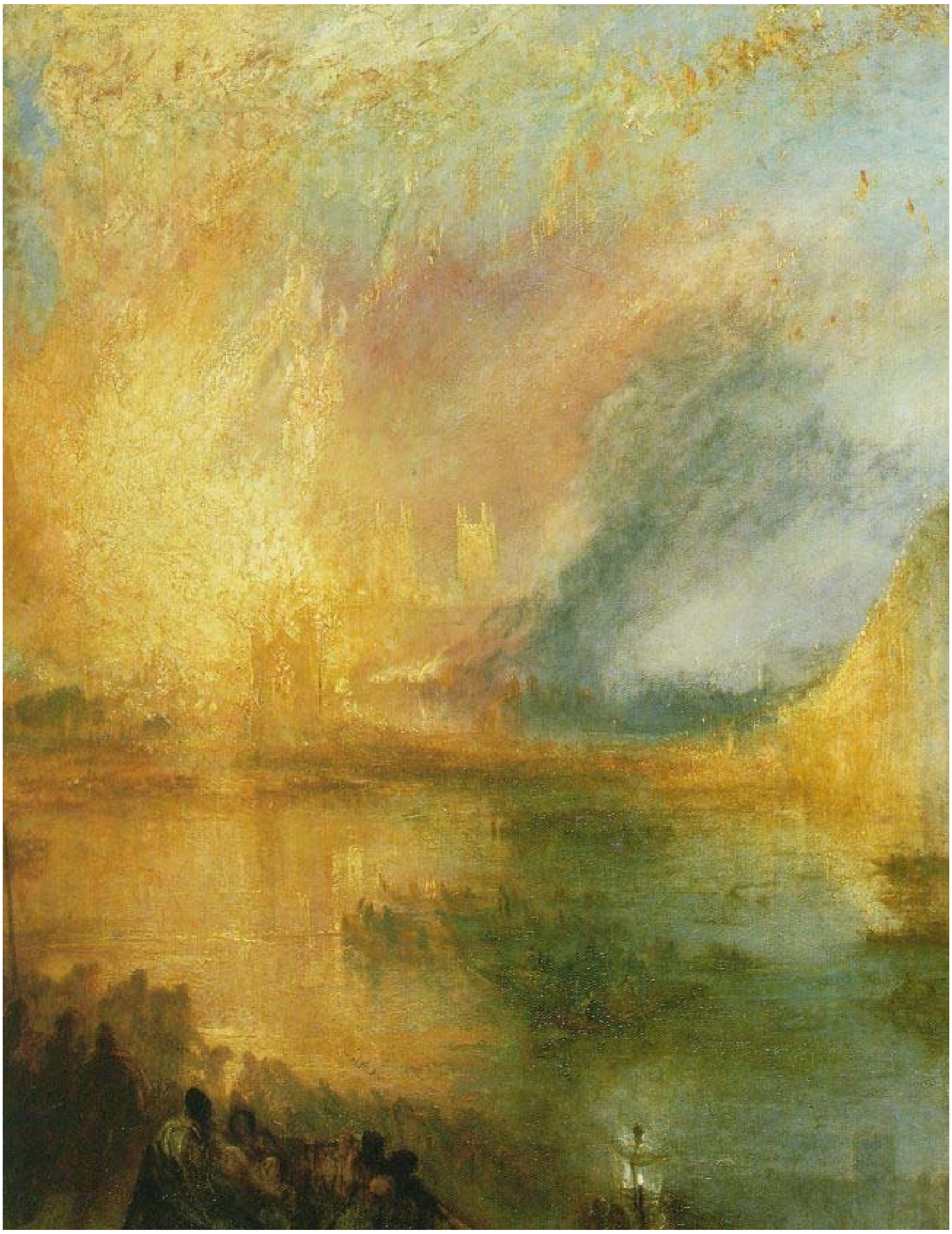
Wildfire resilience in Mediterranean landscapes: a review



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Introduction

Although large wildfires are relatively new in the recent history of the Mediterranean Basin (MB), fires are natural and should not be considered an ecological disaster but rather a part of the natural process. One of the most striking differences between the MB and other Mediterranean-type ecosystems is its millenary history of intensive and extensive land use (Pausas et al., *in press*). European Mediterranean landscapes are the result of thousands of years of anthropogenic disturbances such as fire management (Naveh, 1975; Henry, 1994; Rundel, 1998) - e. g. deliberate rotational burnings - and grazing activities, sometimes combined, to suppress woody vegetation and promote the development of herbaceous plants (Arianoutsou 2001).

Fire resilience of Mediterranean ecosystems tends to reproduce the community existing before and fire plays a major role in these changes by moving back the successional process (Lloret et al., 2002) in distinct manners, according to land-uses/land-covers (LULC). Moreover, land-use change is the main driver of the increases in the number of wildfires and area burned in recent decades (Pausas, 2004), with dominating people-ignited fires and lightning-caused increasing in MB (Vázquez & Moreno 1998).

Systematic changes have occurred since last decades in landscape composition and structure, mainly due to the abandonment of traditional land uses, apparition of new recreative uses, and afforestation practices, altering the landscape fire hazard and fire regime[1] itself (e. g. Moreira et al. 2001; Romero-Calcerrada & Perry 2002; Mouillot et al. 2003). Furthermore, fire does not have the same regime in all five Mediterranean regions of the world and the consequences of altering it may not be the same in South Africa, for example, were fynbos vegetation of the Cape region burns every 10-15 years, or in California and the Mediterranean Basin were natural frequencies are 30-50 years or more (Arianoutsou 2001).

Tendency for ageing of the agricultural population and towards abandonment of the less fertile agricultural areas, and intensification and increase of the population in the

[1] A fire regime includes the patterns of frequency, season, type, severity and extent of fires in a landscape (Bond & Keeley 2005)

more fertile ones, has been general throughout part of MB (Ales et al. 1992). LULC changes have favoured the expansion of shrublands and other flammable vegetation types (Almeida & Moura 1992; Viedma, 2006) like large monospecific patches of pines (Ales et al. 1992) or eucalyptus (Pinto-Correia 1993). In some areas of southern Iberian Peninsula shrubland encroachment has even been the most conspicuous landscape change (Pinto-Correia & Vos 2004).

In moister Mediterranean areas, land abandonment may have shorter-term consequences and the landscape may be regenerated faster to natural vegetation in comparison to drier Mediterranean areas, where intense past land use involves slow growth of resilient species with longer-term consequences (Baeza et al., 2007).

Currently, more than 47 000 fires burn throughout the MB, consuming over 280 000 hectares. Despite that, a lot of resources have been invested in fire prevention and suppression, the number of fires in recent decades has continued to increase markedly (Barbosa et al. 2007). Much of the discussion (fire management and scientific) on changed forest fire regimes has been oriented towards the changes in land use history which has largely occurred after the late 80's in most of the countries (e. g. Moreira et al. 2001; Arianoutsou 2001).

Increased fire frequency may reduce ecosystem resilience, i.e., the ability to recover the pre-disturbance state. This concept has received much attention in the Mediterranean ecosystems in the 80's (e. g. Dell et al. 1986) and a recent renewed interest because of the accelerated loss of biodiversity - resulting in the potential loss of buffers to the impacts of disturbances - and the profound changes in disturbance regimes projected by global change scenarios (Lavorel 1999). Resilience is defined in the context of the amplitude of changes brought by fire and the dynamics of post-fire recovery (Arianoutsou 2007).

Vegetation recovery from fire has been widely studied at the stand level in many types of terrestrial ecosystems, but factors controlling regeneration at the landscape-scale are less well known (Díaz-Delgado et al. 2002). This conjuncture leads to recent needs to accurately understand fire regimes and post-fire vegetation resilience at a supra-level (Mouillot et al. 2003).

Although many Mediterranean ecosystems are highly resilient to fire (shrublands and oak forest), some are fire-sensitive (e.g., pine woodlands) (Pausas et al., *in press*). Information on successional trajectories in these areas is essential for applying management strategies, silvicultural treatments and afforestation procedures that facilitate the transition towards later successional stages and mitigate the effects of new disturbances (Baeza et al. 2007).

Postfire plant dynamics in Mediterranean Basin

In the MB, broadleaved evergreen shrublands dominated by resprouting species (e. g. *Quercus coccifera*, kermes oak) are very common and might be sensitive to fire interval or fire severity. Other shrublands dominated by non-resprouting species growing in fire-prone ecosystems are seeder species highly flammable, which in general regenerate well after fire. Shrub species that neither resprout nor recruit after fire are rare in the fire-prone ecosystems of the MB. In what concerns to broadleaved evergreen sclerophyllous woodlands, Mediterranean evergreen oaks resprout vigorously following severe disturbances. The most abundant in the west of the basin, *Q. ilex* (Holm oak) and *Q. suber* (Cork oak), have strong resprouting capacity after fire (Pausas et al., in press). In fact, fire may provide an advantage to oaks versus pines in mixed forests, and it may also open regeneration windows for oak establishment and colonization of new environments (e.g., pine woodlands) (Pons & Pausas, 2006). However, several works in Spanish, French and Portuguese oak forests point out for a decrease in these forests resilience and their switch into shrublands (e. g. Díaz-Delgado et al. 2002) as a result of higher wildfire frequencies and droughts (Acácio et al. 2008). Frequent or intense wildfires may kill adult cork oak trees, especially if wildfires occurring after cork extraction (Moreira et al. 2007), which takes place in the summer, when the wildfire season begins in Mediterranean Europe (Acácio et al. 2008).

As for pine woodlands, none of the pines in the Mediterranean basin is able to resprout. For the most common lowland Mediterranean pines (like *P. pinaster*), post-fire regeneration relies on the canopy seed bank. Despite the high post-fire resilience of *P. pinaster*, regeneration of this pine may fail when time intervals between fires are shorter than the time required to accumulate a sufficient seed bank. Thus, the current increase in fire recurrence (i.e., reduction in fire-free intervals) in the Mediterranean basin is reducing the capacity of these pines to regenerate after fire (Moreno et al., 1998; Pausas et al., in press). In *P. pinea* (stone pines), occurring in more coastal areas of MB, a general decline seems to be observed as a consequence of the increased fire regime in some areas. In stone pines, short seed dispersal distance (less than 20 m) and the low seedling survival in post-fire conditions would explain the low natural regeneration in burned areas (Rodrigo et. al., 2007). MB montane pines, like *P. sylvestris*, show almost nil regeneration after crown-fire, among other reasons, because short dispersal distance of this species, less than 100 m (Ordoñez et al. 2006), does not allow effective colonization from unburned edges (Pausas et al., in press).

The most fire-sensitive ecosystems are the pine woodlands, especially given the crown-fire regimes observed in the last few decades (Pausas et al., *in press*). Some of the areas they occupied a few decades ago have been repetitively burnt with fire intervals shorter than the time these pines need to produce a large enough seed bank to replace their population (ca. 15-20 years). Thus, many of the early pine woodlands are being taken over by shrublands (Baeza et al. 2007).

One of the recent approaches in prediction of vegetation resilience is the use of plant functional types suitable for modelling based on responses to disturbance (Pausas 1999, Lavorel et al. 1997, Pausas and Lavorel 2003) that can predict the possible population dynamic trends for the four functional types that can be distinguished in the Mediterranean plants (see Figure 1). Since fire acts as a community-level filter, the predictions of post-fire community resilience can be facilitated if species are grouped in functional types (Arianoutsou 2004).

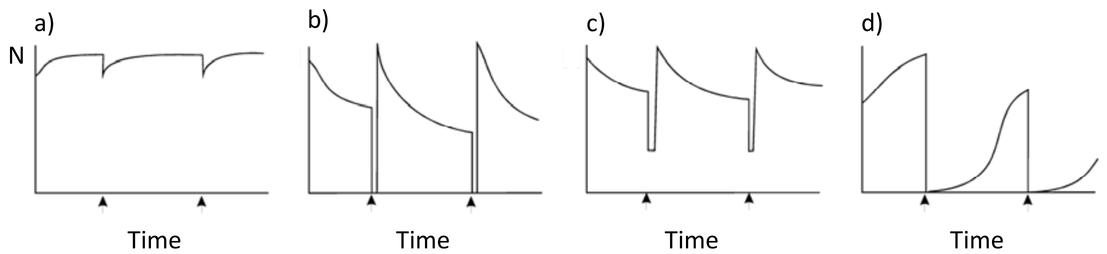

Figure 1. Possible population dynamic trends for different functional types (N=population size). Arrows indicate fires. a) resprouting species; b) species unable to resprout after fire but with recruitment stimulated by fire (disturbance-dependent recruitment); c) resprouting species with the recruitment stimulated by fire and d) non-resprouters with recruitment not-stimulated by fire (adapted from Pausas 1999).

Landscape structure/composition and fire

Studies directly addressing resilience to fire at landscape level are scarce, especially those using empirical data instead of computational modulations. Nevertheless, it's important to refer here other approaches from which we can attain results related to our core issue. Works on *fire effects on landscape* and/or *landscape fire hazard* are more common and are among those producing useful considerations and conclusions on Mediterranean resilience at broad scale.

Several methodological approaches have been used to characterize the spatial patterns of fire occurrence and spread in relation to landscape features. Clarifying at the landscape level fire regime consequences on postfire dynamics and reburning probability is needed, namely to characterize its long-term effects on vegetation (Mouillot *et al.* 2003). However, quantifying dynamically the role of fire regime on landscape patterns can be enormously complex over heterogeneous large areas because landscape is a scale-dependent process result of the interaction of environmental complexity (i.e., topography and climate), disturbance patterns, and other exogenous factors such as human induced land use-land cover changes that vary in space and through time.

It's important to evaluate how landscapes may interact fire occurrence by either promoting it or deterring it (Viedma, 2006). Some environmental elements, like topography, indirectly shapes landscapes through its impact on disturbance regimes and potential successional pathways (Parisien et al. 2006) and others, like climate, has been shown to modulate landscape patterns by driving the soil moisture distribution (Brown, 1994). Small changes in landscape structure can mean big changes in fire-proneness (Turner 1989) and, on another hand, changes in fire regime can produce alterations in structure, emphasizing an interaction between the two processes (Turner et al. 1993; Cueva & Martín 2008).

The role of landscape features (vegetation composition and structure), topography, precipitation and/or human elements on spatial patterns of fires has been studied by several authors in the Mediterranean ecosystems (e. g. Romero-Calcerrada & Perry,

2002) and in other ecosystems around the world (e. g. Mermoz et al. 2005) in a wide variety of scales, metrics, spatial patterns and vegetation classes.

In general, all these studies have demonstrated that topography, landscape features and human activities are important correlates of fire patterns. For instance, social changes in perceptions and values - particularly when timber values disappear -, and the increased hazard of the postfire vegetation may cause burned areas to burn again at a much greater pace than that of the first time (Vázquez & Moreno 1998). Landscape fire-proneness is due to interactions of cultural and ecological factors and the main work hypothesis to explain the probability of fire occurrence and spread is the spatial homogenization of landscape and fuel continuity.

The spatio-temporal pattern imposed by fire in landscape spatial composition and structure did not emerge solely from the behavior of individuals but the regional abundances, the spatial patterns of predisturbed vegetation and the effect of some properties of disturbance regime (frequency, size, severity and spatial autocorrelation). Hence, one topic of interest is related to the effects of fire frequency on plant reestablishment. Some works have developed simulation models (FATE or BROLLA models) to predict changes in plant functional types due to changes in fire recurrence (fire rotation intervals) in Mediterranean areas.

Understanding the effects of the parallel interplay of LULC (Land Use/Land Cover) changes and fire occurrence on landscape spatial patterns is also poor, particularly in view of possible consequences for landscape fire-hazard and, ultimately fire occurrence (Viedma, 2006).

Hitherto, a characteristic of empirical studies about the role of fire and environmental constraints on vegetation dynamics, is that they have been carried out at local scale mainly considering only the burned areas. In addition, several studies at regional scale have applied partial spatial approaches comparing disjunt portions of the landscape with different fire regimes, disturbance types or burned-unburned areas.

Weather and climate vs. fuels characteristics

In fire landscape-scale studies there is a discussion about the role of fuel age and/or weather conditions on fire probability (Viedma 2006). As a generic rule, exposure to extreme fire weather appears to override the sensitivity of a fire regime to fuels characteristics in Mediterranean-type shrublands. Several studies suggest weather and climate as dominant controls on Mediterranean fire regimes, as opposed to age and spatial patterns of fuels (e. g. Pausas 2004). If so, it is obvious that landscape characteristics in terms of resilience will be a key point for a good recuperation after extreme meteorological conditions.

Regarding fire frequency, climate changes also tend to decrease the time interval between fires, leading to shrub-dominated landscapes (Mouillot et al. 2002).

Scale problem

Assessing the ecological role of wildfires on landscape patterns are not comparable at different spatial scales due to the hierarchical nature of landscapes, and the differences in the conceptual model of how vegetation response to environmental forces.

Several studies have been devoted on the interacting relationship between fire and vegetation patterns, and a large number of different approaches can be described according to the way in which the spatial and temporal components are considered.

In several places around world, authors have demonstrated that long-term fire regime is controlled by climate patterns at regional scale, and by landscape components at local scale, both components having a great impact on the distribution and dynamic of vegetation (Viedma 2006).

Usually studies necessity for addressing vegetation dynamics related to fire resilience is attached to a particular scale level. For example, Viedma (2006) call out for more comprehensive studies to understand the complex pattern-process relationship inherent in forested landscapes at regional scale. Also, the role of topography, climatic conditions and prefire vegetation in the regeneration process has been evaluated by several authors in Mediterranean burned areas at local scale but less works at broader scale than burned areas.

At stand level, combinatorial techniques of optimization can be used to affect the composition and structure of the entire landscape with respect to fire risk (González et al. 2005, 2006). As fuel characteristics are partly determined by stand structure, which varies between forest stand classes, **landscape-scale fuels management** may be feasible (Cumming, 2001) either by fuel reduction programs or commercial forestry, used to achieve hazard reduction without excessive costs if spatial aspects of fire spread are taken into account (Loehle 2004). Effects of alternative vegetation management scenarios on forest succession can even be modeled to assess fire risk (e. g. Gustafson et al. 2004).

Land-cover changes and resilience to fire

In landscape models, fine-scale processes influencing resilience, such as plants physiologies and life histories are integrated across temporal scales not by simulating them directly but representing them as aggregated spatial and temporal phenomena.

Sometimes, one characteristic of studies dealing with fire history is that they report on fire frequency and intervals, but not on landscape changes (Trabaud & Galtié 1996), from which we can assess landscape resilience to fire. Despite increased recognition of the importance of disturbance in determining composition and structure, few studies have assessed the relative influence of land use changes and fire history. There are several studies considering these two parameters separately but few on their combination (Arianoutsou 2002).

Landscape dynamics are driven by the interaction in space and time of human processes, such as demographics, economic conditions and planning, and biophysical processes. Studies of landscape change and disturbance regime (e.g. fire) often overlook social-economic factors. Important shifts in landscape dynamics (e.g. agricultural abandonment or intensification, fire suppression) are often determined by social, economic or political factors (Romero-Calcerrada & Perry 2002). It is not possible to understand current vegetation patterns in the MB without taking into account past anthropogenic activities and land-uses.

Fire occurrence, burned area and land cover changes are likely to be inter-related but this relation is not always obvious. For instance, stability through time in terms of land-cover type does not necessarily imply stability of flammability-related characteristics, as theses may change with age as a result of, for example, the accumulation of litter, as happens in pine woodlands (Trabaud and Galtiè 1996), thereby increasing fire susceptibility through time.

Another aspect of interest is the relation between land cover types and velocity of recovery. Fires may induce rapid changes in the vegetation by transforming burned areas into the same state of recovery (Viedma, 2006), but, given the slower growth rate of trees, forests, for instance, are expected to recover more slowly than shrublands.

Fire promotes different successional stages to coexist in the same landscape (Romme, 1982) and sometimes fire interrupts the successional transition from shrublands to forests. After sufficient time, the secondary succession occurring in abandoned cultures leads to shrublands, and finally to forests (Lloret et al., 2002).

Land abandonment

In some areas of MB, land abandonment is the most widespread change (e. g. Sluiter & Jong 2007). Land abandonment is defined by Baudry (1991) as a change towards a less intensive pattern in land use or as the total termination of the use and managing of the soil: soils are left to their own spontaneous dynamics. Pausas (1999) states three main scenarios of land abandonment currently observed in Mediterranean landscapes which are the consequences of recent socio-economic changes: (a) previous production forests, overexploited and burned, that currently appear as shrubland dominated by resprouter species; (b) previous land use of farming, abandoned and currently dominated by seeder species maintained by recurrent fires and (c) old fields with invasion by resprouter species, occurring in moist Mediterranean areas.

Several environmental and non-environmental factors were found to be important variables for the land abandonment process. Differences in soil class explain a large part of the land abandonment pattern and the associated transition paths and transition rates. In MB, fire risk may increase due to homogenization of the landscape in combination with the accumulation of inflammable biomass in abandoned land (Scarascia-Mugnozza et al. 2000). Transition paths and landscape-fire dynamics following land abandonment are still little understood because of the complex social and ecological conditions in the Mediterranean region. Studies like Bonet (2004) and Debussche et al. (1996) describe a quick transition of pioneer vegetation types into other vegetation types in old-fields, while the results of Sluiter & Jong (2007) don't confirm this.

Edge effects

An edge is the transition zone between different patches, usually characterized by gradients of environmental variables (e.g., temperature, moisture and fuel loading) between the boundary and the interior of the patch (Chen et al. 1992). Relative to the interior, forest edges, for instance, tend to show a high density of saplings, greater shrub cover and invasion by species more typical of open habitats. Edge is a common and sometimes dominant element in many landscapes due to widespread disturbances and fragmentation (Watkins et al. 2003). Recent research suggests that edges are important structural landscape elements for plants and have been shown to influence landscape-level ecosystem processes, but the fuel structure of the area of edge influence has not been thoroughly examined (La Croix et al. 2008) on fire-landscape context. Patch edges play very significant roles in controlling fire spread because they are dominant elements in fragmented landscapes and they provide a highly linear fuel source. Hence, best fire management plans for a more resilient landscape should consider better understanding of patch edge effects. Lately, the fire area simulator FARSITE, a GIS computer model of fire growth, was used by La Croix et al. (2008) for examine fire spread movement with different edge structures scenarios.

Fire cycle vs. landscape resilience

In Mediterranean regions the landscape is a mosaic of fire histories, since all fires burn areas already burned in the past (Arianoutsou 2004). As mentioned before, some works have pointed out in the influence of the spatial factors (neighborhood effects) in the distribution of wildfires at landscape scale. There are evidences that fires tend to be highly aggregated in space and it appears that the fire cycle may be accelerated as a result of fire (Vázquez & Moreno 2001), what is rather different of what it is commonly acknowledge in other Mediterranean-type areas where the hazard of burning increases with time since the last fire (Minnich 2001), sometimes as a consequence of fire suppression leading to fuel accumulation (Bond & Keeley 2005). In some other landscapes, long intervals without fire may result in a decreased probability of fire due to successional replacement of fire-prone species by less flammable species (Odion et al. 2004).

In this context, recovery time for Mediterranean communities is a non neglectful issue, since time period might be long enough or not to allow the burned communities to recover (Trabaud & Galtié 1996; Arianoutsou 2004). *Pinus* spp. are examples where self-regeneration has been described as recurrence-dependent, i.e., it will not occur if the fire-free period is short, with pines burning at an early age (Faraco et al., 1993).

Using empirical data, some authors have concluded that the spatial and temporal patterns of fire affect clearly the regeneration process. In general, vegetation recovery is faster after the first fire than after recurrent fires, suggesting that fire recurrence has a negative impact in the resilience of several communities. It has been observed that time since last fire is an important factor explaining the great compositional convergence of several burned areas through time. However, a unique vegetation gradient related to time after disturbance is insufficient to account for the full complexity of long-term changes in vegetation composition following fire.

Some methods, like the use of time series satellite images, are particularly useful and may help to gain further insights in postfire vegetation dynamics over large regions and long time periods (Díaz-Delgado *et al.* 2002).

Fire as a stochastic process

In the temporal dimension, the spatial interaction between fire and landscape features is non-constant over time showing an important stochastic component. Several models have been developed using stochastic approaches to examine the relationship between fire regimes and landscape heterogeneity, as well as fire-affected landscape changes through time.

Some empirical and simulation models of succession used stochastic state-based transition approaches in which vegetation cover types change probabilistically among discrete states (Markov models). But forest succession and the resulting landscape patterns are influenced by a large array of ecological factors that vary no linearly through time making the probabilities of change not constant over time. In this sense, some advances have been carried out by means semi-Markov transition models. These models included time lags making transitions dependent on history, but the issue in generating semi-Markov models relay on how to estimate the parameters of the delay density function.

Carmel et al. (2001) developed a modeling approach for predicting vegetation dynamics in northern Israel in which: present vegetation in any location was modeled as a function of past vegetation and environmental factors (i.e., topography and disturbances), and future vegetation was then modeled as a function of current vegetation and effects of environmental factors. Hence, a more realistic time-space span at which stands respond to environmental effects should be established.

Time series in dynamical fire-landscape studies

The apparent length of some chronosequences does not turn them into a time series, in a stochastic sense, because temporal values are obtained from different sites for which there are not enough replicates during the entire temporal range. According to this, the dynamics of vegetation have been only related to time elapsed since last fire being the spatial dimension treated as constant (Acevedo *et al.* 1995).

Because the transitory nature of many of landscape changes, studies based on continuous time series are needed. Yet such research is scarce, particularly in Mediterranean landscapes.

The most common problem in dynamical fire-landscape studies relay on the stationary consideration of recovery process after fire. Several works have analyzed the spatial patterns imposed by fire on landscape from short-time analysis or through time under a static point of view using interrupted series of point years or based on chronosequences of disturbed sites by time since last disturbance.

Postfire homogenization

Besides the auto-succession in plant communities, one aspect of interest is to understand the resilience of pre-existing landscape structure after fire. At broad scale, NDVI variations from satellite images have been used to assess short-time effects of fire on landscape patterns (e. g. Chuvieco 1999) or quantify different recovery rates (Díaz-Delgado & Pons 2001). Chuvieco (1999) observed that immediate-fire effects on landscape patterns conduced to a spatial homogenization, whereas no general trends were observed in several fires studied in Eastern Spain, where some fires increased landscape heterogeneity while others, reduced it (Viedma et al., 1998). Ricotta et al. (1998) observed that two years after fire, the restoration of the spatial relations among distinctive patches was almost accomplished.

Some other studies have identified significant effects of fires on long-term vegetation dynamic, in particular the homogenization of patches (Mouillot et al. 2003). Except during the very first years following fire - when some authors observed an early post-fire diversity influenced by shrubs life-history specialization - burned areas tended to present reduced patch density, increased mean patch size and reduced diversity values. After 6-8 years, landscape characteristics of burned areas tended to return to previous conditions, albeit with some differences depending on the type of vegetation burned. While burned shrublands tended to quickly return to their prefire status, burned pine woodlands were more unstable and remained more heterogeneous some years after fire. These results might be an estimation of the resilience of different land covers, being higher in shrublands.

In MB, reseeding burned forest areas like maritime pine stands is not uncommon, and that may successfully regenerate the initial forest. In any case, not only with pines, the early postfire vegetation is dominated by shrubs, conducing to vegetation that after 3-5 years is continuous and, in many cases, can accumulate high fuel loads. This vegetation tends to be quite similar in composition and structure, irrespective of past post-fire management, fire severity, fire history, or land-use history. This, however, may not be so everywhere in the Mediterranean region.

Neural network models and logistic regression have also been used to investigate the relationship between local landscape heterogeneity and wildfire occurrence and results supported the hypothesis that greater homogeneity implied greater probability of an area burning (e. g. Vega-Garcia & Chuvieco, 2006)

Dynamical fire-landscape studies

Leouffre & Leclerc (1995) in an area of the French Prealps characterized landscape structure transformations and land cover changes between 1956 and 1991 using aerial photographic interpretation and GIS. These transformations were evaluated in terms of fire risk evolution. Land cover classes were: roads and rivers; cultivated lands; conifers; broadleaved forests; shrublands; pastures. Shrubland and pastures were subdivided according to percentage of tree density until 75%. At the end, a total of 14 classes were considered and each of them identified with a level of combustibility (quite strong: the conifers and shrublands; moderated: broadleaved forests and pastures with 50-75% of tree density; weak: cultivated lands or pastures, with less 50% tree density; null: roads and rivers). Between 1956 and 1991, shrubland areas progressed, forests surface almost tripled and landscape diversity (H') decrease. Combustibility areas quite strong or moderated occupied 46% in 1956 and 72% in 1991. Patch border perimeters were also measured. A great length decrease was verified in frontiers between patches quite combustibles and those with weak or null combustibility (frontiers of potential rupture in fire dynamics). On the contrary, lines of contact between conifers and shrublands increased. Authors concluded that, not considering conditions of extreme propagation, from the point of view of landscape structure, a fire at 1991 would be larger and of great intensity than a fire that broke out in 1956.

Another French study by Trabaud & Galtiè (1996) studied changes due to recurring wildfires over a period of 50 years (beginning at 1945) in southern France areas dominated by *Quercus suber* and *Q. ilex* series. Maps at 1:50000 scale covering time interval resulted from a comparison of historical and cartographical documents - interpretation of aerial photographs and field surveys - and an accurate map of major wildfires. Four types of fire histories were identified: areas not burned or those crossed by 1, 2 or 3 fires. Main vegetation types analyzed were: forests (tree cover 50-100%), treed shrublands (tree cover 25-50%) and shrublands (tree cover <25%). Community changes were analyzed according to transition matrices and the results presented in percentages of land occupation (Table 1). Values between areas with different fire histories were compared in pairs - in synchronic or dynamic diachronic terms - using the reduced deviation (**E**) method following normal distribution. Main results suggest that three successive wildfires led to a decrease in forest areas and an increase in shrublands - in areas were shrublands dominated even in 1945. This leads to the idea of synergy and reciprocity of reoccurrence of fire producing shrubland increasings and shrublands inducing wildfires frequency. In no fire areas, large proportion of forests remained forests and still dominating, whereas forested land had significantly decreased overall. Results also support the idea of less frequent fire occurrence inducing more complex heterogeneity and greater landscape diversity.

Table 1. An example of transition matrices of areas (%) occupied by vegetation types, according to number of times burning (adapted from Trabaud & Galtié 1996)

VECTOR 1945				VECTOR 1992				
n. times burned				*n. times burned*				
0	*1*	*2*	*3*	*0*	*1*	*2*	*3*	
60	61	64	27	43	26	9	2	**Forests**
20	23	8	5	36	38	30	24	**Treed shrublands**
10	11	21	60	16	34	59	71	**Shrublands**
10	5	7	8	5	2	2	3	**Fields**

	Forests				**Treed shrublands**				**Shrublands**				**Fields**			
	n. times burned															
	0	*1*	*2*	*3*	*0*	*1*	*2*	*3*	*0*	*1*	*2*	*3*	*0*	*1*	*2*	*3*
Forests	71	61	17	26	21	23	18	16	7	16	65	58	1	0	0	0
Treed shrublands	20	43	5	0	64	38	4	0	16	19	91	100	0	0	0	0
Shrublands	40	49	2	3	28	0	0	2	24	51	98	95	8	0	0	0
Fields	39	16	12	0	21	14	20	12	8	15	24	63	32	55	44	25

In an international symposium, Varela et al. (1999) have presented an empirical work describing land-use change processes in relation to forest fire occurrence in an area of

Greece. Land-use maps from 1945, 1971 and 1995 were created through photo-interpretation and classification of satellite images. The six land land-use categories considered were: dense pine forest, sparse pine forest, shrublands, cultivated areas, settlements, other. Land-use changes (major analysis on transitions within forests and non-forested areas), correlated with 120 fire records (known ignition points) from an official administrative entity (scale 1:20000), were analysed in a GIS (e. g. crosstabulation). Changes were observed mostly near the boundaries of large forested and agricultural areas, where more fire ignitions occurred. Abandoned agricultural land was partially burned (with ignition points located elsewhere) and afforested.

The work of Moreira et al. (2001), in northwestern Portugal, emphasizes the importance of social-economic factors in landscape-fire studies in human-dominated landscapes of MB. Authors tested the hypotheses that landscape changes occurring in 3697 ha across 40 years (1958, 1968, 1983 and 1995) could have been predicted from socioeconomic and political events and assess the relation between changes and trends in fire frequency. Photointerpretation (patches > 0.5 ha) was integrated in a raster-based GIS in 7 categories: urban areas, agriculture, low shrubland (<50 cm), tall shrubland (50–250 cm), deciduous, conifer and mixed forests. An estimated fuel load was attributed to each category. Multiplying the area of each land use by its fuel score yielded an index of fuel accumulation for the whole landscape. Pixel-to-pixel changes in LU categories were crosstabulated and transition matrices obtained. Wildfires limits were available from National Forest Agency, photointerpretation and field work. Correlation and regression were used to test the existence of significant trends in the number of fires and burned area. Two main trends in LU change found were: agricultural land to shrublands and forest; low shrublands to tall shrublands and forest. Predictions of landscape change based on socioeconomic variables were mostly confirmed by data. Deciduous forests’ increasing was caused by afforestation and land abandonment, leading to vegetation succession. Like predicted, a large fuel accumulation (20-40%) is suggested by models, contributing to increasing the number of fires. No trend was observed for total burned area, suggesting that it is independent of the number of occurrences.

With another approach, Vázquez & Moreno (2001) evaluated the impact of forest fires in a 14km×14km study area of Central Spain. Yearly fire perimeters (≥4ha; *n*=75) occurred during 1970-1990 were made by means of aerial photographs (scale 1:20000) aided by field inspection and incorporated to a GIS. This study used a land-use map at 1:50000 only to differentiate forest territory - areas covered by conifers (*Pinus pinaster* and, to a lesser extent, *P. sylvestris*), shrublands and small patches of *Quercus pyrenaica* - from non-forest. Results indicate that fires tended to aggregate spatially and became more frequent in areas already burned, having consequences in forest resilience. The mean age of the first-burned pine woodlands was 25 years, whereas in the reburned stands more than half were burned with less than 6 years (see Figure 2).

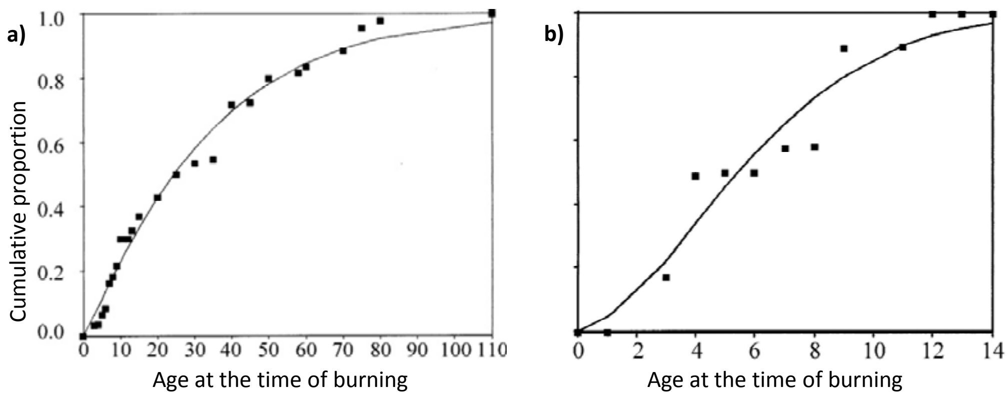

Figure 2. a) Cumulative proportion of *Pinus pinaster* burned areas as a function of the age of the burned stand; b) cumulative proportion of the reburned areas as a function of the number of years since the last fire (adapted from Vázquez & Moreno 2001).

In another study, in coastal NE of Spain, Díaz-Delgado & Pons (2001) depict a time series between 1975 and 1995 and attempted an approach to monitor post-burn regeneration through NDVI. Fire scars detection was based on the subtraction of NDVI images and used variable thresholds and burned areas compared with fires inventoried by an independent source (statistical validation giving omission and commission errors). This resulted in a map of fire scars (>0.3km^2) for 1975-1993 (plus provided burn perimeters for 1994-5) and a map of fire recurrence level, all incorporated in a GIS. Among variables monitored to study recovery rate of vegetation after fire, the quotient between mean NDVI values of burned areas and mean NDVI values of control plots not burned (Q_{NDVI}) - which shared similar phonological variation and dominant species composition before fire -, permitted authors to concluded, for a monitored area previously covered with cork-oak a smaller time than other affected areas (covered by dominant vegetation not able to resprout) to reach prior to fire conditions.

After that study, Díaz-Delgado et al. (2002) made another one with the same study area, the same time series and also using NDVI (Q_{NDVI}, as previously defined) from Landsat imagery to monitor vegetation recovery after successive fires. Estimation of resilience was based on the proportion of prefire Q_{NDVI} by postfire Q_{NDVI} at several time intervals. 139 areas (>0.3km2) burned once and 25 burned twice were analyzed in conjunction with 8 different vegetation types: forests dominated by the evergreen oaks *Quercus suber* and *Q. ilex*, the pines *Pinus halepensis*, *P. sylvestris*, and *P. nigra*, mixed forests of pines and oaks, shrublands, and Eucalyptus plantations. Using other adequated data, authors concluded that climate and altitude had significant effects on postfire resilience. In areas burned twice regrowth was lower after second fire than after the first, but this trend was observed only several years after burning and not immediately following fire. Forests dominated by *Quercus* spp. were more resilient to fire, but they showed a larger decrease in resilience after the second fire than did forests dominated by *Pinus* spp. In once-burned areas, resilience is higher in communities dominated by resprouting species (*Quercus suber*, *Q. ilex*, *Eucalyptus* sp.) than in communities dominated by non-resprouting pines (see Figure 3). As main conclusions, this study states three factors contributing to postfire resilience: fire regime, dominant life-history traits of vegetation, and postfire conditions. The fit between fire recurrence and the regenerative type of dominant species, coupled with the traits of suitable species to replace them, determines the biotic potential of regeneration.

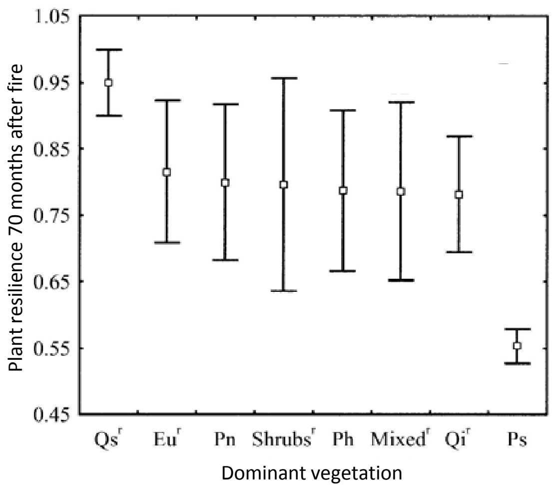

Figure 3. Fire resilience (mean ± 1 SD) of once-burned areas in relation to dominant vegetation. Categories with a superscript r are resprouting species. Abbreviations: Qs, *Quercus suber*; Eu, *Eucalyptus* sp.; Pn, *Pinus nigra*; shrubs, shrubland; Ph, *P. halepensis*; Mixed, mixed forest; Qi, *Q. ilex*; Ps, *P. sylvestris*. (adapted from Diaz-Delgado et al. 2002)

In Lloret et al. (2002) work, land cover changes and wildfire occurrence have been monitored in areas dominated by human activity at a municipality of Eastern Iberian Peninsula. Three land cover maps were acquired and overlaid with fire maps obtained with Normalized Difference Vegetation Index (NDVI), with posterior validation. Changes in the four more abundant land covers - dense forest, open forest, shrubland, and agricultural land - were analyzed by transition matrices. Using 1Km2 quadrats, a proportion of burned area for each type of land cover was calculated as the ratio $(\mathrm{bi}\ /\mathrm{si})/(\mathrm{si}\ /\mathrm{st})$, where st was the total area of the territory, si was the area of each land cover category i, and bi the burned area in each land cover category i. Results show that a large percentage of burned pine forests changed to shrublands after fire, this change being more relevant than in unburned areas. The percentage of forests remaining in the same category was lower in open than in dense forests. Wildfires decreased the change rate of both open forests and shrublands to dense forests. Post-fire recovery from forests was very low in open forests, which mostly became shrublands. The percentage of remaining open forests is lower than the percentage of remaining dense forest, perhaps because the seed bank is not enough to restore pine populations. Post-fire recovery from forests is very low in open forests, which mostly became shrublands. The percentage of remaining open forests is lower than the percentage of remaining dense forest, perhaps because the seed bank is not enough to restore pine populations.

In an area of Central Spain, Romero-Calcerrada & Perry (2002) used a classification method to derive time series of categorical land-cover/land-use maps of 1984, 1991 and 1999 (deciduous trees, pines, holm oak, shrubland, pastureland, croplands, burned areas, other land uses), allowing analysis of landscape changes, including quantification of the rates and patterns of such change. Having no data on fuel loads and biomass accumulation, they used three alternative qualitative models of fuel accumulation and multiplied values by area of each land use, achieving an Index of Fuel Accumulation. Possible effects of changes on fire risk are discussed. Analysis shows a high increase of proportion of scrubland/pastures and non-forest burned areas and a high decrease of tree forest burned areas. Shrubland increased abundance and spatial homogeneity and encroach onto old-field sites. Landscape indices show no significant changes at the landscape-level between the different dates. Shannon's Evenness Index declined suggesting an increasing dominance of some landscape classes. Since density and distribution of the biomass and landscape fragmentation increased, propagation of fire may also rise.

In Greece, Arianoutsou et al. (2002) addressed the influence of land-use interactions and fire history on plant diversity in a mountainous region of Mediterranean Alepo pine communities. Land cover maps derived from aerial photographs from 1945, 1971 and 1995. LCLU considered were: cultivations; shrublands; pines. Study sites (n=60) selections were made within 1995-burned areas of *Pinus halepensis*, reflecting various combinations of LU changes. Sites characterization: geological substrate, post-fire age, time interval between the two more recent fires and number of fires. Fire data: available since 1970. Field work and/or data validation took place in 1999 (one $5 \times 20 m^2$ plot in each site; all plant taxa recorded and woody/herbaceous vegetation cover estimated). Species presence/absence was analyzed with CANOCO application (ordination of sites by canonical correspondence analysis). The Monte Carlo permutation test was used for variables correlation. Results: In observed LU changes, fire regime was the most important factor in shaping plant communities. Cover in woody component of the vegetation dramatically decreases with number and frequency of fires, while woody plants species richness is affected by short fire interval.

Cover of herbaceous wasn't affected by fires number but herbaceous species richness (colonizing species) increases with fire frequency.

In a region submitted to land abandonment at Corsica, a French Mediterranean island, Mouillot et al. (2003) obtained some conclusions on fire regime parameters *vs.* vegetation dynamic. They registered on a GIS maps of fires (>4ha) acquired yearly on the base of validated (ex: by aerial photographs) fire fighters or police reports and a topographical map at 1:25000 scale with 20-m resolution, leading to a complete database for the 1970-1997 period on which was added a fire frequency map (1957-1970). This work had the land cover types: Vegetation: Riparian forest; Dense forest; Open forest; High maquis shrubland; Low shrubland; Mixed shrub-grassland; grassland; bare soil. Land use types: Cultivated; Urban. Vegetation types were subdivided in 4 classes according to percentage of occupation of trees or different shrubs height. The authors chose not to use any statistic to test whether a given physical or vegetation variable is related to fires because they assume no independence between neighboring spatial units, due to horizontal fluxes like seed dispersal and fire spread. They found no clear evidence that fires affect more particularly a vegetation type in the first or second burning but shrublands were most affected by several fires, indicating that fires occurred more frequently in the middle and early stages of succession. Results also indicate that vegetation is highly affected by the time since last fire. Dense forests, like fire resistant *Quercus suber* forests, can reappear as soon as 3 or 4 years after fire. First fires seem to be driven by topography only. Reburnings, however, preferentially occur on the south slopes and previously burnt areas. Sites previously burnt at least once, were more susceptible to be burnt than never burnt areas. As a main result, they obtain a mean fire return interval of 40 years at the regional level and two fire regimes at landscape level: one part of landscape subjected to infrequent fires, and another with a 20 year fire return interval. This dichotomy, in one hand allows the development of forest in the never burnt areas and, on the other hand, maintained the shrublands in an early successional stage.

Mouillot et al. (2005) studied two hundred years of landscape changes on a typical Mediterranean environment, where fire history was created. Authors analyzed and simulate rates and patterns of change in landscape composition after land abandonment, in relation to topography and fire. Temporal analyses was done using transition matrices by cross-tabulating maps, and the forest expansion in relation to topography and fire was examined by spatial map analysis and modeling within a GIS. The differences in forest expansion between burnt and unburnt sites were tested using a matched pairs Student T-test. Results show that forest expansion was more rapid in unburnt sites than in burnt sites - mostly because the initial amount of forests was greater - and that the expansion was more uniformly distributed within the burnt area. Because of the border effect, the combination of past landscape pattern and short distance colonization abilities of forest species may have allowed the shrublands to persist in some places after land abandonment. Transition matrices show that forests have mainly increased at the expense of shrublands rather than cultivated areas.

In central Spain, Viedma et al. (2006) verified that in the burned area, the area covered by pine woodlands (main species Pinus pinaster and P. sylvestris dominant at higher elevations) tended to decrease, and that covered by shrublands to increase. For a 15 years period, they used the LULC classifications by the CORINE programme to classify their annual Landsat Multispectral Scanner images, which were analyzed to quantify annual changes in land use/land cover (LULC). Fires were mapped using NDVI, comparing pre-fire and post-fire. The temporal dynamics were analyzed by annually computing the fraction occupied by each LULC type and landscape structural properties. Authors undertook the temporal analysis of LULC changes by annually calculating the percentage occupation of the LULC types for the whole area or for the burned and unburned areas separately.

In eastern Iberian Peninsula Baeza et al. (2007) studied the longterm post-fire vegetation regeneration at the landscape scale; explored the importance of environmental and disturbance factors in explaining the current vegetation patterns; suggest likely successional trajectories in vegetation dynamics after disturbances. The area had a big wildfire in a forest of *Pinus halepensis* and *P. pinaster* forest in 1979, and subsequent several smaller fires between 1984 and 1996. With a multivariate classification of 17 different geomorphological and fire-recurrence units, vegetation cover and floristic composition were measured on 113 plots randomly selected. Results indicate shrublands and grasslands return to their previous state in just a few years. Canonical correspondence analysis results show that, at the landscape level, fire was the main driver of vegetation structure and composition in the area during the study period (23 years). Soil characteristics also affected transition rates. 23 years after one forest fire the site has change from mature pine forest to mainly shrubland. In areas affected by two fires the dominant vegetation is mainly open shrubland/grassland without pines. Less than 5% land cover values of some key tree species like *Q. ilex* and *P. pinaster* indicate a very slow regeneration in the medium term.

In a recent study concerning the same area of Spain, using the same fire maps and a digital elevation model (DEM) used to assess topographical complexity, Viedma (2008) attempted to quantify the influence of topography and fire and their co-variation on the landscape patterns (i.e., composition and structure). Main land covers identified were: deciduous forest, pine woodland, shrubland, pasture, cropland, dehesa (managed pastures with sparse oak trees), bare soil, urban areas and water body. Applying a concept of functional regions - i.e., areas with identical percentage burned area and topographic properties (regions obtained from various classifications with cluster analysis) - and a canonical variance partition method to quantify the co-variation of topography and fire on land cover patterns through time, their results indicate that analyzing portions of the landscape under similar conditions, instead of areas with high environmental heterogeneity, can highlight the effects of fire on the spatio-temporal dynamics of main land covers. Topography was a bigger shaping factor of landscape composition through time than fire and, among landscape structure metrics, only Shannon´s landscape diversity index in burned sites showed certain sensitivity to fire effects. When sites were grouped by the topographical region, fire effects on landscape composition increased and, with the finest classification (groups of burned sites split by topographical regions), the influence of fire and its co-variation with topography on landscape composition increased. Impact of fire on landscape patterns was high variable among regions due to the **different regeneration abilities of main land covers**, the topographic constraints and the fire histories of each region. Authors also concluded that not only fire occurrence neither topography may explain completely the spatio-temporal dynamic of main land covers of their study area, but

land use changes context is also an important driving factor of landscape composition and structure.

Considering all peninsular Spain, Cueva & Martín (2008) address landscape dynamics focusing on land cover changes in vegetation types - mapped by CORINE program - and analysing its relationship with fire occurrence within 1987-2000 period. The original legend was simplified (6 classes: non forestry uses, agro-forestry systems, forests [broadleaved, conifers and mixed forests] and treeless forestry uses) and the major changes synthesised (9 transitions: changes within non forestry; agro-forestry to forestry; within forest areas; forest to treeless forestry; forestry to agro-forestry; non forestry to forestry; agro-forestry to non forestry; treeless forestry to forest; changes within treeless forestry). Fire data was 10×10km UTM quadrats referenced to each fire (≥0.1ha) origin (source: mainly Forestry Administration). GIS was used for crosstabulations and a transition matrix was obtained. Analysis was based on Spearman ranked correlations and on canonical ordination (by redundancy analysis, using CANOCO application) between several fire variables (number of fires and burned area of: forestry system; forest; treeless forestry) and the land cover changes. Results indicate that forest landscapes are more dynamical - with more transitions - and have more fire incidence. Moreover, the more important changes verified - forest to treeless forestry; changes within treeless forestry; treeless forestry to forest - were also the more correlated with fire incidence (see ordination diagram, Figure 4). First two are directly related to forest wildfires effect, while others, like transitions from treeless forestry to forest and from agro-forestry to forest, mean that Spanish counties with more landscape dynamics in terms of changes are also more affected by forest wildfires.

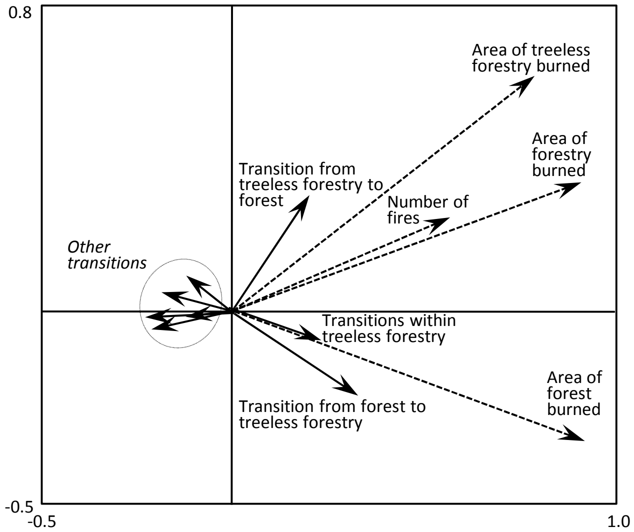

Figure 4. Biplot of correlations based on Redundancy Analysis (RDA) between fire incidence and land cover changes. Each vector is the direction of maximum variation and its length indicates the correlation strength. Same direction indicates correlation between variables. Adapted from Cueva & Martín (2008).

In an area of Mediterranean oak forests of southern Portugal, Acácio et al. (2008) attempted to assess the role of drought and wildfire to explain transitions between vegetation types during 1958-2002 period. Digital orthophotos and scanned aerial photographs were interpreted on screen in 441 sampling units of 50 m-radius circles on a regular 0.5×0.5km grid, from which 10% were field validated. These images covered the time period in 5 years and had different reference scales. Each unit was classified into 5 vegetation types for each image year: cork oak forests; cork oak savannas (tree cover: 10-30%); shrublands; grasslands; others. Information was analysed on GIS and 5 transition matrices outputted. Yearly wildfires limits were available (from National Forest Agency) for 1984-2002 period and were overlaid on GIS with classified sampling units. These authors have used logistic regression to explore the relative importance of variables like wildfire occurrence on the observed vegetation changes. Results point out for a combination of increasing temperatures and wildfire frequency contribution to the expansion of shrublands in previous cork oak dominated areas. Forests and savannas conversion to shrublands took place at an increasing rate and converted patches persist irreversibly. Moreover, shrubland persistence was positively correlated with wildfire occurrence and, in the period 1995-2002, wildfire also increased the probability of transition from forests to shrublands. Shrublands and forests were more persistent vegetation than savannas. The main vegetation changes / persistences along the study period were those above 20% in Figure 5. Authors discussed some changes as indirect transitions. For instance, forest patches change first into savannas and then these into shrublands. Grasslands decreased 300% since 1972 and are remnants today, maintained for family subsistence close to human settlements.

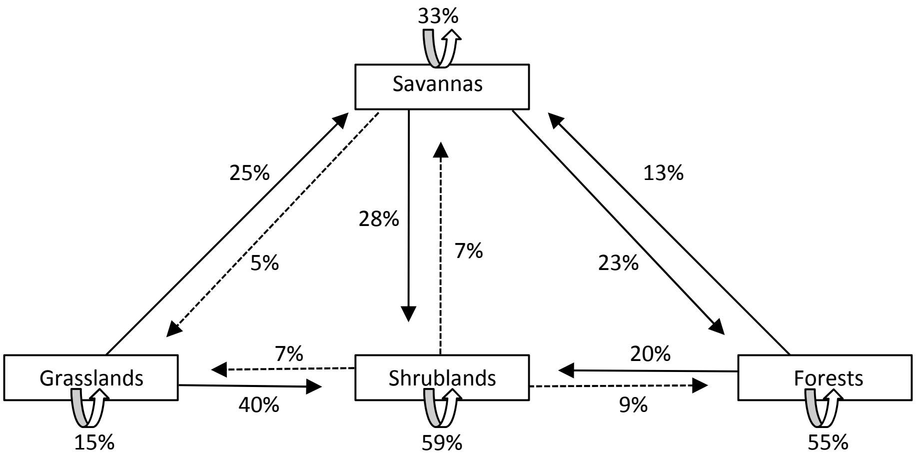

Figure 5. State-and-transition model with observed transitions (%) between vegetation patch-types in southern Portugal (1958–2002). Dotted lines: transitions < 10% (adapted from Acácio et al. (2008)

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