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Research article

Redirecting fire-prone Mediterranean ecosystems toward more resilient and less flammable communities

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ABSTRACT

The extensive abandonment of agricultural lands in the Mediterranean basin has led to large landscapes being dominated by early-successional species, characterized by high flammability and an increasing fire risk. This fact promotes fire occurrence and places ecosystems in a state of arrested succession. In this work, we assessed the effectiveness of several restoration actions in redirecting these ecosystems toward more resilient communities dominated by resprouting species. These actions included the mechanical clearing of early-successional species, the plantation of resprouting species, and the combination of both treatments. For 13 years, we assessed shifts in the successional trajectory and ecosystem flammability by changes in: species composition, species richness, ecosystem evenness, the natural colonization of resprouting species, total biomass and proportion of dead biomass. We observed that the plantation and clearing combination was a suitable strategy to promote resilience. Species richness increased as well as the presence of the resprouting species introduced by planting. The natural colonization of the resprouting species was also enhanced. These changes in the successional trajectory were accompanied by a possible reduction of fire risk by reducing dead fuel proportion. These findings are relevant for the management of Mediterranean basin areas, but also suggest new tools for redirecting systems in fire-prone areas worldwide.

1. Introduction

Fire is one of the most determinant factors driving vegetation dynamics worldwide (Bond et al., 2005). The most classic view is that of fire initiating secondary succession by a unidirectional trajectory toward mature stages (Hanes, 1971; Trabaud and Lepart, 1980). Nevertheless, the mechanisms that underlie vegetation dynamics and their interactions with fire are not always so simplistic. Recurrent fires in short periods of time can produce catastrophic shifts in vegetation structure if certain ecological thresholds are surpassed (Bowman et al., 2013). In other cases, transitions to mature stages can be strongly delayed or practically stopped by the precluding effect of early-successional species (Acacio et al., 2007; Siles et al., 2008). In this sense, expensive ecological restoration techniques should be implemented if these shifts need to be reverted and the restoration success is somewhat uncertain (Vallejo and Alloza, 2015).

In the Mediterranean Basin, the extensive abandonment of agricultural lands in the 20th century has led to large landscape areas in early succession stages (Weissteiner et al., 2011). These human-promoted landscapes are dominated by early-successional species, which are distinguished by their high colonization ability and fast growth (Verdú, 2000; Baeza and Santana, 2015). Commonly named “seeders”, dominant species produce and store numerous seeds in soil or canopy seed banks to ensure their regeneration after disturbances (Clemente et al., 2007; Santana et al., 2014a). Species with soil seed banks often present physical dormancy broken by fire or daily soil temperature fluctuations, which promote a flush of germination immediately after disturbances (Lloret, 1998). Cones forming canopy seed banks (mainly *Pinus* species) usually open after fires for ensuring species regeneration (Verkaik and Espelta, 2006). Many of these early successional seeder species are characterized by their high flammability, conferred by the accumulation of high proportions of dead fine biomass in their plant structure (Saura-Mas et al., 2010; Baeza and Santana, 2015). This dead biomass plays an important role in the

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initiation of fires (Anderson and Anderson, 2010; Marino et al., 2010; Davies and Legg, 2011) and propagation (Fernandes, 2001; Baeza et al., 2002; Davies and Legg, 2011) because its low intrinsic water content.

Recurrent fires in the Mediterranean Basin produce catastrophic shifts in vegetation structure, with changes from forests to shrublands (Karavani et al., 2018). These changes in vegetation composition and structure are also associated with losses in soil organic carbon and fertility (Mayor et al., 2016). In line with this, ecosystem diversity can be negatively affected as a result of the immaturity risk of species; i.e., short fire intervals may led local extinctions because sexual maturity is not reached or seed banks are not replenished (Santana et al., 2014a). Even so, established seeding shrublands can enhance these degradation processes by arresting the colonization of woody resprouting species and other tree species (mainly pines), important for the capacity of vegetation's recovery and their incidence in soil functioning (López-Poma and Bautista, 2014). Dense shrub layers repel seed dispersers (i.e., birds) and preclude seedling establishment by competition (Gómez, 2004; Acácio et al., 2007; Pons and Pausas, 2007). Apart from affecting species diversity, the arrest of bird-dispersed species establishment is a fundamental process to avoid transitions to more resilient communities dominated by woody resprouting species. It has been suggested that communities with higher presence of resprouting species are more resilient because they reduce the response time after disturbance and lower the probabilities of regeneration failure (Vallejo et al., 2006; Riva et al., 2016). For example in the Mediterranean Basin, a typical seeding shrubland is the *Ulex parviflorus* gorseland, which intermixes with *Rosmarinus officinalis* (Baeza et al., 2007). This shrubland is highly flammable because it accumulates high dead fine biomass loads in standing vegetation (Baeza et al., 2006), and it can arrest the transition toward more mature communities dominated by resprouting tree and shrub species (e.g., *Quercus ilex*, *Rhamnus alaternus*, and *Juniperus oxycedrus* among others) (Santana et al., 2010).

In the Mediterranean Basin, interest has been traditionally shown in restoring these mature communities dominated by resprouting species to the detriment of highly flammable seeding shrublands (Vallejo et al., 2006; Moreira et al., 2011). However, practically all the studies have centered on sporadic actions, whose success is assessed in short times (Valdecantos et al., 2009; Siles et al., 2010; Gavinet et al., 2016), obviating successful redirections in the community trajectory toward these states with time. In order to promote transitions from states of arrested succession to more mature states, it is fundamental to overcome the resistance and resilience of the starting community (Alday and Marrs, 2014). In Mediterranean shrublands, management techniques should remove seeding shrubs and limit their regeneration, while the establishment of resprouting species is promoted at the same time (Riva et al., 2016). Mechanical clearing and the subsequent mulching of chopped vegetation could be suitable techniques to overcome shrubs' resistance/resilience (Baeza et al., 2003; Potts and Stephens, 2009; Fernández and Vega, 2016). Some studies have observed that, apart from removing shrubs by clearing, mulching can reduce the regeneration of seeder species by hindering the breakage of seed dormancy and germination (Baeza and Roy, 2008; Santana et al., 2014b). Moreover, plantations of resprouting species may be fundamental to implant a mature community, with greater resilience thanks to their regeneration capacity (Verdú, 2000). However, no studies have dealt with selective clearing, mulching and planting resprouter seedlings as a whole, aiming to redirect the vegetation community toward a desired community in the mid term, and especially in the long term.

This work assessed the effectiveness of several restoration actions for redirecting Mediterranean old fields toward more mature and resilient communities. Mechanical clearing with mulching and plantations of resprouting species was performed in flammable communities dominated by seeding shrubs. First, we assessed the possible overcoming of shrubland resistance/resilience of any treatment, and if the community trajectory was redirected to the desired community (Alday and Marrs, 2014). Second, we evaluated if the changes in community composition were associated with increases in species richness, evenness, and lower biomass loads and dead biomass proportions. We hypothesized that these treatments may be effective in the redirection of the community toward more resilient stages.

2. Material and methods

2.1. Study site

The study site is located in the Valencian region, east Spain. It is a mountainous area made up of a mosaic of agricultural lands, abandoned croplands and pine forests (mainly *Pinus pinaster*, but also mixed with *P. halepensis*) (Baeza et al., 2007). Mature vegetation is usually a sclerophyllous oak forest of *Quercus ilex* accompanied by other resprouting broad-leaved shrubs, but this vegetation is currently absent as a result of a long-standing history of human deforestation and cultivation. Only small isolated patches are present in valley bottoms and on steep north-facing slopes. Soils are mainly Regosols developed from marls. Climate is typical Mediterranean, where mean annual temperature and rainfall are 13.4 °C and 458 mm, respectively. In 1979 a huge wildfire affected more than 33,000 ha of this area, which burned mainly the *P. pinaster* forests that colonized the old fields that had been abandoned in the mid-20th century.

Twenty-four years after the 1979 fire, regenerated vegetation in the burned old fields comprised dense *Ulex parviflorus* gorseland, accompanied by some sparse pines. Other obligate seeding shrubs, such as *Rosmarinus officinalis* and *Cistus albidus,* were present but to a lesser extent, along with isolated resprouting shrub individuals of *Quercus coccifera* and *Juniperus oxycedrus*. This gorseland is characterized by both its high biomass loads and dead fine biomass proportions, which confer high fire risk levels (Baeza et al., 2006). The dominant species in the first post-fire stages is usually *U. parviflorus,* but approximately 17 years after disturbance, this species has become senescent and starts to decline (Baeza et al., 2006). The community is thus becoming dominated by other seeding species, such as *R. officinalis*, which is much longer-lived.

2.2. Experimental design

In 2003, an experiment to test the suitability of combining two management techniques (selective clearing and plantation) in flammable Mediterranean shrublands was set up. The experiment was replicated at three different sites: Roñoso (39°07′22″N, 0°57′56″W), Morera (39°07′17″N, 0°57′11″W) and Gachas (39°01′58″N, 0°53′30″W). All the sites were old fields that faced NE, and their elevation ranged from 978 to 1032 m above sea level. For more details of the study site, see Valdecantos et al. (2009).

The experimental design consisted in combining two different techniques; i.e., selective clearing and planting. In 2003, four neighboring plots of ca. 1000 m^2 were selected at each site to apply treatments. The four performed treatments followed a complete factorial design of the applied techniques: (i) Clearing; (ii) Plantation; (iii) Clearing + Plantation; (iv) Control.

Clearing consisted in removing the *U. parviflorus* gorseland with a scrub-clearing machine equipped with a vertical-axle chain drive (Fig. S1 in the supplementary material). The cutting height of the