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Interactions between large high-severity fires and salvage logging on a short return interval reduce the regrowth of fire-prone serotinous forests

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ABSTRACT

New fire disturbance regimes under accelerating global environmental change can have unprecedented consequences for ecosystem resilience, lessening ecosystem natural regeneration. In the Mediterranean Basin, fire-dependent obligate seeder forests that are prone to increasingly frequent stand-replacing fires and then salvaged logged repeatedly can be vulnerable to additional disturbances for decades. In this study, we investigated, for the first time, the cumulative and interactive effects of two large high-severity fires at a short (< 15-year) return interval and the subsequent burned timber harvesting with biomass removal on the post-disturbance recovery of such forests. We further assessed the type and amount of the material legacies (deadwood) that persisted through the different post-disturbance successional trajectories, as well as the influence of these legacies on forest regeneration. The early recovery of the studied forests after two consecutive large fires and post-fire logging was, in the first place, driven by fire repetition, which led to reduced seedling recruitment and enhanced regrowth of resprouter shrubs. Despite no interactive effects between fire and logging were detected after a single large fire event, two repeated fires followed by salvage harvesting had a greater negative impact than two fires alone (synergistic effects) on seedling establishment; while a lower positive impact (subadditive effects) on the recovery of resprouter shrubs. There was also an interaction modification effect in which fire repetition worsened the per-unit impact of salvage logging on forest regeneration. Nonetheless, the residual legacies, i.e., fine and coarse woody debris (unburned needles, downed branches, pieces of deadwood, and burned pine cones) that remained after the manual harvesting of the burned trees, aided seedling re-establishment and hindered the regrowth of the shrubby understorey. These findings indicate that high-intensity salvage logging after two large high-severity fires at a short return interval is inadvisable in fire-prone serotinous pine forests, unless it explicitly retains the key material legacies that help tree natural regeneration and enhance ecosystem resilience to the next disturbance.

1. Introduction

Disturbances are worldwide recognized as major drivers of ecosystem dynamics, influencing service provision and human wellbeing (Thom & Seidl, 2016; Turner, 2010). Latest advances in disturbance ecology emphasize the complex nature and commonness of interactions involving both natural (e.g., wildfires, insect outbreaks, floods) and human (e.g., logging, grazing, sod-cutting) disturbances in many types of ecosystems (reviewed by Buma, 2015; Johnstone et al., 2016). Multiple disturbance interactions generally have unanticipated (sometimes counterintuitive) impacts on key ecosystem processes (Thom & Seidl, 2016) that are unpredictable from knowledge of either disturbance alone (Buma, 2015; Doblas-Miranda et al., 2017) and critical to the management of ecosystems (Foster et al., 2016). This is particularly relevant in the Mediterranean Basin, a rich and unique biodiversity region with a long history of disturbances, but where knowledge on the ecological impacts of disturbance interactions remains scarce (Doblas-Miranda et al., 2014, 2017).

Rapid shifts in disturbance regimes (i.e., disturbance size, intensity, severity, and return interval; Turner, 2010) under accelerating global environmental change have further unprecedented consequences for ecosystem recovery and resilience to the next disturbance (Doblas-Miranda et al., 2017; Johnstone et al., 2016). These changes very often lead to novel combinations of disturbances (Lindenmayer, 2016), new post-disturbance successional trajectories (Trumbore et al., 2015; Turner, 2010) and altered disturbance legacies (Donato et al., 2016; Johnstone et al., 2016; Turetsky et al., 2017); which can trigger abrupt ecosystem transitions to alternate states (Johnstone et al., 2016) risking

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ecosystem collapse (Keith et al., 2013; Lindenmayer et al., 2016). For example, wildfires occur with greater frequency, extent and severity than in the past in Mediterranean ecosystems under a warmer and drier climate (Pausas & Fernández-Muñoz, 2012; Pausas & Vallejo, 1999; Pausas et al., 2008), promoting transitions to high-flammability shrublands (Baeza et al., 2007; González-De Vega et al., 2016; Retana et al., 2002) and challenging policy and landscape management (Moreira et al., 2011). Despite this, to our knowledge, there are no studies assessing the interactive effects and the potential cumulative impact ('double whammy' effect; Lindenmayer, 2016; Turner, 2010) of new wildfire regimes and post-fire management in Mediterranean ecosystems.

Large (> 500 ha) high-severity fires and post-fire salvage logging (i.e., the removal of burned trees and remaining woody debris) can interact via many different mechanistic pathways, basically divided into interaction chain and interaction modification effects (Didham et al., 2007; see also Foster et al., 2016). Fire can affect the likelihood of execution, and the nature and timing of post-fire logging (e.g., dependent on fire extent and severity), indirectly influencing harvest effects on ecosystem recovery (Fernández et al., 2008) (a chain interaction). Similarly, logging can affect the probability of occurrence and the magnitude of a subsequent fire by altering fuel and post-fire successional trajectories (Dunn & Bailey, 2015; Fraver et al., 2011; Lindenmayer, 2016), also indirectly influencing fire effects on ecosystem recovery (a chain interaction). On the other hand, fire and post-fire logging can influence each other's impact on ecosystem regeneration, by altering e.g., plant species composition and response strategies (Blair et al., 2016; Calvo et al., 2012; Leverkus et al., 2014; Pausas et al., 2008), seedling recruitment and mortality (Castro et al., 2011; Espelta et al., 2008; Eugenio et al., 2006; Fernández et al., 2008), and the net outcome of plant interactions (Castro et al., 2011; Marañón-Jiménez et al., 2013; Marzano et al., 2013; Taboada et al., 2017) (an interaction modification). Disentangling the nature and relative importance of these interactions requires uncoupling their constituent legacies (Buma, 2015), and is crucial to develop novel management interventions to speed up ecosystem recovery under new disturbance scenarios (Didham et al., 2007; Foster et al., 2016; see e.g., Mandle & Ticktin, 2012).

In this study, we analyse the interactions between and the potential cumulative effects of two sequential large high-severity fires and the subsequent salvage logging operations on the recovery of a Mediterranean fire-dependent obligate seeder forest (namely, serotinous maritime pine forest) threatened by increasing wildfire frequency (Bowman et al., 2014; Buma et al., 2013). We further examine the effects of the material legacies (deadwood) (Johnstone et al., 2016) that persisted through the different post-disturbance successional trajectories (i.e., recovery trajectories; Johnstone et al., 2016; Turner, 2010) on ecosystem regeneration. The regrowth of Mediterranean serotinous pine forests after a single fire is achieved by direct regeneration of the preceding plant community (associated to fire-stimulated seed germination and to the activation of resprouter species; Calvo et al., 2012; De las Heras et al., 2012; Pausas et al., 2008; Rodrigo et al., 2004). However, their recovery after a large high-severity fire that eliminates most of the vegetation can be undermined with prolonged deleterious effects (González-De Vega et al., 2016). We, therefore, expect that the occurrence of two consecutive large high-severity fires at a short return interval (< 15 years) will lessen forest regrowth as it will (i) lower the reproductive ability, recruitment and performance of serotinous pines (Espelta et al., 2008; Eugenio et al., 2006) and (ii) favour either fast-growing resprouter shrubs adapted to frequent fires (Calvo et al., 2012; Pausas & Vallejo, 1999) or obligate seeder shrubs with fire-stimulated germination and tolerant to high-severity fires (Pausas & Keeley 2014) and high water limitation (Moya et al., 2015).

We also expect a greater negative impact of a large high-severity fire on forest regrowth in combination with post-fire salvage logging (synergistic interactive effects); together with an interaction modification effect (Didham et al., 2007) in which (i) the per-unit impact of fire on forest recovery will be aggravated when harvesting is executed immediately (< 1 year) following fire (Fernández et al., 2008; Moya et al., 2015), and (ii) the per-unit effect of salvage logging will be worsened after two repeated fires at a short return interval. The disturbance caused by salvage logging operations (i.e., trampling, tree felling, and dragging) will damage the soil seed bank and increase soil compaction (Malvar et al., 2017) when removing potential nurse objects (burned tree trunks, branches, logs, and snags) that facilitate seedling establishment, overall reducing seedling recruitment and performance (Castro et al., 2011; Marañón-Jiménez et al., 2013). Moreover, salvage harvesting with biomass removal will strongly decrease or eliminate other fire-derived material legacies (particularly, fine and coarse woody residuals; Dunn & Bailey, 2015; Hood et al., 2017; Keyser et al., 2009) that are important to seedling establishment (Marzano et al., 2013; Vacchiano et al., 2014), thus, negatively affecting forest regeneration (Lindenmayer & Noss, 2006). We therefore expect a significant cumulative impact of repeated salvage logging after two consecutive large fires over relatively short time (< 15 years) on post-disturbance forest recovery (Lindenmayer, 2016).

2. Materials and methods

2.1. Study area and fire history

The study was conducted in Sierra del Teleno mountain range (NW Spain; 42°15′34″N/06°12′13″W; 915–1200 m a.s.l.; 10% average slope; Fig. 1), a landscape dominated by maritime pine (*Pinus pinaster* Ait.) natural forests (ca. 20,000 ha) for timber and resin production and with a tall (up to 1.5 m height) shrubby understorey [*Erica australis* L., *Pterospartum tridentatum* (L.) Willk., *Halimium lasianthum* spp. *alyssoides* (Lam.) Greuter]. The climate is Mediterranean with mean annual precipitation between 650–900 mm, mean annual temperature of 10 °C, and 2–3 months of summer drought.

Wildfires are very frequent, typically caused by dry lightning storms [172 small fires (< 500 ha) in 1974–2007; Santamaría, 2015], and favoured by the coexistence of high plant productivity (fuel accumulation) and summer drought (Fernandes & Rigolot, 2007). *P. pinaster* forests in the study area are highly adapted to intense crown fires with more than 95% of the trees bearing serotinous cones (Tapias et al., 2004). However, under the current fire return intervals (less than 10–15 years; Santamaría, 2015) *P. pinaster* is frequently unable to reach reproductive maturity between repeated fires (Pausas et al., 2008; Tapias et al., 2001), and, therefore, at risk of disappearance in favour of shrublands, as in many areas of the western Mediterranean Basin (Baeza et al., 2007; Fernandes & Rigolot, 2007).

In 1998, a large high-severity wildfire burned the area (13–14 September, 3670 ha, pine tree density = 500–900 individuals/ha, pine tree age = 60–85 years-old) (Fig. 1). In 2012, a second large high-severity wildfire occurred (19–21 August, 9971 ha affected by a single large fire event, mean pine tree density = 906 individuals/ha, pine tree age = 35–95 years-old), partially overlapping the 1998 burn (1920 ha affected by the two large fire events, mean pine tree density = 12,778 individuals/ha, pine tree age = 12–14 years-old) (Fig. 1). Burn severity values ranged 2.25–3 as measured directly in the field by the Composite Burn Index on a total of 111 30-m-diameter circular plots after the 2012 fire (Quintano et al., 2015, Quintano et al. (2017)). In both large fire events, the understorey was totally destroyed and the majority of tree crowns were completely consumed by fire. Subsequent to the two large fires, salvage logging of the burned stands was implemented by the regional Forest Service (Government of Castilla and León) with the same harvesting intensity (i.e., high intensity, with 70–80% of merchantable burned wood removed), either immediately following fire (< 1 year; in 1999 and 2013, respectively) or after a short delay (> 1 year; in 2014) due to the vast extent of the burned area (Table 1). In the salvaged stands, all dead trees were cut and felled by mechanical