Chapter 3
Wildfires and landscape dynamics in Portugal: a regional assessment and global implications

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Abstract Wildfire is an important and complex factor that both shapes landscapes and is shaped by landscapes. In this chapter, we discuss some of the factors that have shaped wildfire frequency and size in Portugal from a landscape perspective and describe the expected changes that will result from a combination of the predicted future climate change and socioeconomic changes such as the abandonment of agricultural land. Some landscapes, such as shrublands, are more vulnerable to fire than others, and the frequency and size of wildfires depend in complex ways on the proximity to humans, who provide both the major source of fire ignition (humans are responsible for more than 95 % of all wildfires in Portugal) and the major agent for fire suppression. Based on the results of our analysis in Portugal, we propose some generalizations that are likely to apply to other regions around the world, such as the need to manage and coexist with fire rather than adopting a strategy based exclusively on fire suppression. This will become particularly important in the context of global climate change, which is expected to increase wildfire frequency.

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3.1 Introduction

Portugal is part of the Iberian Peninsula and extends over approximately 89 000 km^2. It is bounded on the west and south by the Atlantic Ocean and on the north and east by Spain but has a Mediterranean climate with several localized variants according to the Köppen classification. There is a wide climatic variation across the country, with average annual precipitation ranging between 500 and 1500 mm. Portugal has an average population density of 121 residents km^{-2}, but in rural districts this decreases to 15 residents km^{-2} (Nunes 2012). Portugal is mainly covered by forests (around 33 % of the total area), followed by agricultural land (around 30 %) and shrublands (around 25 %). More than 80 % of the forest area is dominated by only four species: maritime pine (*Pinus pinaster*), eucalyptus (*Eucalyptus globulus*), cork oak (*Quercus suber*), and holm oak (*Quercus rotundifolia*) (Marques et al. 2011). The shrublands are mostly dominated by species in the Ericaceae, Cistaceae, and Fabaceae.

More than half a million forest fires were registered in official databases from 1980 to 2009. During this period, fires burned around 3.2 million ha, which amounts to around one-third of mainland Portugal. In recent decades, there has been an increase in the number of ignitions, reaching an average of 26 000 per year from 2000 to 2009 (Nunes 2012). According to remotely sensed data covering the period from 1975 to 2007, the area that burned in a single year (including all fires ≥5 ha) ranged from 15 500 ha in 1977 to 440 000 ha in 2003. The largest fire occurred in 2003, extending over about 58 000 ha (Marques et al. 2011). These figures show a very high incidence of fire in Portugal, even in comparison with other areas that have similar climatic and landscape characteristics within the Mediterranean region (San-Miguel and Camia 2009). For this reason, it is not surprising that there have been many studies of the interaction between wildfires and the landscape in Portugal.

Landscape ecology can provide valuable insights into this interaction by examining the relationships between fire, the ecosystems that sustain it, and human activities at different scales. In this chapter, we will characterize and discuss these relationships based on studies from Portugal. This regional perspective of the interaction between fire and landscapes includes a review of our present knowledge of wildfires and a prediction of future trends based on likely scenarios for human activities and climate. In the final sections, we extend our discussion to a more general basis, focusing on the main problems we have discussed and suggesting possible solutions and implications.

3.2 Landscapes and fire ignition

Wildfires are often ignited by a point source, whose location at the time of ignition is commonly not precisely known. However, despite the difficulty of predicting the time and location of this ignition, it is widely recognized that managers must understand the spatial and temporal patterns of fire ignition, since this is an essential element in analyzing and assessing wildfire danger (e.g., Finney 2005).

The primary causes of ignition vary in different parts of the world. Although lightning is the primary cause of fire in several regions (e.g., Rorig and Ferguson 1999), such as the world's boreal forests, most contemporary wildfires are of human origin in other regions, including the most populated areas. Because of the variability among different regions of the world, different studies have reached different conclusions about the primary factors that influence the spatial patterns of fire ignition (e.g., Badia-Perpinyã and Pallares-Barbera 2006, Cardille et al. 2001, Yang et al. 2007).

However, in the Iberian Peninsula, official statistics for both Portugal and Spain indicate that around 97 % of all investigated wildfires were human-caused (DGRF 2006, MMA 2007). Accordingly, most studies in this region have concluded that human-related factors are the most important factors that determine the spatial and temporal patterns of ignition (Catry et al. 2007, Romero-Calcerrada et al. 2008, Vasconcelos et al. 2001, Vega-Garcia et al. 1996).

In Portugal, the number of fire ignitions is high in comparison with other European countries with a similar population density (San-Miguel and Camia 2009). Using a database of fire ignitions, Catry et al. (2009) were able to illustrate the importance of various factors associated with human presence and activity in predicting spatial patterns of fire ignition. They evaluated the importance of population density, proximity to roads, land use, and elevation by comparing the locations of more than 127 000 ignitions between 2001 and 2005 to a random selection of points throughout the country. The comparison of the frequency of the ignition for each class of the factors that they analyzed with a purely random distribution revealed the main factors involved in determining the spatial pattern of ignitions (Fig. 3.1).

The authors concluded that human activities were the primary cause of wildfires because about 60 % of the ignitions were observed in areas with a population density greater than 100 persons km^{-2} (Fig. 3.1a). In addition, around 60 % of the ignitions occurred within 500 m of the nearest road (Fig. 3.1b). Different land uses were also found to be associated with different levels of ignition (Fig. 3.1c). Approximately 25 % of all ignitions occurred in the area classified as interspersed urban–rural. About 60 % of the wildfires started in agricultural areas, possibly because of the traditional practice of burning to eliminate agricultural residues. Elevation was also considered, since the authors hypothesized that burning for the renovation of mountain pastures to improve conditions for livestock and lightning-caused ignitions would both be more common at higher elevations (e.g., Vazquez and Moreno 1998), but this factor was not as significant as the authors expected; the observed ignition frequencies were not significantly different from a random distribution (Fig. 3.1d).

Analyses of the factors associated with ignition sources make it possible to develop predictive spatial models. Most studies have used logistic regression models (Catry et al. 2009, Preisler et al. 2004, Vega-Garcia et al. 1995), but other authors used different approaches, such as artificial neural networks (Chuvieco et al. 2003,

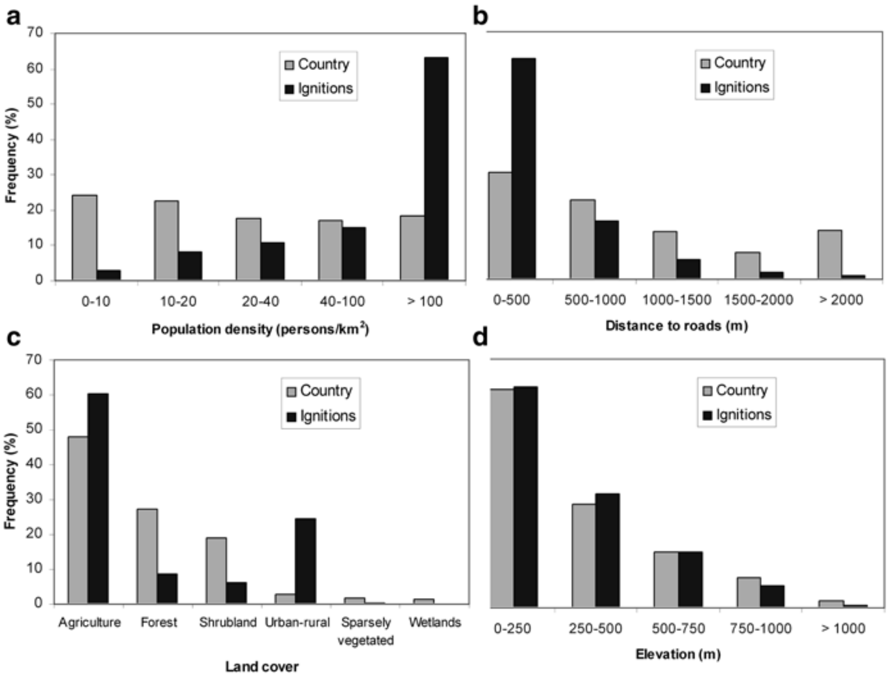

Figure 3.1 Comparison of observed ignition frequencies to frequencies expected under a random distribution for the country as a whole as a function of different variables: (**a**) population density, (**b**) distance to the nearest road, (**c**) land-cover type, and (**d**) elevation (Catry et al. 2009). "Country" represents the results for a randomized sample throughout the country; "ignitions" represents the actual recorded fires

Vasconcelos et al. 2001) or classification and regression-tree algorithms (Carreiras and Pereira 2006). In many of these models, human-related variables (e.g., population density) were included. Where land-use and cover type characteristics were included, most models in southern Europe (e.g., Badia-Perpinyã and Pallares-Barbera 2006) and in some other regions of the world (e.g., Cardille and Ventura 2001) indicated that fires, independently of the resulting fire size, were much more likely to start in non-forested areas than within forests, even though forests provide an environment that promotes the spread of fires.

Wildfire ignitions result in burned areas of different sizes. The geographical distribution of ignitions that resulted in large fires differed from the distribution of ignitions for all fire sizes combined, as can be observed in data from Portugal (Fig. 3.2). To explore the size-dependent pattern of fire ignitions in Portugal, Moreira et al. (2010) assigned each fire to one of several size classes: 5, 50, 100, 250, and 500 ha. They then modeled the probability of an ignition resulting in a different burned area by means of logistic regressions using the three main explanatory variables previously used by Catry et al. (2009): population density, distance to the nearest road, and land use. They then compared the coefficients of the variables across the models for the different size classes (Fig. 3.3).

Figure 3.2 Geographical distribution of (*left*) all fire ignitions in Portugal between 2001 and 2003 and (*right*) ignitions that resulted in burned areas greater than 500 ha (Moreira et al. 2010)

The regression coefficients for population density were always negative, and were more negative for larger burned areas, indicating that once ignition occurs, the likelihood of a large fire decreases with increasing population density. For distance to the nearest road, the coefficient was positive for medium-sized fires (5 to 250 ha), indicating that fires of moderate size are more likely to occur farther from roads, whereas the coefficients for the largest fires were not significant, indicating that distance was not a significant factor for the largest fires. In contrast, land-use and cover type seemed to be important for some types (i.e., had a larger coefficient) but not for others in terms of increasing the likelihood of larger fires. The coefficients for shrublands and forests became increasingly positive with increasing fire size, particularly when compared with agriculture, suggesting that the transition to a larger fire is increasingly easy in the former land-cover types (Moreira et al. 2010).

From these previous studies, we can conclude that the same factors (population density, distance to the nearest road, and land cover) are responsible for the patterns of fire ignition and the final burned area but that their effects are quite different.

Population density was positively correlated with the number of ignitions in many studies (e.g., Cardille et al. 2001, Catry et al. 2009, Mercer and Prestemon 2005, Yang et al. 2007) but was simultaneously negatively associated with the

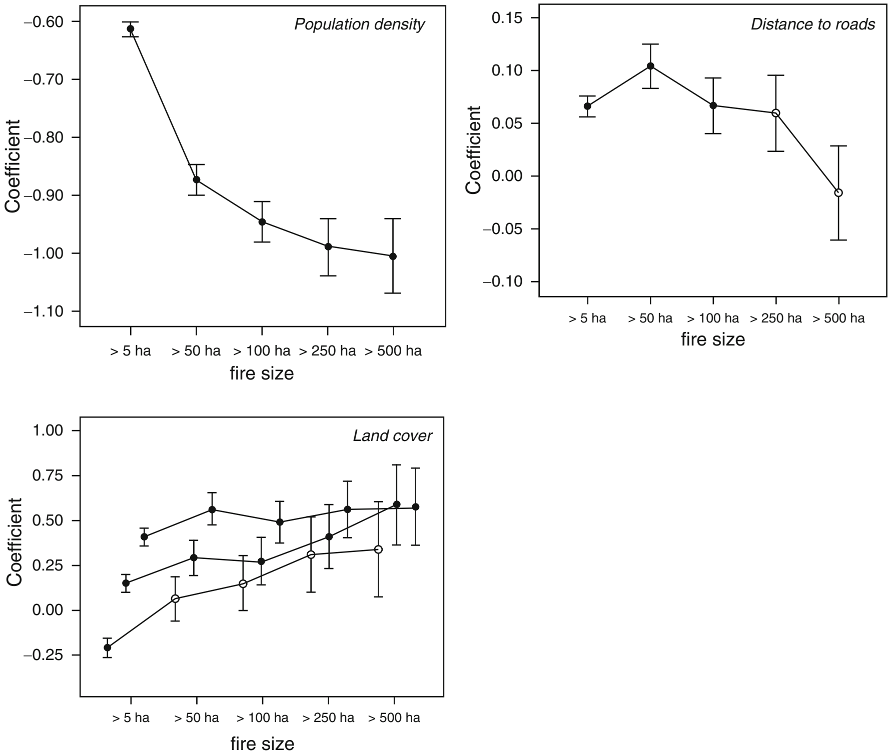

Figure 3.3 Regression coefficients (mean ± SE) for fire size as a function of population density, distance to the nearest road, and land-cover type in different logistic regression models that expressed the likelihood of an ignition resulting in a burned area of a given size (Moreira et al. 2010). Land cover is a categorical variable, with the reference category being agricultural land. The *upper*, *middle*, and *bottom lines* represent, respectively, shrublands, forests, and interspersed urban–rural areas. *White dots* indicate nonsignificant regression coefficients

burned area, indicating that population density plays a dual role in defining fire patterns: simultaneously, it represents a source of ignition and a higher likelihood of controlling the size of the burned area, probably as a consequence of earlier detection and more effective suppression (Moreira et al. 2010).

Proximity to roads was clearly associated with ignition probability in several studies (e.g., Catry et al. 2009, Romero-Calcerrada et al. 2008, Vega-Garcia et al. 1996), and it seems that medium-sized fires were more likely to occur farther from roads, possibly because of more difficult detection and a greater distance that suppression crews must travel from the road. However, larger fires seem to develop independently of the distance to the nearest road (Moreira et al. 2010).

Land cover is known from various studies around the world to be an important factor that determines fire ignition (e.g., Cardille and Ventura 2001, Yang et al. 2007), and the study by Catry et al. (2009) in Portugal confirmed these findings: they concluded that the vast majority of ignitions were concentrated in agricultural areas and in interspersed urban–rural areas. Nevertheless, subsequent studies indicated that very large fires are much more likely to spread in forests and shrublands, probably because these are areas with low population density, which delays detection, and with higher and more continuous fuel accumulation, which makes fire fighting more difficult (Moreira et al. 2010).

3.3 Landscape types and fire probability

Several papers have addressed the relationships between landscape types and fire spread. For example, Nunes et al. (2005) studied the patterns of fire spread in Portugal during the 1991 fire season and found the highest probability of fire in shrublands, followed by forests. In Sardinia, a nearby Mediterranean region, Bajocco and Ricotta (2008) also found that fires burned the landscape selectively, following a pattern similar to that in Portugal.

In another study to estimate the fire probability as a function of the land-use or cover type, Moreira et al. (2009) used data from 5591 fires that burned in Portugal between 1990 and 1994 to compare the land-use and cover type composition before the fire in a buffer surrounding (and including) each burned patch (land-cover availability) with the composition within the patch (land-cover use). If a given land-use or cover type burned more or less often than the relative abundance of that type within the regional landscape, different land-use or cover type compositions would be expected to appear within the burned patch and in the buffer surrounding the patch, and fire would therefore be considered to be selective.

This approach used selection ratios to characterize the patterns of land-use or cover type selection by fire (as in Moreira et al. 2001) and was analogous to studies of habitat preferences by animals (Manly et al. 1993). The selection ratio for a given land-use or cover type was estimated as the ratio of the proportion of that type in the burned patches to the proportion of that type in the surrounding landscape. The results of this study at a national scale indicated that annual crops, permanent crops, and agroforestry systems were the least likely to burn, with fires occurring at less than half of the rate expected based on their proportions of the landscape (Fig. 3.4). Shrublands were clearly most at risk of fire and burned twice as often as expected. Forests as a whole showed intermediate behavior, with some variation among coniferous, eucalyptus, broadleaved, and mixed forests.

Agricultural crops are recognized by various authors as being the least fire-prone cover type, possibly because of the lower fuel loads and the generally higher moisture contents (e.g., Sebastián-López et al. 2008), but also because cultivated land is usually closer to houses, making fire detection faster and firefighting both easier and a high priority (Moreira et al. 2009).

Shrublands are clearly the most fire-prone land-cover type in Portugal (Marques et al. 2011, Nunes et al. 2005), which agrees with similar findings in other parts of the Mediterranean region (González and Pukkala 2007, Wittenberg and Malkinson 2009). These results have been explained by a combination of both the special fuel

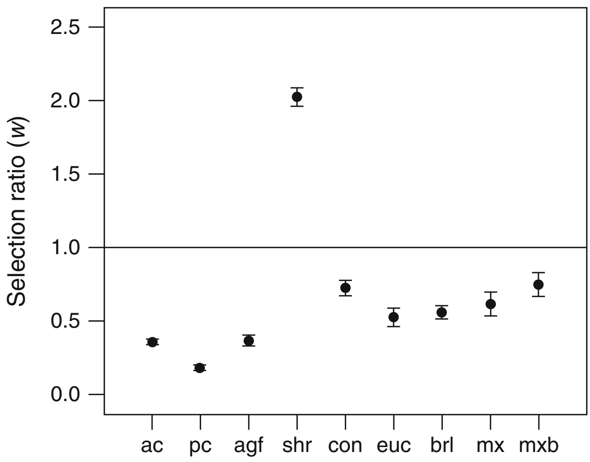

Figure 3.4 Mean selection ratios (*w*; mean ± 95 % confidence interval) for the land-cover types that burned in Portugal between 1990 and 1994. Land-cover types in this analysis were annual crops (ac), permanent crops (pc), agroforestry land (agf), shrublands (shr), coniferous forests (con), eucalyptus forests (euc), broadleaved forests (brl), mixed coniferous and eucalyptus forests (mx), and mixed forests of broadleaved and coniferous or broadleaved and eucalyptus trees (mxb). Data are from Moreira et al. (2009)

characteristics of shrublands (e.g., a dense and continuous supply of fuel, located close to the ground; high contents of flammable volatile compounds) and a potentially lower firefighting priority, as they are generally perceived to be a low-value land cover (Moreira et al. 2009).

Forests vary in their probability of fire but are generally at a level of fire selectivity intermediate between agricultural crops and shrublands. However, there is also regional variation depending on the characteristics of the different forest types. To study this specific issue in Portugal, Silva et al. (2009) used different approaches to assess fire probability and used the results to rank fire probability in the following order: greatest for maritime pine (*Pinus pinaster*) forests, followed by eucalyptus (*Eucalyptus globulus*) forests, unspecified broadleaved forests, unspecified coniferous forests, cork oak (*Quercus suber*) forests, chestnut (*Castanea* spp.) forests, holm oak (*Quercus rotundifolia*) forests, and stone pine (*Pinus pinea*) forests.

However, despite these general patterns, tree cover had an important influence on the fire probability of the different forest types. Silva et al. (2009) developed a fire probability model by means of logistic regression that related fire probability to a cumulative cover index that was computed from the vegetation cover values for the different vegetation strata. This index represented a measure of the degree of light extinction across seven forest layers, with a value of 0 representing no vegetation and 1.0 corresponding to complete shade at the soil surface. Figure 3.5 shows the results for the five main forest types.

Unspecified broadleaved forest is a diverse category, but many of these stands typically have low height, reduced dominance by trees, and high fuel continuity and

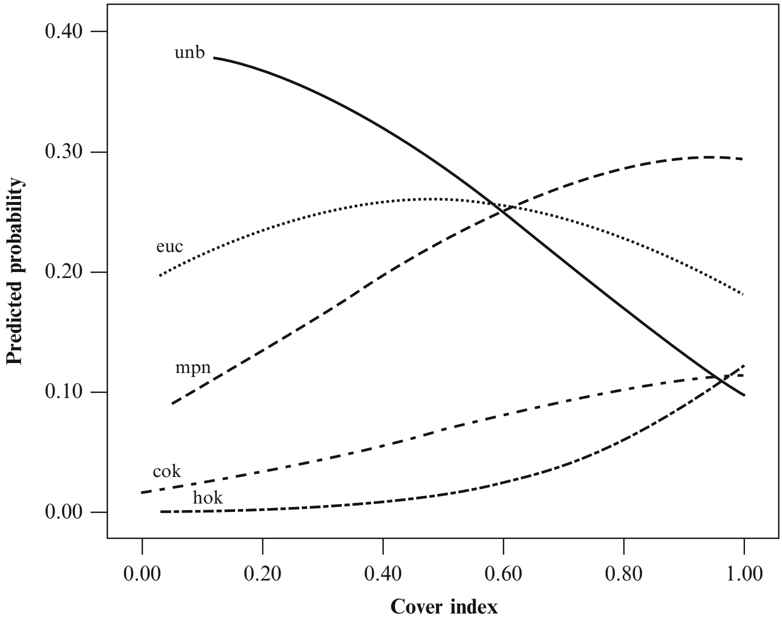

Figure 3.5 Probability of fire occurrence (from 1998 to 2005) as a function of a cumulative cover index, for which a value of 0 represents full sunlight at ground level and a value of 1 represents complete shade (Silva et al. 2009). Values are for the five main forest types in Portugal: *cok* cork oak (*Quercus suber*), *euc* eucalyptus (*Eucalyptus globulus*), *hok* holm oak (*Quercus rotundifolia*), *mpn* maritime pine (*Pinus pinaster*), and *unb* unspecified broadleaved trees

therefore resemble shrublands (Godinho-Ferreira et al. 2005). In this forest type, an increase in cover corresponds to a decrease in the probability of ignition, which suggests that as these stands age, they shift from shrubland-type plant communities (which are at high risk of fire) to closed broadleaved stands, which are much less likely to burn. Many studies have confirmed this pattern for various regions of the world (e.g., González et al. 2006, Mermoz et al. 2005, Wang 2002) and have confirmed that a lower probability of fire results from the lower flammability of the associated fuels.

Cork oak and holm oak stands have the lowest fire probability (Fig. 3.5). These stands are commonly managed using an agroforestry system named *montado*, which includes the presence of pastures and crops that maintain a low cover of scattered trees, with low fuel accumulations in the understory. As we have noted previously, agricultural land (including agroforestry systems) is less likely to burn than most other land-use types. However, when the vegetation cover increases, especially in the understory, the fire probability increases to values similar to those of unspecified broadleaved forest (Acácio et al. 2009).

Eucalyptus and maritime pine stands showed sharp increases in fire probability with increasing cover (Fig. 3.5) although the former showed a decreasing trend for very high densities. This can be explained by the fact that eucalyptus tends to have

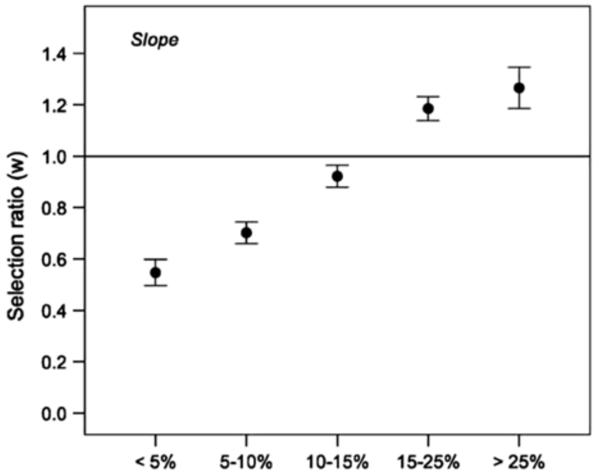

Figure 3.6 Average selection ratios (*w*; mean ± 95 % confidence interval) for different slope classes in northern Portugal (Carmo et al. 2011)

a high content of flammable volatile compounds, whereas there has been a general lack of management of maritime pine stands recently, resulting in increased vegetation cover due to invasion of these forests by shrubby understory vegetation that increases the probability of fire. In general, these conclusions agree with the findings of other authors, who also concluded that eucalyptus and pine stands are more flammable than other forest types (e.g., Wittenberg and Malkinson 2009, Xanthopoulos et al. 2012).

In addition to land-use and cover type, it is important to consider other landscape features that may strongly affect fire spread. One important aspect to consider is topography, which plays an important role in terms of both ignition and subsequent fire propagation. The relationship between topography and fire has been well established from experimental evidence (Rothermel 1983), but until recently, there were no approaches based on landscape analysis that examined the role of topography in fire spread in Portugal.

The existence of a relationship between topography and fire was hypothesized by Carmo et al. (2011), who analyzed the influences of land-use and cover type and topography on wildfire occurrence in northern Portugal, using the selection ratio approach to evaluate the fire probability for different topographic categories (based on slope and aspect). To do so, they characterized 1382 wildfires larger than 5 ha that occurred in 1990 and 1991. They found that a given type of vegetation in different aspect classes largely burned in proportion to its abundance within the landscape (i.e., aspect had little effect on the probability of fire). They found that the probability of a fire increased with increasing slope and that slopes steeper than 15 % were at particularly high risk of fire (Fig. 3.6). However, the problem can be more complex than this analysis suggests, as topography is often linked with land-use and cover type. For example, agricultural areas may be preferentially located in flat areas, whereas forests or shrublands may be most common in sloping land; this may

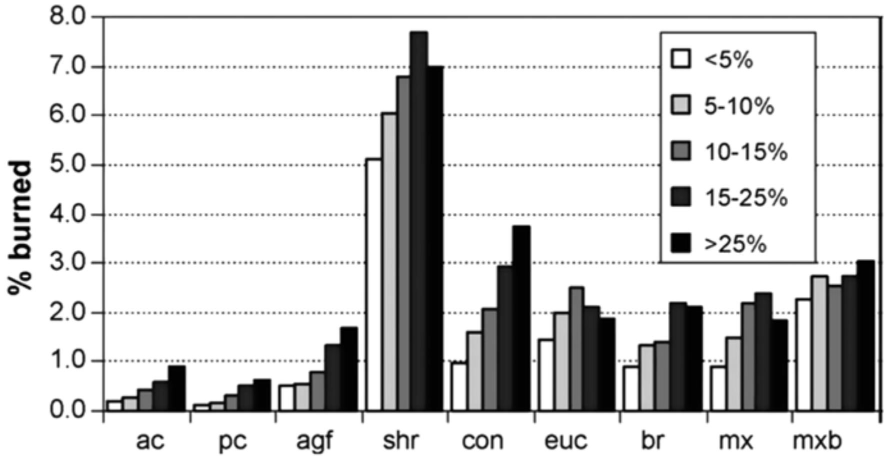

Figure 3.7 Proportion of the area of a given land-cover type that burned as a function of slope in northern Portugal (Carmo et al. 2011). Abbreviations for land-cover type: *ac* annual crops, *pc* permanent crops, *agf* agroforestry systems, *shr* shrublands, *con* coniferous forests, *euc* eucalyptus forests, *br* broadleaved forests, *mx* mixed coniferous and eucalyptus forests, *mxb* mixed broadleaved and coniferous or broadleaved and eucalyptus forests

have confounding effects on the factors that govern fire spread. It was therefore necessary to understand whether the effect of slope was independent of the land-use and cover type. Carmo et al. concluded that due to the physical effect of slope on fire behavior, the fire probability increased similarly with increasing slope for all land-use and cover types (Fig. 3.7). These results have important implications for landscape planning, since they can support the definition of landscape-scale fuel breaks. For example, areas that are prioritized for protection should include agricultural (or agroforestry) areas on shallow slopes (Carmo et al. 2011).

3.4 The dynamic interactions between landscapes and wildfires

The relationships between land-use changes and wildfires have been discussed for a long time, and general relationships have been proposed (Rego 1992). In a recent review of the interactions between landscape and wildfire in southern Europe, Moreira et al. (2011) concluded that socioeconomic factors were driving the abandonment of agricultural land and other land-use changes, contributing to more frequent and larger wildfires that promoted the development of more homogeneous landscapes covered by fire-prone shrublands; these, in turn, promoted fire spread and future fires. This trend seems to be common in many regions, particularly those with a Mediterranean climatic or cultural influence (Chuvieco 1999, Lloret et al. 2002, Loepfe et al. 2010, van Leeuwen et al. 2010, Viedma et al. 2006).

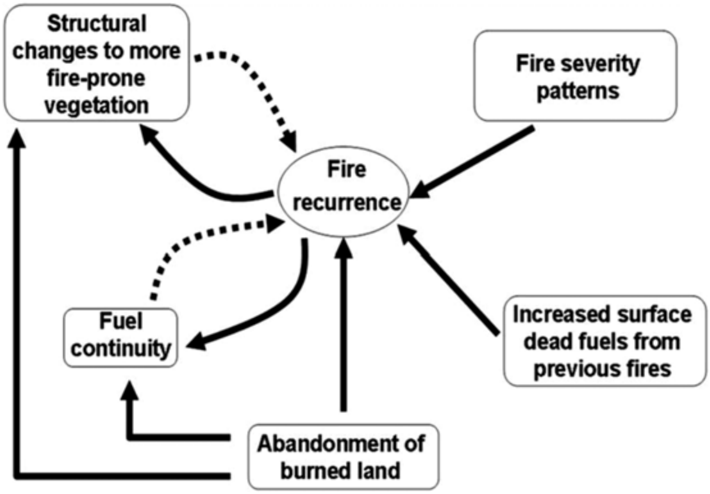

Figure 3.8 Possible feedback mechanisms that may lead to increasing fire probability in Mediterranean landscapes (Moreira et al. 2011)

This feedback mechanism is enhanced by the fact that there is a general public perception that the shrub-dominated landscapes created by wildfires are less valuable than other landscapes. This, in turn, makes them more prone to abandonment, leading to a higher probability of fire that can further promote the development of shrubland (Espelta et al. 2008, Vazquez and Moreno 2001), as shown in Figure 3.8.

The implications of wildfires for landscape dynamics can be assessed at various scales. In a detailed study at a local level in Bragança (in northeastern Portugal), Silva et al. (2011) assessed landscape changes from 1990 to 2005. The role of fire in these land-cover dynamics was assessed by building separate transition matrices for burned and unburned areas (Fig. 3.9). This example confirmed the results of other studies, which showed that fire is associated with a higher persistence of shrublands, simultaneously reducing the area of vegetation types that are vulnerable to fire and favoring transitions of all other land-use and cover classes into shrublands. It is particularly important to note the dramatic differences between the transitions for unburned and burned areas in coniferous and mixed forests: fire converted these forest types almost completely into shrublands, possibly because the persistence of maritime pine depends on a seed bank in serotinous cones, and this seed bank might not develop if the stand burns before reaching reproductive maturity (Fernandes and Rigolot 2007). In all cases, fire seems to have caused a decrease in the transitions to agricultural uses, which can be interpreted as a two-way association between fire and land abandonment: agricultural abandonment increases the probability of fire, and fire increases the probability of agricultural abandonment.

Silva et al. (2011) simulated future landscapes using transition matrices in a Markov-chain analysis to project the future landscape composition. These projections

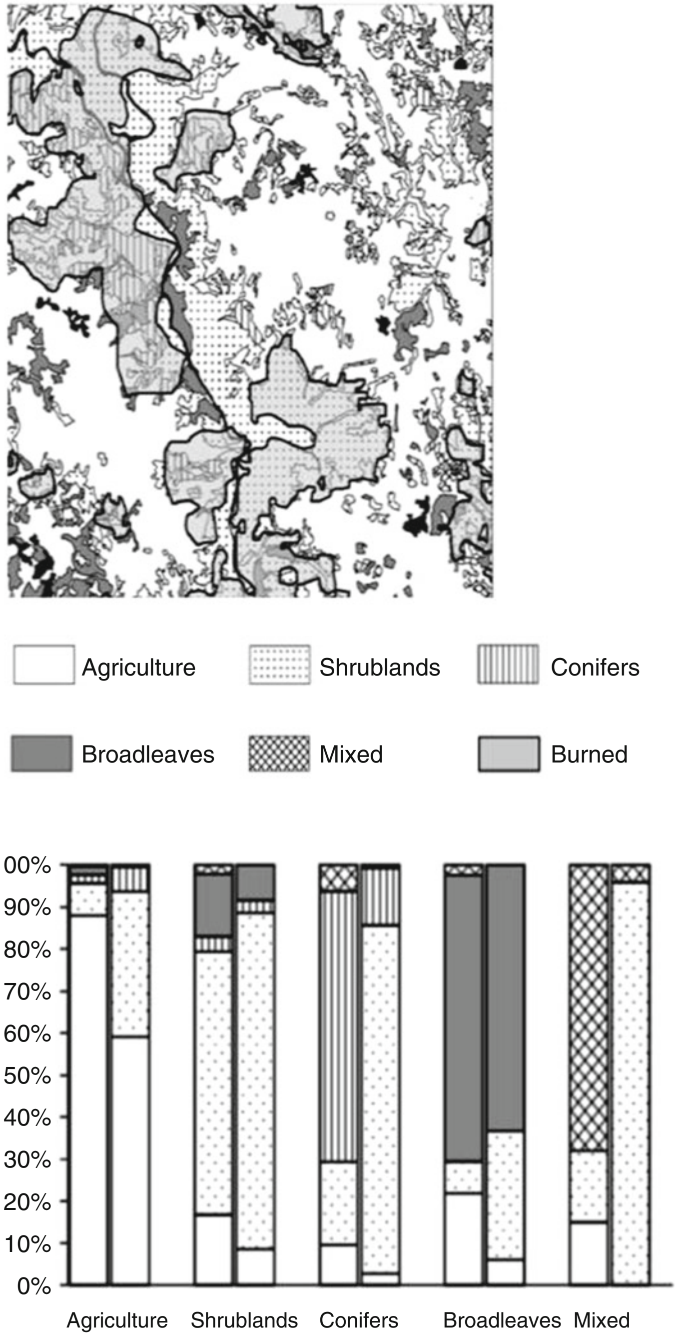

Figure 3.9 (*Top*) Map of the Bragança study area in Portugal (11 500 ha), showing the mosaic of land uses and cover types in 1990 and the areas burned from 1990 until 2005. (*Bottom*) Graphical representation of the transition matrices for unburned areas (*first bar*) and burned areas (*second bar*). Within each bar, the different proportions represent the proportion of the initial land cover in 1990 (classes on the horizontal axis) that transitioned to a different land cover in 2005 (patterns inside each bar), as shown by Silva et al. (2011)

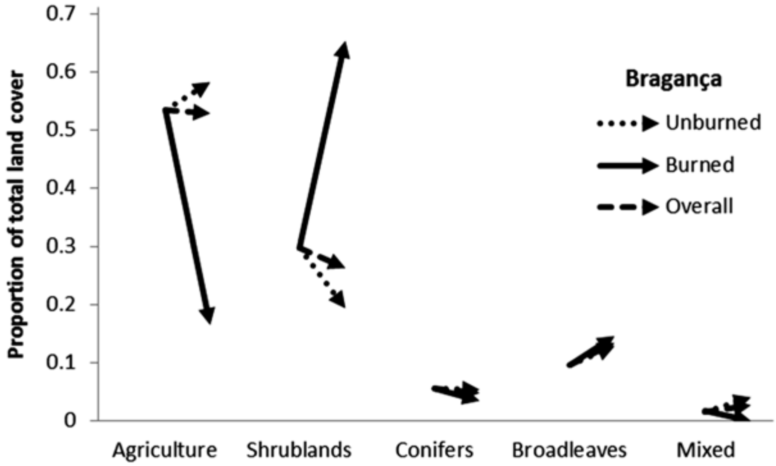

Figure 3.10 Long-term projected trends (from 2005 to 2095) based on three fire scenarios: Overall, the current fire regime; Unburned, a regime without fires; and Burned, a regime in which the whole area burned completely in each 15-year period (Silva et al. 2011). The percentage of each land cover in 2005 is represented by the start of each *arrow*. The percentage of each land cover in 2095 is represented by the tip of each *arrow*

allowed us to assess the effects of wildfires on landscape dynamics and predict the expected landscape pattern if the modeled land-use and cover type transitions were maintained. Projections were compared based on the current (Overall) fire regime with projections based on a regime without fires (Unburned) and a regime in which the whole area burned completely in each 15-year period (Burned). Figure 3.10 shows the results. Based on the overall transition matrix, the projected landscape would still be dominated by agriculture in the Overall scenario, with a decrease in shrublands and an increase in broadleaved and mixed forests. Similarly, the Unburned scenario would create a landscape with more agriculture, less shrubland, and an increase in the proportions of broadleaved and mixed forests. In contrast, fire-driven transition dynamics (the Burned scenario) would create a landscape strongly dominated by shrubland, with greatly reduced areas of agriculture but with an increased broadleaved forest component at the expense of coniferous and mixed forests (Silva et al. 2011).

3.5 A broader perspective on relationships between fires and the landscape: main problems and proposed solutions

Similarly to the situation in Portugal, most regions of the world include landscapes where fire is an important element of change (Pausas and Keeley 2009). As a consequence, there has been considerable effort to study and understand the relationships between fire and landscapes around the world. Based on these studies, it has been widely argued that plant species have evolved and adapted to natural fire regimes and that landscapes may reach a *quasi* equilibrium under any given fire regime (e.g., Pausas and Keeley 2009, Vogl 1982). However, human activities have modified fire regimes for millennia in many parts of the world. Alterations in land use, fire use, fuel patterns, and human-caused ignitions, as well as recent efforts in wildfire suppression, have all strongly influenced fire regimes at a range of scales (Bowman et al. 2009, Marlon et al. 2008, Pausas and Fernández-Muñoz 2012). Furthermore, observed and anticipated shifts in climate and weather patterns are expected to cause further alterations in fire regimes at many scales—from continental to regional or even local (e.g., Moritz et al. 2012, Raymond and McKenzie 2012).

As our discussion of the Portuguese situation showed, studies of relationships between fires and the landscape must address the spatial distribution of wildfires. Wildfires do not ignite and spread randomly across the landscape (e.g., Mermoz et al. 2005, Pezzatti et al. 2009, Verdú et al. 2012). Understanding the nonuniform distribution of wildfires is essential to understand why different regions of the world and even different parts of a region with the same climate may have completely different fire regimes. In the case of wildfire ignition, we can start by distinguishing regions where fire is still mostly a natural phenomenon from regions where it is mainly human-caused. In the latter case, the distributions of human activities within the landscape and of the associated human infrastructures are crucial aspects that define the distribution of fire ignitions across a study region. Moreover, wildfire databases show that the size of wildfires follows a markedly skewed distribution (Li et al. 1999, Pausas and Fernández-Muñoz 2012), with a few large burned areas that account for most of the total area that is burned annually. This leads to the problem of learning how fires spread across a landscape. This problem, which can be described as fire selectivity (see Sect. 3), can be tackled at different levels, depending on the study's scale and the problems for which answers are needed. An assessment of fire selectivity for coarse land-use and cover classes is suitable for a regional analysis of fire probability. However, at a more local scale, we might instead be interested in knowing the differences in fire probability for subtypes of the main landscape categories. This is clearly the case for forests, which have the highest probability of fire in some regions (e.g., Bajocco and Ricotta 2008, Cumming 2001). If we can understand which forest types burn most often, we can use this information to drive or at least influence management decisions that may determine the future fire regime.

Although the characteristics of fires are strongly determined by the characteristics of the landscape, fires may also change certain characteristics of the landscape, making the landscape more or less likely to support new fires; that is, feedbacks may occur. Under the influence of natural fire regimes, this dynamic interaction assumes different characteristics (e.g., exhibits different fire frequencies) in different ecosystems, eventually leading to dynamic steady states, such as those that develop in predator–prey relationships (Bond and Keeley 2005). However, these processes may not be balanced under the influence of human impacts, which may lead to drastic changes in the fire regime and therefore in the resulting landscape.

The results of such scenarios are not straightforward to forecast (Silva and Harrison 2010). Particularly in recent decades, there have been considerable changes in many human societies (e.g., the rapid rates of urbanization and socioeconomic development in China) that have further increased the unpredictability of relationships between fires and the landscape (Bowman et al. 2011). Hence, it is of paramount importance to assess the fate of burned landscapes and the resulting feedback on fire regimes at both regional and more local scales.

In addition to changes in human societies, we should consider the issue of global climate change. Fires are driven by climate, since climate directly affects fuel moisture content and vegetation development. The predicted climate change is therefore likely to have a strong influence on future fire regimes, on future landscapes, and on the resulting interactions (Brennan 2010, Robinson 2009). This influence adds to the unpredictability that results from social change, but most scenarios predict a higher likelihood of large wildfires due to global warming (Liu et al. 2010). In addition to the consequences of this change for landscapes, an increased occurrence of large wildfires will pose a strong threat to people and their livelihoods. Because of this problem, much effort is being devoted around the world to improve our ability to fight fires. However, the results have been discouraging in at least some regions, as the occurrence of large wildfires is increasing (Montiel and Kraus 2010). As a result, a new vision about the fire–landscape relationship has arisen, with the goal of mitigating this problem. This vision considers fire to be an intrinsic element of landscape dynamics that can be managed and not seen only as a threat. This ecological view of fire has contributed to the development of knowledge and expertise in "fire management". Fire management has proven to be an efficient way of preventing the occurrence of large wildfires (Silva et al. 2010) and must therefore be considered an important strategy for coping with global warming (Robinson 2009).

The role of wildfires in shaping landscapes has been studied in various parts of the Mediterranean region, including Greece (Arianoutsou 2001) and France (Trabaud and Galtié 1996). Mazzoleni et al. (2004) provide an excellent review of examples of landscape change in this region, most of them related to a growing migration of rural populations away from rural areas towards coastal or heavily urbanized regions. Many regions of the world face a continuing population decline in rural areas. The so-called *rural exodus syndrome* has decreased the area of agricultural land and increased vegetation biomass over wide areas (e.g., MacDonald et al. 2000). The implications of these changes, including the possibility of an increased fire probability, have been addressed in several studies. For example, Moreira et al. (2001) estimated a 20 to 40 % increase in fuel accumulation at a landscape level in northwestern Portugal between 1958 and 1995. The combination of fuel accumulation and the current climatic trends of less rainfall and warmer summers (Santos and Miranda 2006) indicates that large wildfires will become more common in Portugal. In fact, studies both at a local scale (Moreira et al. 2011) and a global scale (e.g., Pausas and Keeley 2009) indicate that there is a clear trend in many regions for increased fuel accumulation due to changes in land use and a clear trend for more extreme weather due to climate change. The combination of these changes in fuel and weather will create favorable conditions for a higher frequency of large wildfires in many regions of the world (Robinson 2009). These predictions make it crucial for us to understand how the role of fire in the landscape could change.

An approach that has been suggested (and sometimes applied) is based on the use of fire to solve the problems caused by fire. It is well known that when land is abandoned and biomass use decreases, policies based only on fire exclusion and suppression result in large fuel accumulations. Under extreme weather conditions, this buildup of fuels may create conditions suitable for catastrophic wildfires. Several authors (e.g., Birot and Rigolot 2009, Myers 2006) have reached the conclusion that the best option is to learn how to live with fire. Therefore, the reduction of wildfire hazard and the sustainable management of ecosystems in Europe and elsewhere may require new management practices, such as "prescribed burning", which has been defined as a "controlled application of fire to vegetation in either their natural or modified states, under specified environmental conditions, which allow the fire to be confined to a predetermined area and, at the same time, to provide the intensity of heat and rate of spread, which are required to attain planned resource management objectives" (FAO 1986). Prescribed burning has been studied and developed in some European countries. The European Fire Paradox project (http://www.fireparadox.org/), which was conducted from 2006 to 2010, was essentially dedicated to studying and developing the potential of fire management through fire use (Fernandes et al. 2011, Montiel and Kraus 2010, Rego et al. 2010, Silva et al. 2010).

The effectiveness of prescribed burning has been reviewed by Fernandes and Botelho (2003), who concluded that significant reductions in the area burned by wildfires could be achieved by strategic use of this fuel management technique. Figure 3.11 illustrates the use of prescribed burning to disrupt the continuity of shrubland in Portugal. Successful use of prescribed burning has been described in several situations, but its use is often discontinued due to poor decisionmaking when managers fail to account for the benefits of this process of living with fire in a sustainable way. One of the few long-term and large-scale programs is in southwestern Australia, where a prescribed fire program has been applied successfully for decades (Burrows 2008). The future of forest landscapes and of fire seems to depend on improving our understanding of the relationships between the two and of the underlying processes. Instead of viewing fire only as an enemy to fight (wildfire), it should be viewed as a tool in vegetation and landscape management (prescribed fire). After all, we should remember the traditional Finnish proverb that "fire is a bad master but a good servant" (Fig. 3.12).

3.6 Concluding remarks

Through the studies we have described, we have tried to illustrate the relationships between fire and landscapes by providing examples from a particular area of the Mediterranean Region. This regional perspective, focused on examples from Portugal, reveals important conclusions about the role of fire in landscapes and the role of landscapes in shaping the characteristics of wildfires. We demonstrated a

Figure 3.11 Two images of the use of prescribed burning to create fuel breaks in mountain shrublands in northern Portugal (photo: P. Fernandes, University of Trás-os-Montes and Alto Douro)

close relationship between the ignition of fires and the type of landscape. Fires are more likely to start in agricultural and interspersed urban–rural areas as a consequence of human actions, and the likelihood of fire increases at higher population densities, particularly close to roads.

However, not all ignitions result in the same probability of large fires. Again, the type of landscape plays a crucial role, since large fires are more likely to occur in areas of shrubland or forest. These results agree with the results of other studies, which showed that fire spreads faster through shrublands and forests than through agricultural and agroforestry landscapes. In Portugal, different forest types present different fire probabilities, and changes in vegetation cover have different effects in different forest types. However, the complex interactions between forest composition and forest structure are not well understood, and additional research

Figure 3.12 The use of fire as a "good servant" in Lousã, Portugal (Photo by Liliana Bento, CEABN/ISA)

will be required to allow a more accurate assessment of the susceptibility of forested landscapes to fire.

The interaction between land-use and cover types and the topography is increasingly evident; for example, agriculture is most common in flat land and forests are most common on steep slopes. This is important because slope strongly affects fire spread in the different landscape types of Portugal. The research literature highlights the complex feedback mechanisms that lead to mutual influence (feedback mechanisms) between fire and the landscape. Fire seems to play an important role in the present trend of abandonment of agricultural land in Portugal, which is in turn making the landscape more vulnerable to future wildfires. This is creating feedback mechanisms that increase the probability of fire and, when combined with the predicted global warming, creates strong concern and the need for new solutions and new approaches.

These new approaches should include a change from the present paradigm, which is primarily reactive (fire fighting), to a proactive attitude based on fire prevention and management. This attitude should account for the vast knowledge acquired in recent years about the ecological role of fire in the landscape and its potential use as a management tool. The use of prescribed fire is far from being a panacea to solve fuel management problems, but it nonetheless has an immense potential that has not been fully explored. Therefore, despite the concerns being raised over trends that are leading to an increased risk of fire in areas such as Portugal, we hope that future policies will include a more comprehensive and sustainable view of the relationships between fire and the landscape.

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