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Wildfire patterns and landscape changes in Mediterranean oak woodlands

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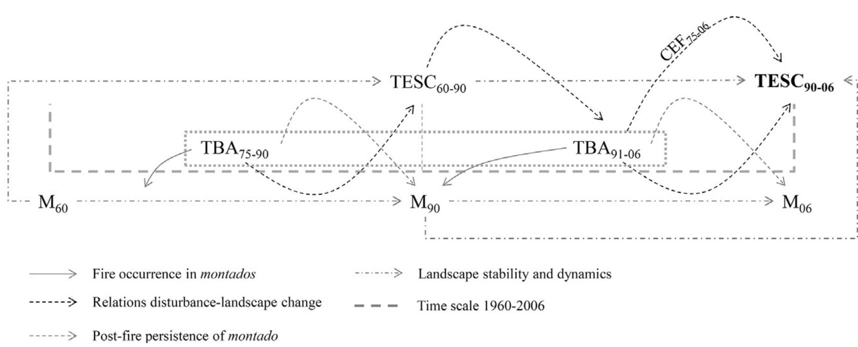
HIGHLIGHTS

- Transitions in Mediterranean oak woodlands (*montados*) were assessed;
- Low spatial connectedness in *montado* landscape increases its vulnerability;
- Changes were mostly explained by fire characteristics and spatial factors;
- Large fires have a major role in transitions from *montado* to pioneer communities.

GRAPHICAL ABSTRACT



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ABSTRACT

Fire is infrequent in the oak woodlands of southern Portugal (*montado*) but large and severe fires affected these agro-forestry systems in 2003–2005. We hypothesised transition from forest to shrubland as a fire-driven process and investigated the links between fire incidence and *montado* change to other land cover types, particularly those related with the presence of pioneer communities (generically designed in this context as "transitions to early-successional communities"). We present a landscape-scale framework for assessing the probability of transition from *montado* to pioneer communities, considering three sets of explanatory variables: *montado* patterns in 1990 and prior changes from *montado* to early-successional communities (occurred between 1960 and 1990), fire patterns, and spatial factors. These three sets of factors captured 78.2% of the observed variability in the transitions from *montado* to pioneer vegetation. The contributions of fire patterns and spatial factors were high, respectively 60.6% and 43.4%, the influence of *montado* patterns and former changes in *montado* being lower (34.4%). The highest amount of explained variation in the occurrence of transitions from *montado* to early-successional communities was related to the pure effect of fire patterns (19.9%). Low spatial connectedness in *montado* landscape can increase vulnerability to changes, namely to pioneer vegetation, but the observed changes were mostly explained by fire characteristics and spatial factors. Among all metrics used to characterize fire patterns and extent, effective mesh size provided the best modelling results. Transitions from *montado* to pioneer communities are more likely in the presence of high values of the effective mesh size of total burned area. This

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cross-boundary metric is an indicator of the influence of large fires in the distribution of the identified transitions and, therefore, we conclude that the occurrence of large fires in *montado* increases its probability of transition to shrubland.

1. Introduction

In fire-prone ecosystems high resilience following fire has often been observed (e.g. Donato et al., 2009; Wittenberg et al., 2007), whether resulting from fire-adaptive or exaptive plant traits (Bradshaw et al., 2011; Keeley et al., 2011). As an example, one can highlight the corky strategy characterized by the presence of thick heat-insulating bark to avoid topkill and allowing the plants to resprout from epicormic buds found along the stems (Dantas and Pausas, 2013). This strategy can be observed in some Brazilian cerrados, cork oak *montados*/*dehesas* in the western Mediterranean basin, pine forests in the Canary islands and northwestern Africa, some American oak woodlands, Californian chaparral or South African fynbos (Dantas and Pausas, 2013; Pausas, 2015). However, as pointed out by Keeley et al. (2011) and Pausas (2015), each observed adaptation is fire-regime dependent and plant species may not show the same response following changes in fire regime. Therefore, decreasing resilience in several fire-prone ecosystems has been observed with increased fire frequency (e.g. Malkinson et al., 2011; Schaffhauser et al., 2011). In this context, post-fire obligate seeders face an immaturity risk resulting from too short fire-free periods to accumulate a seed bank (Keeley et al., 1999), while short-time intervals may affect post-fire resprouters through the exhaustion of belowground energy resources required for regeneration (Paula and Ojeda, 2009).

Fire severity also affects the post-fire responses of plant species (Bernhardt et al., 2011; Moreira et al., 2009a). As stated by Gagnon et al. (2010) survival of plant's belowground and nearby propagules during fire is related of both the flame-front residence time and degree of damage of the aboveground plant's tissues. Moreover, relationships between fire severity and fire extent can also be established to explain habitat loss or landscape changes (Duffy et al., 2007), despite the spatial heterogeneity in fire severity observed following large fires (Bradstock, 2008). Large-scale disturbances lead to high uncertainty in successional pathways differing from the smaller ones if biological legacies are destroyed and colonization from unburned edges is required (Turner et al., 1998). Changes in disturbance regime may then result in the depletion or loss of biological legacies leading to large-scale shifts in vegetation communities, since these legacies are foremost components of ecological resilience determining the composition and structure of ecosystems and landscapes (Fernandes et al., 2015; Seidl et al., 2014). In human-modified landscapes, increased fire activity is usually linked to landscape changes that increased forest fuels connectivity driving transitions from fuel-limited to drought-driven fire regime (Fernandes et al., 2014; Pausas and Fernández-Muñoz, 2012). However, the assessment of fire effects on the landscape is more complex and uncertain in traditional cultural landscapes such as large-scale wood-pastures and agro-silvo-pastoral systems.

Land use systems with scattered trees occur throughout the world, including fire-prone regions. Well-established open oak woodlands can be found in south-western Iberian Peninsula (Pinto-Correia et al., 2011), in eastern Mediterranean basin (Plieninger et al., 2011), and in North America (McEwan and McCarthy, 2008). In south-eastern Australia, similar human-modified landscapes dominated by eucalypts can also be observed (Manning et al., 2006); in central Chile the dominant agroforestry system, known as "espinal", is characterized by the presence of *Acacia caven* (Ovalle et al., 1990); and in northern Algeria open forests with short-needled conifers constitute another example of these open grazed woodlands (Slimani et al., 2014).

These multifunctional landscapes are characterized by the presence of two strata. The overstory is composed of scattered trees highly variable in canopy density (Eichhorn et al., 2006; Godinho et al., 2014a), as a result of wood-cutting and coppicing, shrub clearing and burning, cultivating and grazing (e.g. McEwan and McCarthy, 2008; Naveh and Carmel, 2004). The understory is dominated by annual crops or grasslands often used for grazing and to a lesser extent by evergreen shrubs (Mosquera-Losada et al., 2005). The agricultural and grazing management-related activities maintain low fuel loads and low connectivity between fire-prone fuel types, decreasing fire-spread potential. Some authors emphasized the reduction in fire frequency after livestock introduction (Madany and West, 1983; Savage and Swetnam, 1990), whereas others showed that agroforestry systems or heterogeneous agricultural areas are less fire-prone than other land cover classes (Moreira et al., 2009b; Silva et al., 2009). However, these landscapes face new challenges accentuated by woodland-ageing, regeneration failure and, consequently, global decline of biological legacies (Lindenmayer et al., 2014; Russell and Fowler, 1999). This is particularly alarming in the Mediterranean region as one of the most altered biodiversity hotspots of the world due to centuries of intense land use (Blondel et al., 2010; Naveh and Carmel, 2004).

Are these fuel-limited landscapes, characterized by long fire-free cycles and composed by fire resilient species, currently threatened by fire? To answer this question, we focus on the agroforestry systems in the southern Iberian Peninsula (named *dehesas* in Spain and *montados* in Portugal), as a representative example of cultural landscapes with scattered trees. Decreasing resilience in Mediterranean oak woodlands may be related to more frequent fire (e.g. Schaffhauser et al., 2011) or higher fire severity (e.g. Moreira et al., 2009a). In addition, the interaction between fire and summer-drought could also affect the long-term viability of cork oak stands (Acácio et al., 2009). Transitions from pioneer shrublands to late-successional communities after fire may also be hampered by arrested succession in early-successional communities (Acácio et al., 2007; Putz and Canham, 1992). Some management practices could also affect temporarily the resilience of these land use systems, such as the increased cork oak's vulnerability to fire that can be observed following cork extraction (Catry et al., 2012; Moreira et al., 2007). However, further post-fire assessment of *montado* dynamics at large spatial and temporal scales is needed to understand how wildfire characteristics influence the putative *montado* transition to other land cover types. Positive feedbacks among landscape fragmentation, shrub encroachment, fire and tree density decrease (or even tree mortality) have been previously reported (Acácio et al., 2007; Cochrane and Laurance, 2002). Large fires such as those that affected southern Portugal oak woodlands in 2003–2005 (Silva and Catry, 2006) or in Greece in 2007 (Koutsias et al., 2012) imply lower fire selectivity on the landscape (Barros and Pereira, 2014; Nunes et al., 2005). The extent of these fires can decrease connectivity to source populations limiting the recovery of late-successional communities (Cramer et al., 2008; Turner et al., 1998). Considering all the synergistic factors influencing *montado* resilience, fire can be considered as a catalyst for abrupt changes in landscape, as highlighted by Flannigan et al. (2000).

Information on landscape changes following fire in these areas is critically required for adaptive management to make possible the transition towards late-successional communities, as well as to reduce the effects of new disturbances (Baeza et al., 2007). Our overall goal was to better understand fire-landscape relationships in Mediterranean oak woodlands. Fire effects on vegetation are expected to be related to the recurrence, severity and spatial distribution of fires, justifying the investigation of links between fire incidence and changes from *montado* to other land cover types, particularly those of pioneer communities (referred here and throughout as "transitions to early-successional communities" — TESC). This study examines the relative relevance of