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Temporal characterisation of soil-plant natural recovery related to fire severity in burned *Pinus halepensis* Mill. forests

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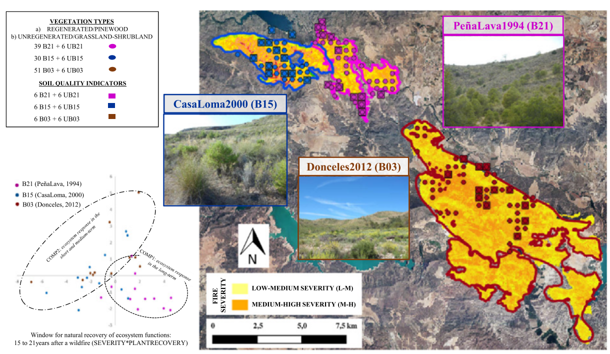
HIGHLIGHTS

- The plant-soil interphase is related to fire severity and post-fire time.
- Fire severity affects ecosystem recovery in the short term.
- Plant recovery promotes soil biochemical recovery in the mid term.
- Soil properties recover in the long term after fire (21 years).
- The plant-soil window for natural recovery in semiarid areas is 15–21 years.

GRAPHICAL ABSTRACT



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ABSTRACT

Despite Mediterranean ecosystems' high resilience to fire, both climate and land use change, and alterations in fire regimes increase their vulnerability to fire by affecting the long-term natural recovery of ecosystem services. The objective of this work is to study the effects of fire severity on biochemical soil indicators, such as chemical composition or enzymatic activity, related to time after fire and natural vegetation recovery (soil-plant interphase). Soil samples from three wildfires occurring 3, 15 and 21 years ago were taken in the south-eastern Iberian Peninsula (semiarid climate). Sampling included three fire severity levels in naturally regenerated (and changing to shrublands) *Pinus halepensis* Mill. forests.

In the short-term post-fire period, phosphorus concentration, electrical conductivity and urease activity were positively linked to fire severity, and also influenced β-glucosidade activity in a negative relationship. During the 15–21-year post-fire period, the effects related to medium-high fire severity were negligible and soil quality indicators were linked to natural regeneration success. The results showed that most soil properties recovered in the long term after fire (21 years).

These outcomes will help managers and stakeholders to implement management tools to stabilise soils and to restore burned ecosystems affected by medium-high fire severity. Such knowledge can be considered in adaptive

Abbreviations: SEVERITY, fire severity classification at three levels:; L-M, low-medium severity; M-H, medium-high severity; YEAR, Time after wildfire, years from fire to sampling in spring 2015; B21, PeñaLava wildfire, 1994 (1305 ha burned); B15, CasaLoma wildfire, 2000 (1130 ha burned); B03, Donceles wildfire, 2012 (5500 ha burned); UB15, UB21, UB03, Mature stands (no wildfire from >80 years); PLANTRECOV, Successful natural vegetation recovery related to vegetation types; PINE, Vegetation type dominated by Aleppo pine stands; SHRUBLAND, Vegetation type dominated by shrublands-scrubland-Alpha grasslands; REG, Plant regenerated successfully, similar pre- and post-fire vegetation type; UNREG, Plant regenerated to a degraded successional post-fire stage.

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forest management to reduce the negative effects of wildfires and desertification, and to improve the resilience of vulnerable ecosystems in a global change scenario.

1. Introduction

Fires are a major ecosystem process in Mediterranean biomes that play a key role in the distribution and composition of terrestrial ecosystems (Bond and Keeley, 2005). In the Mediterranean Region, fire acts as evolutionary pressure that shapes plant traits in ecosystems (Keeley et al., 2012). However, in the second half of the 20th century, fire regime changes were due mainly to climate change and rural collapse (Pausas and Keeley, 2014), which promoted increasing socio-economic costs (Dale et al., 2001). Indeed the number and size of wildfires increased in Spain and Portugal the whole year, and affected landscape change dynamics by reducing woodland surface, mainly in areas burned by large fires (>500 ha) (San-Miguel-Ayanz et al., 2012). Fire plays an important role in the management of Mediterranean ecosystems, especially in arid and semiarid regions where biological soil stability in undermanaged stands is more vulnerable (Hedo et al., 2015). Fire recurrence also plays a key role in the vulnerability and resistance of the plant-soil interphase (Guénon et al., 2013), and should be considered in adaptive forest management (e.g. climate change, fire regime) (Doblas-Miranda et al., 2017). In Mediterranean ecosystems, fire recurrence higher than four in <50 years is a threshold to reduce woody cover, and endangers soil quality by affecting soil carbon cycling and microbial activity (Tessler et al., 2016; Zavala et al., 2014).

Mediterranean soils are sensitive to wildfires, but their impact depends on fire severity, recurrence and time after the fire (Bodí et al., 2013; Mataix-Solera et al., 2009; Bárcenas-Moreno et al., 2016; Vega et al., 2013b). Fire severity is defined as the loss of or a change in aboveground and belowground organic matter (Keeley, 2009; Vega et al., 2013a). It is the most critical factor that directly and indirectly affects vegetation (Vallejo et al., 2012) and soil response (Maia et al., 2012; Bárcenas-Moreno et al., 2016), especially in semiarid areas of the Mediterranean Basin (Hedo et al., 2015).

Soil-plant interphase feedback is a research priority to improve ecosystems management and to enhance their resilience. This includes standardised protocols and long-term monitoring to integrate results into models to predict soil changes after wildfires (Doblas-Miranda et al., 2015). The most widely used tools to identify the impact of disturbances and management practices are ecophysiological indices, such as the microbial quotient, the metabolic quotient or enzymatic activities related to soil microbiology (Bárcenas-Moreno et al., 2011; Hedo et al., 2015; Mataix-Solera et al., 2009; Zavala et al., 2014). Soil enzyme activities are a direct expression of the soil microbial community that link resource availability, structure and function to ecosystem processes (Caldwell, 2005). Fire affects soil properties directly, such as pH, and other processes indirectly, such as variations in the fungi/bacteria ratio (Bárcenas-Moreno et al., 2011; Mataix-Solera et al., 2009), or the enhancement of microbial activity related to high carbon availability and low nitrogen loss rates in dry soils (Choromanska and Deluca, 2002). With negative impacts, the recovery of the soil-plant interphase should be supported by implementing active tools to stabilise and restore disturbed ecosystems to enhance their resilience (Certini, 2005; Doblas-Miranda et al., 2015).

Our study was carried out in Aleppo pine forests (*Pinus halepensis* Mill.), which are the most widely distributed forests throughout the low altitude areas of the Mediterranean Basin (Quezel, 2000). Aleppo pine is a pioneering obligate seeder with a dual-life strategy and precocious reproduction that bears both serotinous and nonserotinous cones, is adapted to summer droughts, and is exaptated to wildfires (Keeley et al., 2012). Several studies have focused on its post-fire vegetation in semiarid stands (Alfaro-Sánchez et al., 2014; Moya et al., 2015). Synchronic studies have corroborated the fact that resilient plant communities, such as Aleppo pine forests in the Mediterranean Basin (Capitanio and Carcaillet, 2008; González-De Vega et al., 2016), rapidly recover following the initial floristic composition model of Egler (1954). However, these studies exclude soil recovery. In the Aleppo pine stands that occur in SE Spain, changes in fire regimes and increasing fire severity have reduced the time window for the "immaturity risk" and have induced land use changes that range from pine forests to shrublands (González-De Vega et al., 2016). In these ecosystems, the structure of plant functional groups and fire severity not only influence soil enzymatic activity through alterations in nutrient cycling dynamics, but reduce resilience in these drought- and fire-prone areas (López-Poma and Bautista, 2014; Hinojosa et al., 2016). However, both fire resistance and the working scale influence fire damage to soil (Diaz-Delgado et al., 2003; López-Poma and Bautista, 2014). The main objective was to evaluate the effect of plant recovery, burn severity and time after fire on soil properties in three burnt areas undisturbed for different periods lasting 3, 15 and 21 years. We characterised fire damage on soil by implementing a synchronic approach by recording different quality soil indicators in three large wildfires and relating them to fire severity, natural plant recovery and time after fire. The initial hypothesis was that the unburned areas showed similar soil and vegetation conditions before fires. In this way, the variability and relationships found for quality soil indicators were related to the short-, mid- and long-term post-fire periods, and also to fire severity and the plant community recovery.

2. Materials and methods

2.1. Site description and fire severity mapping

The experimental design was applied to three burned areas in the summers of 1994, 2000 and 2012 in SE Spain, separated by <15 km and from the town of Hellín (in the province of Albacete). These areas presented similarities in vegetation, soil, and climate terms, and had remained unburned for >80 years according to the fire perimeters provided by the Forest Services of the Regional Castilla-La Mancha Government.

The study area has a semiarid Mediterranean climate and is located on the upper meso-Mediterranean bioclimatic belt. The average precipitation and annual temperature values are 278.5 mm and 15.85 °C, respectively (based on the 25-year data period from 1990 to 2014 provided by the Spanish Meteorological Agency). The dry period usually goes from June to September, during which relative humidity is below 50%. The studied soils belong to the order Aridisol, suborder Calcid (Soil Survey Staff, 2014) and have a sandy-clay-loam soil texture (57.32 ± 2.95% sand, 30.52 ± 5.66% clay and 12.16 ± 5.96% silt). The predominant landform is composed of dolomitic limestones that shape strong rocky slopes, whose altitudes range from 500 to 700 m a.s.l. The landscape comprises similar topographic characteristics, plains and hills on which fields and natural vegetation settle. Following Rivas-Martínez (1982), the vegetation series belong to *Rhamno lycioidis-Querceto cocciferae sigmetum*. Before fires, the following grew in the area: *Pinus halepensis* Mill. (Aleppo pine), *Macrochloa tenacissima* (L) *Kunth* (Alpha grass), *Quercus coccifera* L. (Kermes oak) and *Pistacia lentiscus* L. (Mastic tree). In the 19th century, the landscape underwent land-cover and land-use changes, which enhanced the economic benefit of Alpha grass, abandoned in the late 20th century.