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# Forest shifts induced by fire and management legacies in a *Pinus pinaster* woodland

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ABSTRACT

World forests are undergoing contrasted trends. While in some areas pressures continue, in others these are decreasing, setting forests into a trajectory of recovery. However, disturbances can interact with this process, inducing shifts toward alternative states. Here we investigated the post-fire recovery of an ancient *Pinus pinaster* forest with *Quercus pyrenaica* in the understory in Central Spain, in which intensive management had decreased. Post-fire forest recovery was sampled and stand history was characterized using forest planning records. Stand history, structure and other geophysical data, including fire severity, were utilized as predictors, as appropriate, of pre-fire stand structure and of the post-fire forest using boosted regression trees. We found that pre-fire *Quercus* stem density tended to be higher in stands without recent management plans, although overall stand structure was poorly predictable. The post-fire forest was dominated by *Pinus*, *Quercus*, or a mixture of both. *Pinus* density was mostly unpredictable, while *Quercus* abundance was highly dependent on its pre-fire stem density: In stands with over 200 *Quercus* stems per hectare, the post-fire forest was dominated by *Quercus*. Therefore, fire mediated a forest shift from *Pinus* to *Quercus*, driven by the pre-fire colonization of *Quercus* in the understory in areas with a longer time without management plans. Arguably, in case of recurrent fire, shifts will continue occurring where *Pinus* is still dominant. However, in the longer term, *Quercus* persistence in the area is threatened by climate change, since the climate space will be drastically reduced for *Quercus*, not for *Pinus*.

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## 1. Introduction

Pressures on forests across the world are undergoing contrasted trends. In some areas, anthropogenic pressures continue increasing, often conducing to loss of forest structure and function (Dietze and Moorcroft, 2011; Davidson et al., 2012; Reyer et al., 2015). There is increasing evidence that past certain thresholds the resilience of forest ecosystems decreases, leading to a persistent shift in ecosystem state (Chapin et al., 2004; Folke et al., 2004; Reyer et al., 2015). Moreover, new states can be maintained through disturbance or biological feedbacks (Lindenmayer et al., 2011). On the other hand, in other parts of the world the reverse is occurring, where anthropogenic pressures are decreasing and forests are being less intensively managed (Liu et al., 2015). Once management is altered or ceased altogether, vegetation recovers (Dobson et al., 1997; Cramer et al., 2008; Jones and Schmitz, 2009). The trajectory of recovery, however, may not be straightforward toward the historic vegetation state. Biological processes interact with disturbances to modify forest dynamics and pave the way to alternative states (Suding et al., 2004; Cramer et al., 2008). Identifying tipping points in forest ecosystem dynamics beyond which changes to possible alternative states occur as a result of management or lack of thereof is an important subject in forest ecological research. In fire-prone areas, reducing exploitation management activities, abandoning of forests, or fire suppression can lead to alterations in forest composition and structure that could affect the fire regime. For example, in some North American ecosystems, fire suppression has led to increases of shade-tolerant, low-flammability and fire-sensitive species in the understory, decreasing the probability of fire and, in the end, altering the ecosystem itself (Nowacki and Abrams, 2008; Odion et al., 2010).

In other cases, suppressing fires leads to increases in understory vegetation, fuel loads and their horizontal and vertical continuity (Covington et al., 1997; Larson et al., 2013). Such modifications can also result into changes in fire regimes and deep changes in the ecosystems (Covington et al., 1997; Larson et al., 2013; Cocking et al., 2014). Notwithstanding, the result of these changes

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is not always clear, and alternative states are possible. For instance, Larson et al. (2013) found that *Pinus ponderosa* forests are resilient to recurring fire, recovering the pre-settlement open structure characterized by large trees that supports, and is maintained by, frequent surface fires. However, they also found transitions toward a state dominated by dense, young *Pinus contorta* trees in which crown fires are likely. Examples like this illustrate that there may be thresholds at which the response to a fire can set forest dynamics into divergent trajectories, each of which can be equally stable.

Divergent post-management forest dynamics can result in part from the legacies of previous management history (Foster et al., 2003; Fraterrigo et al., 2005; James et al., 2007). These legacies can interact with fire characteristics (Thompson et al., 2007), and affect post-fire forest composition and structure (Puerta-Piñero et al., 2012). Moreover, a fire may encounter a variety of vegetation types depending on the time elapsed since abandonment and on the phase of the management cycle at which this occurred (e.g., right after clearing or at a mature state just before clearing). This could open the range of possible post-fire vegetation trajectories.

In the Iberian Peninsula, conifers and broadleaved species of the genus *Pinus* and *Quercus* dominate the forest landscapes, forming pure or mixed stands (Costa et al., 1997). Although *Quercus* species have traditionally been considered the climax community, such role has also been recognized for *Pinus* species (Costa et al., 1997; Rubiales et al., 2010). Species of both genera have attributes that allow them to cope with the environmental conditions of the Mediterranean climate, including fire. Field and modeling studies indicate that fire can induce changes in forest composition and dominance in both *Quercus* and *Pinus* pre-fire-dominated stands (Rodrigo et al., 2004; Broncano et al., 2005). Evidence of shifts between *Pinus* and *Quercus* species has been documented during the Holocene (Carrión et al., 2001; Rubiales et al., 2010). *Pinus* forests increased notably during the second half of the 20th century due to large afforestation plans (Valbuena-Carabaña et al., 2010), but in the last decades many of these forests have not received active management (Madrigal, 1998) and are now frequently subject to fires (Moreno et al., 1998; Fernandes and Rigolot, 2007). This includes *Pinus pinaster* Aiton forests, which are the most abundant in the Iberian Peninsula. Many of these forests are being colonized by *Quercus* in the understory (Urbieta et al., 2011; Navarro-González et al., 2013). *Quercus pyrenaica* Willd. and *P. pinaster* show contrasting strategies of post-fire regeneration; while *Quercus* is a resprouter, often quickly producing a thick and continuous cover (Calvo et al., 2003), *Pinus* is an obligate seeder, with varying degrees of serotiny (Tapias et al., 2001). Moreover, *Pinus* seedlings are shade-intolerant. Therefore, once a fire occurs, depending on the understory there is great potential for abrupt changes in these formerly highly managed forests.

Here we studied the post-fire regeneration of a burned *P. pinaster* forest in central-eastern Spain after a high-severity, stand-replacing fire. The area has a long history of management, but active management declined during the last decades of the 20th century, when exploitation for resin was no longer profitable, and much extensive grazing was discontinued. This opened the way to the colonization of the understory by a number of species including *Q. pyrenaica*. Our objectives were to assess if alternative forest states were possible after fire as a result of differences in the understory, and whether these were related to the legacies of management or lack thereof. Specifically, we expected that (i) stand structure, including *Q. pyrenaica* abundance in the understory, would be a legacy of previous management history; thus, (ii) *P. pinaster* would be dominant after fire in the stands where pre-fire understory was clear of *Q. pyrenaica*. However, we hypothesized that past some threshold of abundance of *Q. pyrenaica* in the understory, this species would dominate the post-fire regeneration due to its great resprouting capacity and competitive exclusion of the shade-intolerant *P. pinaster* seedlings.

## 2. Materials and methods

### 2.1. Study site

The study area is located in the Guadalajara province, in Central-Eastern Spain (40°58′N, 2°13′W) at 1000–1400 m in elevation, and has a continental Mediterranean climate, with mean annual temperature of 10.2 °C and mean annual precipitation of 500 mm (data based on the nearby Molina de Aragón meteorological station). In July 2005, a wildfire burned 12,697 ha, the majority of which was a *P. pinaster* Aiton (from now on, *Pinus*) forest, with an understory of scattered oaks (mostly *Q. pyrenaica* Willd.)(from now on *Quercus*) and shrubs. The *Pinus* forests in the area had been intensively managed for resin extraction throughout the 20th century until it became non-profitable in the 1970's. Since then, many of them received little management, as attested by the lack of management plans for most forest units, although exploitation for timber and other secondary products and services may have continued (Pallarés et al., 2001).

### 2.2. Field sampling

A systematic, regular sampling design was implemented 3 and 4 years after fire. A regular grid, with 15 × 15 m plots at every 650 m, was laid over the whole burned area, resulting in 303 plots. At each plot, plant cover (%) of the main woody and herbaceous species was visually estimated. Salvage logging took place after fire, thus tree density was calculated based on the burned stumps. The number of burned stumps of each tree species was counted for each 10 cm diameter class. Here we focused only on the *Pinus* forest, so only plots within the forest management units (with or without *Pinus* trees), or in which *Pinus* stumps were recorded, were used, resulting in 257 plots (Fig. 1), with all but 13 having *Pinus* before fire.

### 2.3. Data processing

Pre-fire stand structure was estimated from the counts of burned stumps and stems of *Pinus* and *Quercus*. Tree density was calculated, and stand structure heterogeneity was estimated with the coefficient of variation of the diameters of *Pinus* and *Quercus* (CV *Pinus* and *Quercus*). *Pinus* and *Quercus* total aboveground biomass were estimated based on the equations from Montero et al. (2005), and average stand height was estimated based on the data from the Third National Forest Inventory (NFI3). See Viedma et al. (2015) for details.

Data on stand history were obtained from forest management plans available at the archive of the regional forest service. Management plans for the different forest units had been developed at different times between 1905 and 2001, normally at a 10-year interval. Not all forest units had a plan from the same date, so to make historical data comparable among forest units, two periods of time were considered: 1954–1963 and 1973–1984 (50's and 70's, respectively, hereafter). Only forest units with management plans made during these two periods were selected for analysis. This permitted maximizing the number of management units and post-fire field plots, which resulted in six forest units and 115 plots. Out of each forest management plan, data on the number of *Pinus* trees and the respective timber volume calculated for the various subunits were recorded and assigned to the corresponding field plots. Additionally, the differences in *Pinus* trees

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