oak Forests

Filipe X. Catry, Francisco Moreira, Enrique Cardillo, and Juli G. Pausas

9.1 Ecological and Socio-economic Context

Cork oak (*Quercus suber* L.) forests are defined here as the range of habitats from open savanna-like woodland formations to dense forests. According to the European forest type's nomenclature (EEA 2007) these ecosystems are included in the 'broadleaved evergreen forest' class and in the 'Mediterranean evergreen oak forest' type. This forest type is dominated by the evergreen sclerophyllous oak species *Q. suber*, *Q. ilex*, *Q. rotundifolia* and *Q. coccifera*, constituting the main natural forest formation of the meso-Mediterranean vegetation belt (EEA 2007). However, cork oak has a unique characteristic that makes it different from all the other Mediterranean broadleaved species: an outer insulating coat consisting of a corky bark, up to 30 cm thick, made of continuous layers of *suberized* cells that may have evolved as an adaptation to fire, and that has been used by people for millennia (Natividade 1950; Pausas et al. 2009). Periodical bark harvesting of cork oak trees makes them more vulnerable to external agents including wildfires. This is why cork oak forests are treated separately in this book.

F.X. Catry (✉) • F. Moreira
Centre for Applied Ecology, School of Agriculture (ISA), Technical University of Lisbon, Lisbon, Portugal
e-mail: fcatry@isa.utl.pt

E. Cardillo
Institute for the Wood, Cork and Vegetable Coal (IPROCOR), Polígono Industrial El Prado, Badajoz, Spain

J.G. Pausas
Desertification Research Centre, Spanish National Research Council (CIDE-CSIC), Valencia, Spain

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Nowadays, cork oak ecosystems cover nearly 2.5 million hectares of land in the western Mediterranean Basin. They can be found in southern Europe and North Africa, from the Iberian Peninsula and Morocco to the western rim of the Italian Peninsula (Fig. 9.1), occurring in a wide range of ecological conditions (APCOR 2009; Pausas et al. 2009). Cork oak trees show a high ecological plasticity. This species is well adapted to Mediterranean type climate, with mild, wet winters and dry, hot summers, occurring from more continental regions to coastal areas with Mediterranean and Atlantic influence. It grows well with mean annual precipitation of 600–1,000 mm, but stands up to 2,000 mm, 500 mm being the minimum usually considered for a balanced tree development (Natividade 1950; Pereira 2007). The optimum mean annual temperature is in the range 13–16ºC, although the species can also occur in environments with up to 19ºC. Cork oak grows from sea level to 2,000 m of altitude, but optimum growth occurs below 600 m. The species is tolerant to a variety of soils with the exception of calcareous and limestone substrates. It may grow on poor and shallow soils, with low nitrogen and organic matter content and it allows a pH range between 4.8 and 7.0. However, cork oak occurs preferentially in siliceous and sandy soils, preferring deep well aerated and drained soils, being very sensitive to compaction and water logging (Bernal 1999; Pereira 2007).

Most of the present distribution and physiognomy of cork oak forests is the result of an ancient anthropogenic alteration by clearance, coppicing, fires and overgrazing (e.g. EEA 2007), but also reforestation (plantation or seeding). A characteristic physiognomy of these ecosystems in the Iberian peninsula, found also locally elsewhere (Balearic islands, Sardinia), are savanna-like formations (known as *montado* in Portugal and *dehesa* in Spain) in which crops, pasture land or shrublands are shaded by a fairly closed to very open tree canopy (EEA 2007; Fig. 9.2). More rarely, denser cork oak forests can also be found, particularly in steep slopes and mountainous regions (Fig. 9.8).

Cork oak ecosystems play a very important ecological, economic and social role in several Mediterranean countries (e.g. Pereira and Fonseca 2003; Bugalho et al. 2011). Due to their uniqueness, these ecosystems are recognized as habitats of conservation value listed in the Habitats Directive: Habitat 6310 – *Dehesa*s with evergreen *Quercus* spp. and Habitat 9330 – *Quercus suber* forests (EEC 1992).

Cork oak ecosystems support a large variety of animal, plant and fungi species, including many endemisms (e.g. Bernal 1999). They have remarkable ecological value, providing habitat for several threatened species such as the Imperial eagle *Aquila adalberti*, the black vulture *Aegypius monachus* or the critically endangered Iberian lynx *Linx pardinus* (IUCN 2010).

Plant species composition depends on the ecological characteristics of each region and anthropogenic interventions. In southern Europe, and particularly in the Iberian Peninsula, mixed forests of cork oak and other oaks (*Q. rotundifolia*, *Q. ilex*, *Q. faginea*, *Q. robur*, *Q. pyrenaica*, *Q. canariensis*, *Q. coccifera* and *Q. lusitanica*) can be found. In France and Italy, other oak species, such as *Q. pubescens* and *Q. cerris* can be found; noteworthy are also savanna-like formations of *Q. suber* and *Q. congesta* in Sardinia (EEA 2007).

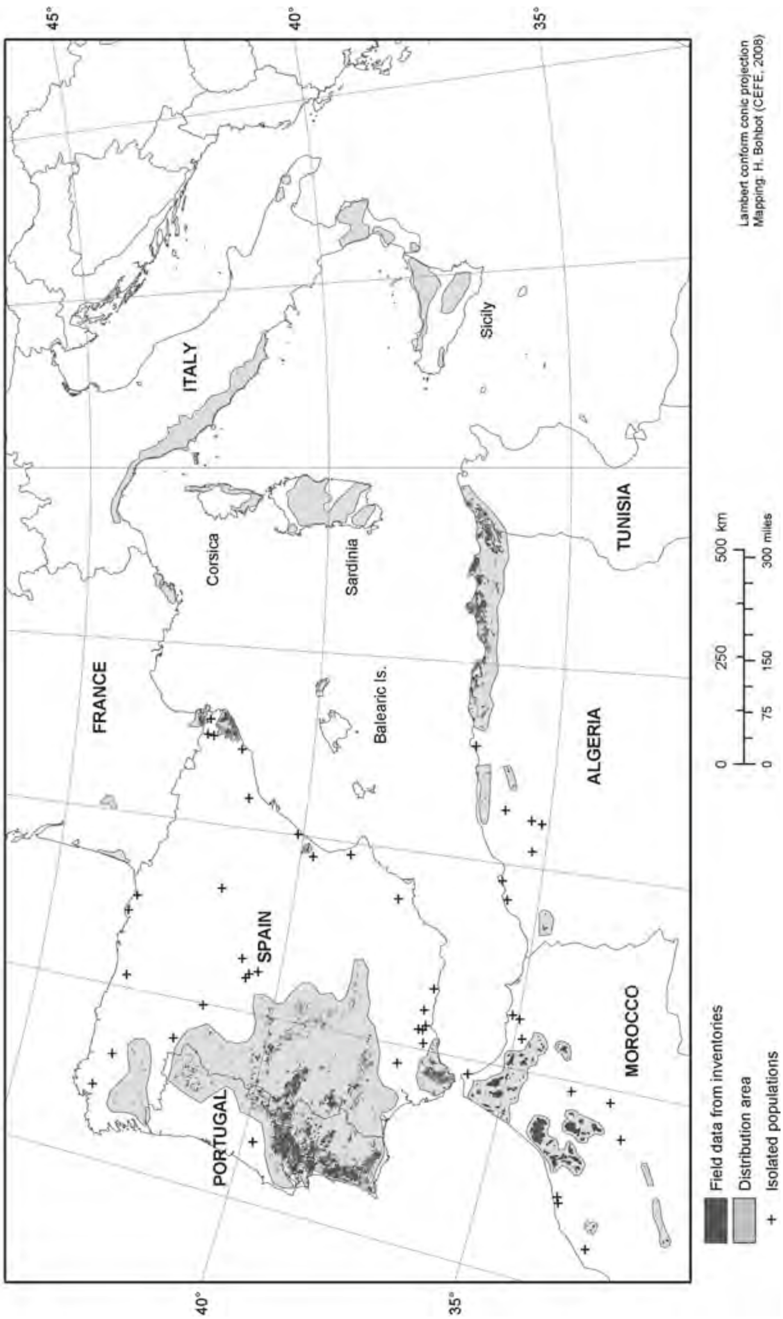

Fig. 9.1 Actual distribution of cork oak forests in the western Mediterranean Basin. Reproduced from Pausas et al. (2009) (copyright © 2009 Island Press; reproduced by permission of Island Press, Washington, DC)

Fig. 9.2 Cork oak forest (savanna-like formation, *left*) and detail of the main trunk and bark of a virgin cork oak tree (*right*) (Photos: F. Catry)

The structure of the more preserved cork oak forests includes a very dense tree cover up to 20 m high, often mixed with other Mediterranean broadleaved species (sometimes with conifers), and with shade-tolerant herbaceous species in the understory (Bernal 1999). Besides oaks, other small trees and large shrubs can coexist in these forests, such as *Arbutus unedo*, *Myrtus communis*, *Olea europaea* var. *sylvestris*, *Pistacia lentiscus*, *P. terebinthus*, *Crataegus monogyna*, *Viburnum tinus*, *Phillyrea angustifolia*, *P. latifolia*, *Rhamnus alaternus* and *Erica arborea*, among others. In more open forests, subjected to over-grazing, wildfires or with poor soils, other plants appear more often, such as species of the genera *Cistus*, *Cytisus*, *Erica*, *Genista*, *Ulex*, *Lavandula* and *Rosmarinus*, among others. Dominance of herbaceous species, such as *Agrostis*, *Brachypodium* or *Festuca*, is characteristic of more degraded woodlands (Bernal 1999).

Cork is a renewable natural resource constituting a valuable and versatile raw material for industry used for a large variety of products. Because of its economical value, cork oak silviculture is usually oriented towards periodical cork harvesting (Pereira 2007). Currently, cork is the second most important marketable non-wood forest product in the western Mediterranean, and the world cork market exports represent near US$2 billion annually (Mendes and Graça 2009; APCOR 2009). This species is particularly important in the Iberian Peninsula, which holds about 55% of the world's cork oak area and 82% of the world's cork production, representing thousands of jobs (Silva and Catry 2006).

However, despite of their value, several factors such as pests and diseases, over-harvesting, over-grazing and land use changes, are endangering *Q. suber* forests. These threats, exacerbated by climate change, affect tree health and increase vulnerability to wildfires (e.g. WWF 2007).

Fig. 9.3 After a wildfire (photos *above*) cork oak often starts regenerating quickly; photos *below* show totally charred trees with crown (epicormic) regeneration three months after fire (*left*), and 16 months after fire (*right*; the tree in background resprouted after fire but died some months later) (Photos: F. Catry)

9.2 Post-Fire Cork Oak Regeneration Strategies

Most of Mediterranean broadleaved species have the capacity to resprout after disturbances, including wildfires, and most of them resprout from basal buds when stems or crowns are severely damaged. Similarly to other oaks, post-fire cork oak recovery occurs mainly through vegetative regeneration. However, cork oak is the only European tree with the capacity to resprout from epicormic buds (i.e. buds positioned underneath the bark) high on the tree (Fig. 9.3), a feature shared with many *Eucalyptus* species and the Canary Island pine (*Pinus canariensis*) but otherwise rare (Pausas et al. 2009). The insulating bark of cork oak, when sufficiently thick (see Sect. 9.3), protects the epicormic buds, permitting trees to resprout quickly and effectively from stem and crown buds after fire. Because of this feature, cork oak is undoubtedly one of the tree species best adapted to persist in recurrently burned ecosystems. The post-fire tree survival is often high and the regeneration of cork oak-dominated landscapes is remarkably quick (Silva and Catry 2006). The fact that cork oak can regenerate after fire from epicormic buds gives this species a competitive advantage over coexisting woody plants. Together with its socio-economic importance and cultural significance, this extraordinary resprouting capacity makes

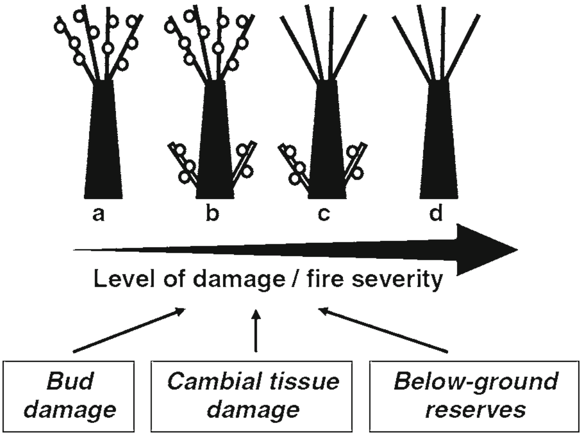

Fig. 9.4 A conceptual model of post-fire responses of a sprouting tree that suffered total crown consumption (combustion of leaves and twigs during a wildfire) in relation to a gradient of increasing damage/fire severity: (**a**) crown resprouting, (**b**) resprouting from both crown and base, (**c**) basal resprouting, (**d**) plant death (reproduced from Moreira et al. 2009)

Fig. 9.5 Jay (*Garrulus glandarius*) (*left*) is the main natural dispersal agent of cork oak acorns (*right*) (Photos: F. Catry)

the cork oak a very good candidate for reforestation programs in fire-prone areas (Pausas et al. 2009).

The post-fire cork oak responses are usually a function of the level of damage (fire severity). A conceptual model of vegetative tree responses was proposed by Moreira et al. (2009). At low levels of damage, a tree is expected to resprout from crown buds that survive the fire. At increasing levels of damage, the individual will resprout from both crown and base, just from the base, or will die (Fig. 9.4).

Cork oaks can also regenerate through seeds (acorns) during the inter-fire period (Pons and Pausas 2007), but rarely just after wildfires as acorns are usually destroyed. However, an increase in oak recruitment may occur not long after fire in areas where jays (*Garrulus glandarius*), the main oak dispersal agent, are abundant (Fig. 9.5). Post-fire conditions are suitable for jays to disperse acorns before the soil is covered by shrubs. A pair of jays may scatter and hoard several thousand acorns in a single season (Cramp 1994).

9.3 Factors Affecting Post-Fire Cork Oak Responses

9.3.1 Influence of Bark Thickness, Bark Exploitation and Tree Size

Previous research showed that bark thickness is a main driver of cork oak responses after fire (Catry et al. 2009, 2010a, b; Moreira et al. 2007, 2009; Pausas 1997). Tree vulnerability to fire significantly decreases with increasing bark thickness until bark reaches about 4 cm thick. Cork oak trees with bark more than 3–4 cm thick are well protected against heat injury having a very low probability of dying or suffering stem mortality (Fig. 9.6). Particularly in what concerns stem mortality it is noteworthy that for bark thickness lower than 3 cm, cork oak is apparently more fire resistant than other Mediterranean broadleaved species (Catry et al. 2010a). This can be explained by the high thermal insulating provided by cork, due to its high proportion of air and low density (Pereira 2007).

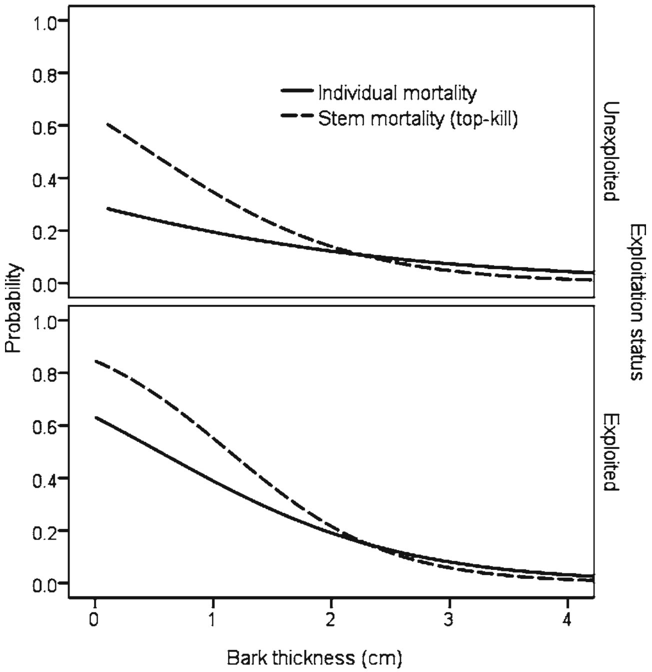

Fig. 9.6 Predicted post-fire cork oak responses (individual mortality and stem mortality) as a function of bark thickness and cork management status (exploited for cork *versus* unexploited) for trees with 20 cm d.b.h. (diameter at breast height) (Catry et al. unpublished)

Cork harvesting does not only drastically reduce bark thickness, but it also has additional effects. Cork exploitation per se has been found to significantly increase tree vulnerability to fire (Fig. 9.6), with mortality being up to 40% higher on exploited trees, even for individuals with the same bark thickness (Catry et al. unpublished, Moreira et al. 2007). Debarking is a major stress factor for trees and has been associated to vigor loss (e.g. Natividade 1950). Bark extraction leads to considerable water losses through the stripped trunk surface which may negatively affect the trees photosynthetic activity and productivity (Correia et al. 1992). The injuries caused by cork harvesting operations can also be associated to loss of tree vigor (Costa et al. 2004). In fact, wounded trees were found to be less fire-resistant than undamaged trees (Catry et al. unpublished). Wounded trees are more vulnerable because bark is usually absent or much thinner near wounds making the trunk more heat-sensitive and more vulnerable to other external agents (Miller 2000). Wounding is also likely to reduce tree vigor, both because of the energy resources needed for cicatrisation and because the active xylem killed reduces the rate of water absorption (Rundel 1973). Additionally, the changes induced by stress reduce the trees ability to defend themselves from insect or fungi attacks (Wargo 1996).

Previous studies also indicate that larger trees (higher d.b.h., and usually older) are more vulnerable to fire damages than smaller trees (Catry et al. 2009; Moreira et al. 2009). Lower fire resistance of larger trees can be explained by the fact that older individuals were debarked more times during its life and were probably subjected more often to poor management practices (e.g. deep ploughing, excessive pruning or stripping damages), thus being less vigorous (Natividade 1950). For example in Sardinia, Barberis et al. (2003) reported that cork oaks stripped more often had higher post-fire mortality (~37%) than trees debarked only once (~17%).

9.3.2 Influence of Fire Regime and Local Factors

The fire regime, particularly fire intensity, severity, frequency and fire season, can also exert determinant effects on post-fire tree responses. The first two components can be evaluated through potential indicators of fire injury, such as the char height, char depth or the crown volume damaged. Previous studies showed that cork oak vulnerability to fire significantly increases with increasing char height (Catry et al. 2009; Moreira et al. 2007), as it happens with other species (e.g. Catry et al. 2010a).

There is very few information available on the effects of fire frequency and returning intervals on cork oak, but it is expected that increasing fire frequency will negatively affect tree resistance to fire, as suggested in a study in southern France (Curt et al. 2010). Similarly, the effects of fire season on post-fire cork oak responses were rarely evaluated. In a recent study (Catry et al. unpublished), trees burned earlier in the summer were found to be more likely to die than those burning later, which could be explained by seasonal variations in plant phenology. In spite of contradictory reports in the literature, several studies showed that plants are more vulnerable to fire damage when they are flowering or actively growing

(DeBano et al. 1998). Although cork oak is an evergreen species, the main growing and flowering periods occurs during spring and early summer, with the maximum stomatal conductance and transpiration rates occurring from March to June (Oliveira et al. 1992). Thus, the tree carbohydrate reserves are expected to be at a low level during this period, and the actively growing tissues are more susceptible to heat damages, which may increase fire vulnerability.

Previous studies also found that trees located in southern aspects are more vulnerable to fire (Catry et al. 2009; Moreira et al. 2007). In the Mediterranean, south-facing aspects are typically dryer and warmer and have less vegetation cover and a thinner soil layer (Kutiel and Lavee 1999; Sternberg and Shoshany 2001), being also more vulnerable to soil erosion (Marques and Mora 2003). Additionally, some of the more important insects and diseases affecting cork oak have been reported to have higher incidence on south-facing slopes (Du Merle and Attié 1992; Moreira and Martins 2005). All these unfavorable conditions are likely to increase tree stress and consequently increase vulnerability to wildfires.

9.4 Post-Fire Management Issues and Alternatives

Although cork oak is known as a fire-resistant and resilient species, wildfires can cause major economic and ecological impacts on cork oak ecosystems. A particular concern exists if trees are exploited for cork production, which is the situation in most cases.

Usually the first bark harvest occurs when tree d.b.h. reaches 19–22 cm (20–40 years old), with subsequent yields at 9–15 year intervals, meaning that a tree can be stripped about 12–20 times during its productive lifetime (150–200 years, although cork oak can live up to 500 years; Natividade 1950; Pereira 2007). The risk of fire damage in exploited trees is at its highest level just after bark harvesting and then it will decrease with time until cork reaches about 3–4 cm thick (see Sect. 9.3), which usually occur at the end of the stripping cycle. This means that most of the time trees face a considerable risk from wildfires, and managers should be aware of it.

9.4.1 Defining Management Objectives

After fire, it is important to define the management objectives and to plan the restoration actions accordingly. In general, the most common objective for burned cork oak stands is to restore cork production as soon as possible.

The post-fire management alternatives in cork oak forests will largely depend on fire severity, thus a multidisciplinary damage assessment should be performed first to identify the direct and indirect economic and ecological impacts and risks (see also Chaps. 1 and 5).

After a wildfire, a strong negative economic impact is expected, both because the charred bark looses its value and productivity decreases. The minimum time required to start extracting good quality cork again (i.e. cork that can be used for stoppers) will be about 40 years for trees that died and need to be replaced, 30 years for the surviving trees with stem mortality, and 10 years for trees with good crown regeneration. At the ecosystem level the more common ecological consequences of fire include factors such as: decrease of tree cover and vigor, decrease acorn production reducing the regeneration potential and food for livestock and wildlife, decrease carbon, nutrients and water retention, and increase soil erosion risk. All these economic and ecological issues should be considered when defining the post-fire management objectives and evaluating the possible alternatives to achieve them.

After the evaluation of the fire impacts and associated risks, the burned area can be divided into units or blocks with homogeneous characteristics. Then, the prescriptions for each management unit should take into account the urgency, resource value, and success possibilities.

9.4.2 Current Post-Fire Management Practices

Management practices in burned cork oak forests can be quite variable from one region to another, depending on managers' objectives and perception of fire impacts, and on available funds. Here we briefly present some of the more common practices.

Usually the decision to cut or not cork oak trees after fire is mostly dependent on field assessments of fire severity and on the cork age. Burned trees with younger (thinner) cork bark (i.e. < 4 years old) or having severe inner bark damages are not expected to recover the crown and are logged, while trees with thicker cork in most cases are left to regenerate.

When trees are not expected to show adequate post-fire crown recover, and in order to make use of their basal sprouting capacity, the official recommendations (in Portugal; DGRF 2006) are that younger trees (less than 40 years, or perimeter at breast height less than 90 cm) should be cut as soon as possible, preferably before the next growing period (i.e. end of following winter) to increase resprouting vigor. Actions to manage basal sprouts include shoot selection, clearing of shrub or herbaceous vegetation, and avoiding animal browsing. Older trees (over 60 years) are assumed not to originate economically interesting resprouts, and are often uprooted and replaced by new trees (seeding or planting). In both natural and artificial regeneration, thinning and shoot selection are usually carried out.

The cut material is either removed from the site, or logs and branches are left on the ground. In some cases, groups of trees or individuals that are less damaged and that can contribute to post-fire regeneration are maintained.

The decision to plant or seed after fire is mainly based on the existence of financial incentives (and market value), and occurrence of scarce post-fire natural regeneration. Active seeding or planting are also both carried out to increase tree density, usually in the period of 1–3 years after fire.

In Portugal and Spain, there are several legal issues related to the post-fire management of burned cork oak stands. First of all, the species is protected by law, thus official permission is needed to cut trees and the land cover cannot be changed after fire. Secondly, the cork of trees with d.b.h. smaller than 19–22 cm cannot be extracted. Thirdly, although cork cannot be extracted before 9 years after the previous extraction, some exceptions are allowed, including the case of burned trees (see Sect. 9.4.6).

9.4.3 Tree Logging

Cork oak trees that died or suffered stem mortality as a consequence of fire can be logged (after getting a permit). In some cases trees showing poor crown regeneration, and particularly those with severe stem damages, can also be logged (Fig. 9.7; see also Sect. 9.5.1).

From a silvicultural point of view, the most interesting cuttings are those aimed to take advantage of the remarkable resprouting capability of cork oaks. Sprouts originating from dormant buds at or near the base of severely damaged trees can be used to regenerate forest stands (see Sect. 9.4.4). The snag reduces sprouting energy and provokes the leaning of sprouts (Barberies et al. 2003). Dormant buds from stumps near or under the soil surface have better chances to survive than buds located higher in a rotting trunk; therefore *liberation cuttings* should be done as soon as possible after fire and lower as possible in the trunk (Cardillo et al. 2007). Trunk cuttings should be made horizontally or slightly inclined, leaving a smooth surface (DGRF 2006).

Sometimes cuttings can also be done for sanitary reasons. Burned cork oaks are exposed to the attack of pests such as ambrosia beetles *Platypus cilindrus* and *Xyleborus monographus* (see Sect. 9.4.8). Rarely the presence of these wood borers is a threat to the nearest forest stands but if their populations increase to outbreak proportions, sanitary cuttings and burning are recommended (Sousa and Inácio 2005). Logging can also be needed for security reasons; trees with seriously damaged trunks located close to buildings and roads can be wind thrown, thus selective cutting should be allowed. In some cases, and depending on management objectives, dead trees can also be left standing or the wood can remain in the ground to increase biodiversity.

Usually the wood from coppiced cork oaks can be only used as firewood or good quality charcoal; thus a market for this wood exists, particularly in the forests near charcoal kilns. In this case salvage logging, with subsequent debarking, is possible. Otherwise cuttings are a net expense and only can be thought as a silvicultural treatment.

Fig. 9.7 Post-fire cork oak management: selective logging of most severely damaged trees (*left*), and shrub clearing 20 years after fire (*right*) avoiding soil ploughing (Extremadura, Spain) (Photos: F. Catry)

9.4.4 Assisting Natural Regeneration

In most cases, if trees were not recently debarked before the fire, burned cork oaks will show vegetative regeneration (i.e. resprouting; Fig. 9.8). When crown resprouts homogeneously, usually no interventions are required. Otherwise, if crown regeneration is absent or is very poor, basal sprouts are a viable way to regenerate cork oak stands, and this method is considerably faster, more effective and cheaper than seeding or planting (see Sect. 9.4.5). Stool sprouts and root sprouts are not frequent in cork oak but they have not silvicultural value since they originate from adventitious buds (Johnson et al. 2009).

A few years after cutting many sprouts have often crowded the stump and begin competing each other, thus thinning is highly recommended (see Chap. 8). One to three of the most vigorous sprouts per stump could be retained depending on stump diameter. Sufficiently spaced trunks (at least 40 cm) could be debarked easily in the future (Cardillo et al. 2007). Sprouts well inserted into the stump below soil surface are best joined to roots and should be preferred instead of those attached to higher parts of stump and exposed to rot. Early pruning is not recommended because sprout canopy helps to control excessive undesirable resprouting (Johnson et al. 2009).

Natural regeneration from seeds is much less common because acorns and flowers are destroyed by fire in most cases, and even if the crowns survive, trees will take at least 2 or 3 years to produce acorns again. The habitual year to year and tree to tree variations in acorn production, the activity of seed-dispersal agents and the action of herbivores and drought over seedlings, are the main factors affecting regeneration from seeds. In addition, seedlings usually need many years to establish and develop. The shelterwood method provides light, shelter and more recruitment while acorn and cork production are in part conserved.

Exclusion from livestock and other herbivores may be required to minimize the negative impacts on natural regeneration (see Sect. 9.4.7). Latter thinning, seeding or planting can also be needed in case of uneven spatial regeneration.

Fig. 9.8 Cork oak forests post-fire natural regeneration: 16 months after fire (*above*; Algarve, south Portugal) and about 20 years after fire (*below*; Extremadura, west Spain) (Photos: F. Catry)

9.4.5 Seeding and Planting

Before planning reforestation actions in burned cork oak stands the presence of natural regeneration should be checked carefully. However, when natural regeneration is not enough to achieve the objectives (in terms of the desired tree density), reforestation by direct seeding or planting is an alternative. The main limitations when using these techniques are the availability of quality seeds, acorn or seedling predation, and summer drought.

Sometimes the number of acorns is not enough because of insufficient production or excessive predation. Mice are efficient in detecting and consuming acorns (although they can also act as short-distance dispersers especially in mast years; Pons and Pausas 2007). Sowing tests can be done in order to evaluate their presence and, if they are present, acorns can be protected with small tree shelters. Wild boars (*Sus scrofa*) are frequent in forested areas and they are able to consume large quantities of acorns. In this case shelters are not effective in protecting acorns against them, but well maintained electric fences can be very effective in relatively small areas. Large herbivores can also exert a negative impact on seedlings, thus protective measures should be taken when they are present (see Sect. 9.4.7).

Seeding season is also a very important issue. On one hand, early seeding in autumn will expose acorns to predation during winter, when food supply in the burned area is reduced, thus, higher success rates can be achieved if seeding is performed in the early spring, after recovery of grasses and shrubs. On the other hand, the summer drought is the main cause of seedling mortality in Mediterranean forests (Cortina et al. 2009), thus the earlier the seedlings reach the soil water table, the higher is the chance of survival. In summary, if the predation and frost risk are low, seeding should be done in autumn and winter; otherwise it is better to perform it in spring, as early as the temperatures begin to stimulate growth and frost risk is minimal. If the objective is to perform seeding in spring, acorns need to be preserved under controlled conditions because they germinate easily during winter. Acorn moisture must be reduced to 45–50% and the seeds stored in a dry and cold place. Moisture should be monitored because a decrease under 35–40% is lethal. Immediately before seeding the acorns should be rehydrated sinking them in water during 24 h. Those floating, light brown colored, with holes or wrinkles should be discarded.

Plantation is another option to reforest burned stands, although it is more expensive and disturbing than seeding. It should be initiated as soon as possible (first autumn or winter after fire) in order to avoid competition with the regenerating vegetation. Soil mobilization should be performed in a way to avoid erosion. Snags can be an obstacle to machinery movement and careless logging or site preparation can increase dramatically erosion rates in slopes. Site preparation should take into account the effects of mechanical operations over remaining root systems of sprouting species, the soil seed bank and the presence of hydrophobic soil layers. For example, subsoiling, a common method used in cork oak reforestation, is a very effective preparation work that improves water infiltration. However it should not be used if significant number of stumps can still sprout; in this case soil preparation in small spots is better. If a young plantation existed in the area before the fire, the shelters should be rapidly removed (and eventually replaced) since they usually melt, physically preventing emergence of seedlings sprouts, that are often vigorous.

As for seeding, one of the most critical issues in plantations (besides herbivory) is the low seedling survival during the summer drought period. A crucial step in restoration projects in the Mediterranean is thus achieving seedling survival during the first growing season. For example, some studies (Mousain et al. 2009) showed that ectomycorrhizal fungi improve water (and mineral) absorption when its availability is reduced, thus inoculation is one of the possible methods helping seedlings to survive long-term drought.

Restoration based on artificial regeneration is a long-term investment, thus different issues and alternatives should be carefully considered from the first stages. Several important aspects such as use of suitable genetic material, nursery cultivation regimes, sowing date, type of container, growing substrate, watering and fertilization, will largely determine the success of reforestation programs in the long-term (see Almeida et al. 2009 for more details). Additionally, several techniques can also be used in the field to improve cork oak seedlings establishment (see Cortina et al. 2009).

9.4.6 Cork Harvesting and Branch Pruning

Cork oaks with post-fire stem survival usually have energy reserves (mainly in the form of carbohydrates) to restore the crown foliage and to heal wounds. However certain stressing silvicultural practices such as cork harvesting and branch pruning, particularly when performed during the years immediately after the fire, will originate new energy demands, resulting in situations of great weakness. Additionally, pests and diseases may take advantage of this weakness and open wounds to attack trees causing more damages (see Sect. 9.4.8).

One of the most controversial issues in relation to cork oak trees affected by fire (when at least part of the crown survives) is related to the time at which the first post-fire cork harvesting should be performed. The charred cork is not useful to make stoppers with enological quality. This product is only useful as composition cork for insulation and it is sold at prices under harvest costs. Therefore managers are usually interested in debarking trees as soon as possible to initiate a new and clean cork production. However debarking too early after fire is not always suitable for tree health or owner economy. Some trees have burns under the cork cracks and need time to healing. Debarking can cause bigger wounds and slow the healing process. Moreover, charred bark offers less resistance to axe penetration, thus more wounds can occur. This causes early stripping to be more expensive than an ordinary debarking operation because workers have to progress slowly, suffering discomfort due to cinder and soot. Finally, and more important, less vigorous trees will produce less cork, representing lower incomes in the medium to long term.

In general, the factors determining the decision about the time to start debarking again should be the cork age (thickness) when the fire occurred, the fire severity, and the tree vigor (e.g. Cardillo et al. 2007). The existing legislation do not clearly defines what can (or cannot) be done. In Portugal, the world leading country in terms of cork production, cork harvesting is not usually allowed until cork is at least 9 years old, but there are a few exceptions (subjected to authorization) including the harvest of burned cork after verification of tree recovery. However the law has no reference to what is meant by recovery, thus the decision can be quite subjective. A recent publication (Portuguese Forest Services, DGRF 2006) recommends that cork stripping should only be performed on trees having at least 75% of the crown covered with foliage, but still, doubts may arise and in several cases this probably will not be enough to guarantee tree recovery. In Spain the IPROCOR (Instituto del Corcho, la Madera y el Carbón Vegetal) have more conservative, explicit and easy to follow guidelines, recommending that managers should wait a minimum of 2–3 years, until the crown has recovered 75% of its pre-fire volume and the cork is at least 2 cm thick.

When the cork is thinner than 2 cm, the odds of producing wounds on inner bark during the harvest increases significantly (Cardillo et al. 2007). Cork stripping should be done early in the season and conservatively, leaving the trees where cork does not detach easily, or reducing the cork harvest height. Another option is to wait until the trees develop a complete layer of cork suitable to stopper production under the charred layer. In this case lower growth rates and lower prices can be obtained but this can be better than waiting less years but debarking without revenues. It is difficult to know what choice is economically the best, but a harvesting delay of a few years for trees slightly damaged and a full technological rotation period for trees with damages of medium severity could be recommended.

Concerning tree pruning (of live branches) there are no specific post-fire regulations, but this should also be avoided during the first years. In a study in Sardinia (Italy) on the post-fire recovery of exploited cork oaks (Barberis et al. 2003), the percentage of viable trees among those that were pruned a few months after fire ranged from 20% to 28% (older and younger trees, respectively), while in not pruned trees (control group) the percentage of viable plants was two to four times higher (about 62% and 82%, respectively).

In fact, both cork harvesting and pruning are known to be stressing activities for trees, thus the law (regardless of fire) establishes a minimum period of time between these two operations (3 years in Spain and 2 years in Portugal), in order to enable tree recovery (e.g. Cardillo et al. 2007). Given that fires often causes crown defoliation and wounds, at least as severe as those caused by pruning, it would be prudent to establish a minimum time interval between fire and subsequent cork harvest or pruning, which should be at least 2 or 3 years.

9.4.7 Protection Against Herbivory

The presence of large wild or domestic herbivores (such as deer, goat, sheep or cattle) may represent a serious factor hindering cork oak regeneration after fire (also regardless of fire). In adult stands where all trees have crown regeneration, the presence of these herbivores is not usually a problem since they will not be able to reach the crown. However, when cork oaks are top-killed, regenerating only from basal sprouts, or when the objective is either to preserve the natural seed regeneration, or to reforest by seeding or planting, the presence of large herbivores in the burned area will likely constitute a serious problem (unless their densities are very low) and

Fig. 9.9 Herbivory can negatively affect cork oak regeneration regardless of fire occurrence, but the impacts are likely to be much stronger in a post-fire situation: deer feeding on cork oak crown foliage and acorns (*left*), and individual protection to prevent post-fire deer browsing (*right*). Photos: M. Bugalho (*left*) and F. Catry (*right*)

some protective measures should be taken (Catry et al. 2010b; Whelan 1995; when seeding, other animals such as wild boars and mice can also be a problem because of acorn predation, see Sect. 9.4.5). This can be done by reducing the number of animals during the first years after fire or, more often, by protecting the plants. The reduction of animal densities to levels that are compatible with plant regeneration could be a good solution; however this may not be feasible or compatible with the area management objectives, and in that case other solutions, such as the physical protection of plants, must be adopted. This may involve fencing of large areas or individual plant protection during time periods that allow the regeneration and re-establishment of vegetation (Fig. 9.9).

The protection of individual trees is adopted in many countries (regardless of fire occurrence), when animals have access to regeneration areas or plantations. Various types of protections of variable prices and efficiency are available. The most common approach is to protect each tree with a protective cylindrical-shaped wire mesh shelter. To adequately fulfill its objective the wire mesh must be sufficiently strong and inelastic, and in areas where red deer (*Cervus elaphus*) are present the protection must be at least 2 m tall (preferably 2.5 m; Catry et al. 2007). Another possible protection method involves the application of chemical repellant but in most cases its effectiveness is short-lived or is still unproved.

Fencing parts of the area to regenerate may be also a good option. Generally for larger areas and higher tree density, this technique is cheaper than the protection of individual plants. Possible disadvantages of this option are the limited access to the area and higher fuel accumulation that may increase fire danger. However, if the fenced area is not very extensive and the surrounding areas have low fuel accumulation, the fire danger is reduced and these areas may act as important refuges for many animal species. Temporary protection by electric fencing is also possible, but it is most suitable for the domestic species or open woodlands, being ill adapted to forest environments where dense vegetation is present (Bonnet and Klein 1966).

9.4.8 Pests and Diseases

Cork oaks can be affected by pests and diseases in various ways and at all stages of their lives. Several insect species and microbial pathogens can negatively affect cork oak, from seeds and seedlings to mature trees. At moderate to high levels of incidence, they may increase mortality and reduce tree vigor, threatening the sustainability of cork oak forests (Branco and Ramos 2009).

Wood-boring insects affect primarily trees that are weakened or decaying, thus their economic impact is usually minor. However in favorable circumstances some species may become major pests. Three main groups of bark- and wood-boring insects are associated with cork oak trees: ambrosia beetles (especially *Platypus cylindrus*), two buprestids of the genus *Coroebus*, and longhorn beetles (*Cerambix cerdo*, *C. welensii*, and *Prinobius* spp.). The longhorn beetles are xylophagous species whose immature stages develop inside the trunks of decaying trees, but despite being secondary pests, *Cerambix* spp. (particularly *C. cerdo*) are associated with oak decline and are able to induce tree death (Martín et al. 2005; Branco and Ramos 2009). Tree weakening caused by increasing aridity in Mediterranean areas benefits *C. cerdo* and several other xylophagous pests. Damages caused by inappropriate cork harvesting or pruning may be a prime cause of the increase in holes made by *C. cerdo* which acts as entryways for fungal infection by *Biscogniauxia mediterranea* (Martín et al. 2005).

Moths (namely *Lymantria dispar*, *Malacosoma neustria*, *Euproctis chrysorrhoea*, and *Tortrix viridiana*) are the most important cork oak defoliators throughout the Mediterranean (Luciano et al. 2005). Severe cork oak defoliations reduce acorn production, stem diameter growth, and cork growth. Cork quantity, quality and cork stripping are also affected in subsequent years. Like for bark- and wood-boring insects, the attacks of defoliators are likely to be more severe on weakened trees. For example Luciano and Roversi (2001) suggested that infestations by *L. dispar* can occur more frequently in declining cork oak stands, such those subjected to overgrazing in Sardinia.

Among the cork oak diseases, cork oak cancer (causal agent *Botryosphaeria stevensii*), charcoal disease (causal agent *B. mediterranea*), and root diseases caused by *Armillaria mellea* and *Phytophthora cinnamomi*, are the four main fungal diseases of cork oak stands (Robin et al. 2001; Branco and Ramos 2009). *P. cinnamomi* has been regarded as the principal cause of cork oak mortality in Portugal and southern Spain (Brasier 1996; Moreira and Martins 2005). Stress and trunk wounds are the main predisposing factors for both cancer and charcoal diseases; therefore, the best control for these diseases lies in proper management practices to improve tree vigor and prevent trunk injuries (Branco and Ramos 2009).

Although the effects of wildfires on insect and diseases dynamics in cork oak forests is poorly known, the existing information suggests that the weakened status of burned trees will predispose them to suffer more severe attacks. On the other hand, fire may drastically impact herbivore arthropod populations directly by altering habitat, abundance, and species composition, or indirectly via cascading effects caused by alterations in food quality and availability (Rieske et al. 2002). Indirect effects of fire on herbivory may manifest themselves through plant growth and changes in foliar chemistry by increasing nutrient concentrations in the soil (Roth et al. 1994). Defensive phenolic compounds may also be affected by the increase in soil nutrients (Hunter and Schultz 1995) or increased sunlight (Dudt and Shure 1994). This is particularly relevant to defoliators such as *L. dispar*, which is responsive to enhanced nutritional substrate and alterations in defensive phenolic compounds (Roth et al. 1994).

9.4.9 Climate Change

Cork oak is adapted to highly variable climatic conditions (both between and within years). However, since the 1970s the frequency of droughts in the Mediterranean has increased significantly, and a long-term process of aridification seems to be under way as a part of the generalized trend of global warming (Pereira et al. 2009). Climate change scenarios suggest an aggravation of environmental conditions for cork oak in the Mediterranean, namely through increasing temperatures and decreasing precipitation (Giannakopoulos et al. 2009; Pausas 2004; Pereira et al. 2009). In general these factors are likely to increase the severity of plant water stress and increase the rate of nutrient losses from the soil (Pereira et al. 2009). More frequent and longer term droughts may negatively affect cork oak ecosystems in the future, by decreasing tree health and increasing the conditions conductive to the spread of some pests and diseases. For example one of the main cork oak diseases (*Phytophthora cinnamomi*) can be widely extended in the next decades due to climate change (Bergot et al. 2004).

Additionally, climate change is also expected to affect the current fire regimes in many regions, including the Mediterranean, by extending the fire season and increasing fire danger (Flannigan et al. 2009; Pausas 2004; Westerling et al. 2006). Wildfires are already a serious concern in the Mediterranean Basin burning nearly half million hectares every year, and most of this area (~87%) concerns the western Mediterranean countries where cork oak occurs (FAO 2006). In Portugal, the world leading country in terms of cork oak area and cork production, wildfires affected 15–20% of the cork oak area since 1990.

Thus, improving fire prevention and restoration techniques, throughout clearly defining the objectives, promoting natural regeneration to allow genetic variability and the possible selection of drought-tolerant genotypes, could increase the ability of cork oak forests to cope with climate change (Pereira et al. 2009).

9.4.10 Preventive Actions to Reduce Fire Damage

Several alternative or complementary actions can be taken in order to reduce the risk of fire damage in cork oak stands. Surface fuel reduction below and around the trees (just before debarking, i.e. every 9–15 years) could be an effective preventive action to avoid severe fires (this should be performed without soil ploughing or just with superficial tillage, in order to prevent tree root damages; Fig. 9.7).

On the other hand, the management of the cork harvesting activities could also decrease the risk of fire damages. Striping wounds are common in exploited cork oaks and they significantly reduce tree vigor and its ability to resist wildfires (Costa et al. 2004; Catry et al. unpublished). Reducing wounding (by employing skilled workers or by using automatic equipment for harvesting) could significantly increase tree resistance to fire. Other measures could include debarking trees of a given stand in different years (reducing the overall risk), increasing the debarking cycle (not necessarily meaning lower economic incomes; Natividade 1950) or decreasing the stripped surface.

Since cork is still the main economical income from these forests, stopping bark exploitation is not a realistic possibility. However, in fire-prone areas where conservation is the main objective, this would probably be the more effective option to increase ecosystem resilience (Fig. 9.10). The valorization of many other services provided by cork oak ecosystems (Bugalho et al. 2011) could create the economic incentives necessary to maintain these systems less dependent on bark exploitation.

9.5 Case Studies

9.5.1 Predicting Post-Fire Crown Recovery of Exploited Cork Oak Trees in Serra do Caldeirão (Algarve, Southern Portugal)

9.5.1.1 The Wildfire

The study area is located in "Serra do Caldeirão", a mountain area in the Algarve region, southern Portugal. The climate is Mediterranean, with mean annual temperature of 16.6°C and mean annual rainfall of 900 mm. Altitude ranges from 150 to 570 m and soil type consists mainly of shallow schist lithosols. The landscape is characterized by cork oak forests with varying tree cover, with an understory of *Arbutus unedo*, *Cistus* spp., *Ulex* spp., and *Erica* spp. Other vegetation types include shrublands dominated by *Cistus ladanifer*, and scattered stands of maritime pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus globulus*), sometimes mixed with cork oak stands. In July 2004 a large wildfire burned about 25,000 ha in this region.

Fig. 9.10 Cork oak showing very good crown recovery only 3 years after wildfire and following complete defoliation (Mafra, Portugal). Trees in this area were not debarked for about 30 years and had a thick bark (Photo: F. Catry)

9.5.1.2 Objectives

One major decision that managers face after wildfires is whether the burned cork oak trees should be coppiced or not and when. Several authors mentioned that trunk coppicing is a good option when trees have serious stem damages that compromise future cork production, and when the crown regeneration is predicted to be nil or very weak (Pampiro et al. 1992; Cardillo and Bernal 2003, Barberies et al. 2003; DGRF 2006). One possible advantage of early coppicing is that it can promote the regeneration from basal sprouts, along with reducing mortality and speeding up the recovery on much damaged trees (Barberis et al. 2003). But, on the other hand, by cutting soon after fire, there is the risk of cutting trees that could show good crown recovery in the future, and cutting a tree implies waiting at least 30 years to start debarking good quality cork again.

The aim of this scientific study was to evaluate whether it is possible to identify, immediately after fire, trees that will likely show good or poor crown recover in the future. For this purpose, models were developed aiming to constitute decision-support tools helping managers to identify trees that will likely recover well, and trees that will likely die or show poor crown regeneration (and thus, potential candidates for trunk coppicing).

9.5.1.3 Methods

One and a half years after the fire, 858 trees being exploited for cork production (these trees represent the more common tree type in cork oak stands and constitute the main concern of managers because of their economic value) were sampled in a total of 40 plots spread across the burned area. Each tree was classified as having poor crown regeneration if regeneration appeared in <50% of the main branches or if it was much localized (also including trees which only resprouted from basal buds or dead trees). On the other hand trees were classified as having good crown regeneration if more than 75% of the main branches in the crown showed a homogeneously distributed regeneration. Trees with an intermediate regeneration state were not assigned to any of the previous groups.

Along with regeneration status, each tree was classified as a function of topographic variables (aspect and slope) of the plot where it was located, the amount of shrub and tree cover at the time of fire (based on aerial photos and burned remains in the field), tree size (height and d.b.h.), bark thickness and bark age (since last stripping), and minimum char height (an indicator of fire damage) expressed as proportion of tree height.

Logistic regression was used to explore which variables had a significant influence on good or poor post-fire crown regeneration in exploited cork oak trees. Different models were built, using original variables and simpler variables that can be easily assessed by forest managers.

9.5.1.4 Results

One-and-a-half years after fire occurrence, 31% of all trees presented a nil or poor crown regeneration (i.e. low probability of maintaining an economic interest in the near future), and 37% presented good crown regeneration, while the remaining 32% presented an intermediate state. The trees which were considered with poor crown regeneration included dead trees (18% of the total).

Bark thickness (and, therefore, cork age) was the most important variable affecting crown regeneration (better regeneration for increasing bark thickness). Char height and aspect (lower probability of good regeneration in drier southern slopes) were also significant variables influencing crown regeneration. Finally, larger trees were more likely to show poor crown regeneration (Fig. 9.11).

The probabilities obtained from the application of the two management models (to predict poor and good crown regeneration) to a given tree are negatively correlated as expected, meaning a decreasing probability of poor crown regeneration as the probability of good crown regeneration increased ($r = -0.874$; $P < 0.001$).

The obtained management models provide an easy way of getting an estimate of crown regeneration probability from only four variables that can be easily measured in the field immediately after a wildfire. More details of this study can be seen on Catry et al. (2009).

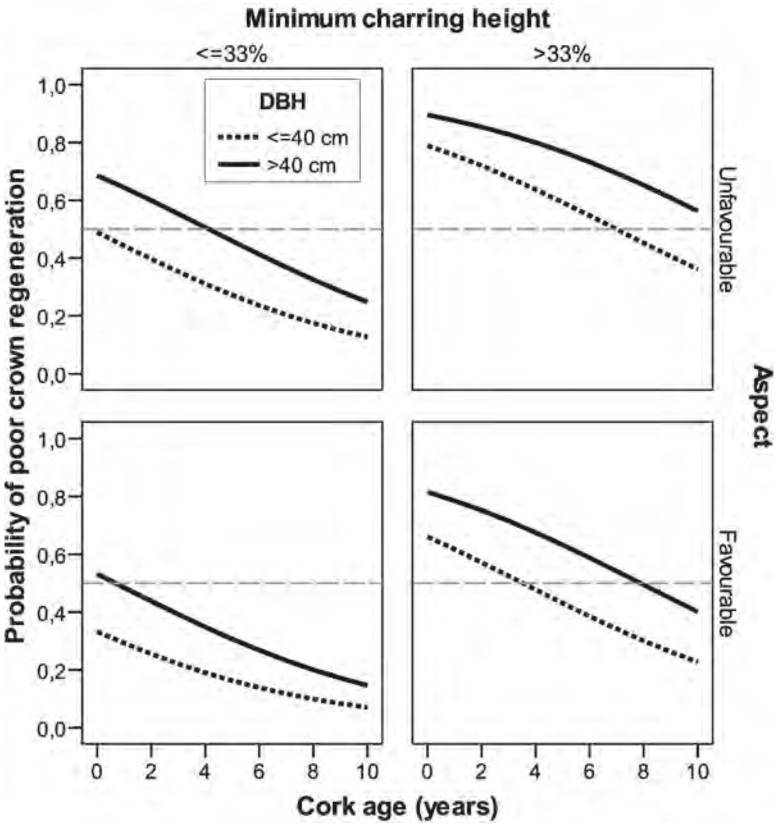

Fig. 9.11 Logistic model prediction of poor crown regeneration in cork oak, 1.5 years after a wildfire. Different combinations of minimum charring height (larger or smaller than one-third of tree height), aspect (favorable vs. unfavorable), cork age when the fire occurred (in years), and d.b.h. (larger or smaller than 40 cm) are shown. The 50% probability line is also shown for each graph. (Reproduced from Catry et al. 2009)

9.5.2 Post-Fire Management of Cork Oak Woodlands in Sierra de San Pedro (Extremadura, West Spain)

9.5.2.1 The Wildfire

In early August 2003 during a dry thunderstorm dozens of lightning discharged upon the cork oak forests in the southern foothills of Sierra de San Pedro in the centre of Extremadura in western Spain, causing a large wildfire (more than 1,000 ha). *Coto de Santa Eulalia* is a private forest farm situated in a southern slope of these hills, with an uneven aged forest of cork oaks dedicated to cork production and hunting.

Before the fire, there were three different landscapes in the farm: in the sierra slopes a dense shrubland with scattered trees called locally *mancha*; in the foothill cork oak savanna-like woodland *dehesa*; and connecting both a narrow forest ecosystem of hardwoods and an orchard of fruit-trees associated to a small seasonal stream. At time of fire, fuels were very dry because they suffered a heat wave during the previous week with temperatures over 30ºC. Therefore a very intense fire (with flames more than 20 m high) developed in the *mancha* stands. In the *dehesa* and stream areas the tall grass led to a medium intensity fire moving very fast. Nine months after the fire a diagnostic and restoration plan was carried out by the farm owner and a local forest research centre (IPROCOR).

9.5.2.2 Objectives of the Management Applied

The main objectives of restoration plan were: (1) Avoid soil erosion and water quality degradation, (2) Reach the normal level of cork production as soon as possible, and (3) Maintain hunting activities where possible.

To achieve the objectives the following activities were carried out:

1. In the sierra slopes, 1 year old cork oaks seedlings were planted in a furrow opened with a winged subsoiler by contour level. Sprouting vegetation was not disturbed between rows and in the area near of root systems of resprouting oaks;
2. Fences in the sierra slopes stands were repaired and strengthened to avoid game browsing over sprouts and seedlings;
3. In rolling or flat areas, acorns were seeded in small furrows (just to remove soil impervious layer and grass seeds in a narrow band). Tube shelters were used to protect seeds from mice predation (detected in previous seeding tests);
4. Dead stems were logged to improve growth and avoid leaning of stump sprouts. Two year later sprouts clumps were thinned to leave one or two vigorous stems per stump. Logs were used as erosion barriers in specific sites;
5. Deciduous broadleaved trees (*Fraxinus angustifolia* and *Celtis australis*) were planted along the stream. Small trees and bushes of the less fire resistant species were planted in a few small plots in order to help their future recovery in the farm.

9.5.2.3 Results

All mature cork oaks in the farm were debarked 1 year before the fire. All trees lost their crowns (stem mortality), and saplings, bushes and grasses disappeared. The soil became impermeable and was covered with a thick layer of ashes. Despite the fact that soils of stepper slopes were subsoiled (with help of local government funds), the ashes and fine soil particles begun to be drawn by the first winter showers and to accumulate in ponds and water lines.

The main conclusions of the post-fire diagnostic (9 months after fire) were:

1. All mature cork oak trees were top-killed, but trees with a diameter less than 50 cm could resprout from stumps vigorously (larger trees died). Tree and shrub species more adapted to wet conditions (those located along the stream) were eliminated;
2. Cork production was totally lost and this lack will last during next 20 years. After that some cork might be harvested from stump sprouts, but pre-fire production level will not be reached before 40 years;
3. Grasses were recovering successfully in gently slopes and bushes were sprouting or germinating from seed bank and covering the soil again moderately (~40%);
4. Game that escaped to nearest forests after fire come back to browse over plants regeneration;
5. The water ponds were filled with ashes and soil particles. Evident signs of erosion could be seen in the stepper slopes.

Today (2011; nearly 8 years after fire) most of the burned area has the same shrub cover existing before the fire. Shrub canopies have reached 2 m height and no new erosion signs are visible. Some log barriers have 5 cm of soil accumulation upslope but wood is rot and very decomposed. Reforestation was more successful at low areas than in the sierra but an average of 400 trees/ha are growing today. Nevertheless no more than 20 trees/ha are obtained from stump sprout (pre-fire mean density was about 45 trees/ha).

9.6 Key Messages

- Cork oak forests and woodlands constitute very important ecosystems providing a large number of socio-economic and ecological services. Thanks to its insulating bark (cork), cork oak trees have a remarkable fire-resistance and resilience, being one of the few tree species in Europe with the ability of crown resprouting after severe fires. This extraordinary resprouting capacity makes the cork oak a very good candidate for reforestation programs in fire-prone areas;
- In spite of remarkable cork oak ability to cope with fire, the periodical bark harvesting activity makes exploited trees much vulnerable to wildfires. Thus, fire risk should be taken into account by managers;
- Several alternative or complementary actions can be taken in order to reduce potential damage from wildfires in cork oak stands. Surface fuel reduction and the management of the cork harvesting activities (not debarking all trees in the same year, reducing wounding, increasing the debarking cycle) could significantly decrease the risk of fire damages;
- Management actions such as cork harvesting or pruning are not advisable at least during the first 2 or 3 years after the wildfire. Depending on factors such as fire severity, crown recovery and bark thickness, managers can decide the time to act, but in general we recommend that cork should be at least 2 cm thick and more than 75% of the pre-fire crown volume should be recovered;

- Restoration of burned areas using artificial regeneration (direct seeding or planting) is usually more expensive, slower and less successful than using natural regeneration of vegetative origin (sprouts);
- Domestic and wild animals (herbivores or omnivores such as goats, sheep, deer, wild boar) can compromise the restoration success of burned cork oak forests, by consuming acorns, seedlings, and resprouts, thus protective measures usually need be adopted when they are present in the areas to recover (unless their densities are very low).

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References

Almeida MH et al (2009) Germplasm selection and nursery techniques. In: Aronson J, Pereira JS, Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and restoration. Island Press, Washington, DC

APCOR (2009) APCOR yearbook 2009. Associação Portuguesa de Cortiça, http://www.realcork.org/userfiles/File/Publicacoes/AnuarioAPCOR2009.pdf. Accessed 10 April 2011

Barberis A, Dettori S, Filigheddu MR (2003) Management problems in Mediterranean cork oak forests: post-fire recovery. J Arid Environ 54:565–569

Bergot M, Cloppet E, Pérarnaud V, Déqué M, Desprez-Loustau ML (2004) Simulation of potential range expansion of oak disease caused by Phytophthora cinnamomi under climate change. Glob Change Biol 10:1539–1552

Bernal C (1999) Guia de las plantas del alcornocal. Dpto. Recursos Naturales Renovables, Instituto CMC, Junta de Extremadura. Artes Gráficas Boysu, s.l., Mérida

Bonnet G, Klein F (1966) Le cerf. Société Géologique de France, Paris

Branco M, Ramos P (2009) Coping with pests and diseases. In: Aronson J, Pereira JS, Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and restoration. Island Press, Washington, DC

Brasier CM (1996) Phytophthora cinnamomi and oak decline in southern Europe. Environmental constraints including climate change. Ann Sci For 53(2/3):347–358

Bugalho MN, Caldeira MC, Pereira JS, Aronson J, Pausas JG (2011) Human-shaped cork oak savannas require human use to sustain biodiversity and ecosystem services. Front Ecol Envir 9:278–286

Cardillo E, Bernal C (2003) Recomendaciones selvícolas para alcornocales afectados por el Fuego. Cuadernos Forestales 1/2003. Instituto del Corcho, la Madera y el Carbón. Junta de Extremadura, Mérida

Cardillo E, Bernal C, Encinas M (2007) El alcornocal y el fuego. IPROCOR, Instituto del Corcho, la Madera y el Carbón Vegetal, Mérida

Catry F, Bugalho M, Silva J (2007) Recuperação da floresta após o fogo. O caso da Tapada Nacional de Mafra. Centro de Ecologia Aplicada Prof. Baeta Neves – Instituto Superior de Agronomia, Lisboa

Catry FX, Moreira F, Duarte I, Acácio V (2009) Factors affecting post-fire crown regeneration of cork oak (Quercus suber) trees. Eur J For Res 128:231–240

Catry FX, Rego F, Moreira F, Fernandes PM, Pausas JG (2010a) Post-fire tree mortality in mixed forests of central Portugal. For Ecol Manag 206:1184–1192

Catry FX, Bugalho M, Silva JS, Fernandes P (2010b) Gestão da vegetação pós-fogo. In: Moreira F, Catry FX, Silva JS, Rego F (eds) Ecologia do fogo e gestão de áreas ardidas. ISA Press, Lisboa, pp 289–327

Correia OA, Oliveira G, Martins-Loução MA, Catarino FM (1992) Effects of bark-stripping on the water relations of Quercus suber L. Sci Gerund 18:195–204

Cortina J, Pérez-Devesa M, Vilagrosa A, Abourouh M, Messaaoudène M, Berrahmouni N, Silva LN, Almeida MH, Khaldi A (2009) Field techniques to improve cork oak establishment. In: Aronson J, Pereira JS, Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and restoration. Island Press, Washington, DC

Costa A, Pereira H, Oliveira A (2004) The effect of cork-stripping damage on diameter growth of Quercus suber L. Forestry 77:1–8

EEC (1992) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Off J Eur Commun L206 (22.7.1992):7–50

Cramp S (ed) (1994) Handbook of the birds of Europe, the middle East, and North Africa. Oxford University Press, Oxford

Curt T, Bertrand R, Borgniet L, Ferrieux T, Marini E (2010) The impact of fire recurrence on populations of Quercus suber in southeastern France. In: Viegas DX (ed) Abstracts of the VI international conference on forest fire research. ADAI/CEIF, University of Coimbra, Portugal, CD Rom 9 pp

DeBano LF, Neary DG, Ffolliott PF (1998) Fire's effects on ecosystems. Wiley, New York

DGRF (2006) Boas práticas de gestão em sobreiro e azinheira. Direcção-Geral dos Recursos Florestais, Lisboa

Du Merle P, Attié M (1992) Coroebus undatus (Coleoptera: Buprestidae) sur chêne liège dans le Sud-Est de la France: estimation des dégâts, relations entre ceux-ci et certains facteurs du milieu. Ann For Sci 49:571–588

Dudt JF, Shure DJ (1994) The influence of light and nutrients on foliar phenolics and insect herbivory. Ecology 75:86–98

EEA (2007) European forest types. Categories and types for sustainable forest management reporting and policy. European Environment Agency (EEA) technical report no 9/2006, 2nd edn, Copenhagen

FAO (2006) Global forest resources assessment 2005 – Report on fires in the Mediterranean Region. Food and Agriculture Organization of the United Nations, Rome

Flannigan MD, Krawchuk MA, Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. Int J Wildland Fire 18:483–507

Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou E, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2 degrees C global warming. Glob Planet Chang 68:209–224

Hunter MD, Schultz JC (1995) Fertilization mitigates chemical induction and herbivore responses within damaged oak trees. Ecology 76:1226–1232

IUCN (2010) IUCN Red list of threatened species. Version 2010.4, www.iucnredlist.org. Accessed 5 March 2011

Johnson PS, Shifley SR, Rogers R (2009) The ecology and silviculture of oaks, 2nd edn. CABI Publishing International, Oxford

Kutiel P, Lavee H (1999) Effect of slope aspect on soil and vegetation properties along an aridity transect. Isr J Plant Sci 47:169–178

Luciano P, Roversi PF (2001) Oak defoliators in Italy. Industria Grafica Poddighe s.r.l, Sassari

Luciano P, Lentini A, Cao OV (2005) La lutte aux lépidoptères défoliateurs des subéraies dans la Province de Sassari. Industria Grafica Poddighe s.r.l, Sassari

Marques MA, Mora E (2003) The influence of aspect on runoff and soil loss in a mediterranean burnt forest (Spain). Catena 19:333–344

Martín J, Cabezas J, Buyolo T, Patón D (2005) The relationship between Cerambyx spp. damage and subsequent Biscogniauxia mediterranum infection on Quercus suber forests. For Ecol Manag 216:166–174

Mendes AMSC, Graça JAR (2009) Cork bottle stoppers and other cork products. In: Aronson J, Pereira JS, Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and restoration. Island Press, Washington, DC

Miller M (2000) Fire autecology. In: Brown JK, Smith JK (eds) Wildland fire in ecosystems: effects of fire on flora. General Technical Report. RMRS-GTR-42-vol 2, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden

Moreira AC, Martins JMS (2005) Influence of site factors on the impact of Phytophthora cinnamomi in cork oak stands in Portugal. For Pathol 35:145–162

Moreira F, Duarte I, Catry F, Acácio V (2007) Cork extraction as a key factor determining post-fire cork oak survival in a mountain region of southern Portugal. For Ecol Manag 253:30–37

Moreira F, Catry F, Duarte I, Acácio V, Silva J (2009) A conceptual model of sprouting responses in relation to fire damage: an example with cork oak (Quercus suber L.) trees in Southern Portugal. Plant Ecol 201:77–85

Mousain D, Boukcim H, Richard F (2009) Mycorrhizal symbiosis and its role in seedling response to drought. In: Aronson J, Pereira JS, Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and restoration. Island Press, Washington, DC

Natividade JV (1950) Subericultura. Ministério da Economia, Direcção Geral dos Serviços Florestais e Aquícolas, Lisboa

Oliveira G, Correia O, Martins Loução M, Catarino FM (1992) Water relations of cork oak (Quercus suber L.) under natural conditions. Vegetatio 100:199–208

Pampiro F, Pintus A, Ruiu PA (1992) Interventi di recupero di una giovane sughereta percorsa da incêndio. In: Instituto de Promoción del Corcho (ed) Simpósio Mediterrâneo sobre Regeneración del Monte Alcornocal, Mérida

Pausas J (1997) Resprouting of Quercus suber in NE Spain after fire. J Veg Sci 8:703–706

Pausas JG (2004) Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean basin). Clim Chang 63:337–350

Pausas JG, Pereira JS, Aronson J (2009) The tree. In: Aronson J, Pereira JS, Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and restoration. Island Press, Washington, DC

Pereira H (2007) Cork: biology, production and uses. Elsevier Publishing, Amsterdam

Pereira P, Fonseca M (2003) Nature vs. nurture: the making of the montado ecosystem. Conserv Ecol 7(3):7

Pereira JS, Correia AV, Joffre R (2009) Facing climate change. In: Aronson J, Pereira JS, Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and restoration. Island Press, Washington, DC

Pons J, Pausas JG (2007) Acorn dispersal estimated by radio-tracking. Oecologia 153:903–911

Rieske LK, Housman HH, Arthur MA (2002) Effects of prescribed fire on canopy foliar chemistry and suitability for an insect herbivore. For Ecol Manag 160:177–187

Robin C, Capron G, Desprez-Loustau ML (2001) Root infection by *Phytophthora cinnamomi* in seedlings of three oak species. Plant Pathol 50:708–716

Roth SK, Lindroth RL, Montgomery ME (1994) Effects of foliar phenolics and ascorbic acid on performance of the gypsy moth (Lymantria dispar). Biochem Syst Ecol 22:341–351

Rundel PW (1973) The relationship between basal fire scars and crown damage in Giant Sequoia. Ecology 54:210–213

Silva JS, Catry F (2006) Forest fires in cork oak (Quercus suber) stands in Portugal. Int J Environ Stud 63:235–257

Sousa E, Inácio ML (2005) New aspects of platypus cylindrus fab. (Coleoptera: Platypodidae) Life history on cork oak stands in Portugal. In: Lieutier F, Ghaioule D (eds) Entomological research in Mediterranean forest ecosystems. INRA Editions, Paris

Sternberg M, Shoshany M (2001) Influence of slope aspect on Mediterranean woody formations: comparison of a semiarid and an arid site in Israel. Ecol Res 16:335–345

Wargo M (1996) Consequences of environmental stress on oak: predisposition to pathogens. Ann For Sci 53:359–368

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier Spring increase western US forest wildfire activity. Science 313:940–943

Whelan RJ (1995) The ecology of fire. Cambridge University Press, New York

WWF (2007) Beyond cork – a wealth of resources for people and nature. World Wide Fund for Nature, Madrid