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Fire behavior in *Pinus halepensis* thickets: Effects of thinning and woody debris decomposition in two rainfall scenarios

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ABSTRACT

Thinning is recommended in overstocked thickets to improve forest structure and reduce high-intensity stand replacing fires. Many studies have outlined the benefits of thinning for forest growth and reproduction but effectiveness in fire intensity needs more attention. Moreover, the effect that slash generated by thinning may have on fire behavior has been seldom explored. Here we simulated fire behavior on unthinned and thinned Aleppo pine (*Pinus halepensis*) thickets in Catalonia (Northeast Spain) where woody residues were left in situ. Furthermore, we simulated fire behavior one year later considering the reduction in the dead fuel load, using decomposition rates empirically determined under high and low rainfall. We could also assess the accuracy of our simulations by measuring fire severity on trees in the same study area after a real wildfire. Simulations predicted that thinning prevents the occurrence of active crown fires and reduces mean flame length (from 6.2 ± 0.8 to 1.5 ± 0.2 m), the rate of fire spread (from 5.4 ± 0.9 to 0.9 ± 0.1 m min^{-1}) and the fireline intensity (from 3631 ± 686 to 446 ± 70 kW m^{-1}) compared to unthinned thickets. In the thinned stands these parameters further decrease one year later owing to the decomposition of woody residues. Decomposition of woody residues was observed to be faster under a high rainfall scenario leading to a reduction in simulated flame length and fire intensity twice as fast as under low rainfall. In accordance with the lack of active crown fires and the lower flame length predicted for thinned thickets, fire severity observed after a real wildfire in the study area was lower in thinned than in unthinned stands (respectively, 2.02 ± 0.13 vs. 2.93 ± 0.15 in a scale of 0–4). The agreement between simulations that predicted a reduction in fire intensity in thinned thickets and the lower fire damage (fire severity) observed confirms the benefits of thinning young *P. halepensis* thickets to reduce fire effects. Moreover, our results indicate that leaving woody residues in situ after the thinning of these young thickets does not increase fire intensity. Yet, the influence of precipitation on the decomposition of woody residues highlights the uncertainties that an increase in drought in Mediterranean-type climates may have in the behavior of future fire events.

1. Introduction

The successful post-fire regeneration of tree species with a “seeder” strategy often results in “thickets” or “dog hair stands”: i.e. extremely dense, highly crowded monospecific forests formed by a single cohort of young trees with similar height (De las Heras et al., 2012). The fast recovery of vegetation cover through profuse seed germination entails positive effects such as maintaining the species dominance while rapidly reassuming the provision of crucial ecosystem services such as carbon sequestration (Moya et al., 2007; De las Heras et al., 2012). Yet overstocking also causes a reduction in tree growth and delays reproduction onset (Verkaik and Espelta, 2006), increasing the so-called “immaturity risk” (see Ne’eman et al., 2004): i.e. the risk that a new stand-replacing wildfire will occur before a seed bank has developed (Espelta et al., 2008).

To ameliorate the forest structure of these overstocked post-fire regeneration thickets, density reduction (thinning) at an early age is strongly recommended and numerous studies have outlined the benefits of this practice to enhance tree growth (González-Ochoa et al., 2004; López-Serrano et al., 2005; Moya et al., 2007), reproduction onset and seed crop size (Verkaik and Espelta, 2006), and even to better cope with other disturbances (e.g. drought in Espelta et al., 2011; Casals et al., 2015). In addition, thinning is one of the most commonly applied silvicultural practices to reduce the amount and continuity of fuels and

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limit the potential of intense fires (Graham et al., 1999), ultimately improving the resistance of forests to this disturbance (Fernandes et al., 2008; Casals et al., 2015). Interestingly, this rationale derives from studies conducted in mature forests (Fulé et al., 2001; Agee and Skinner, 2005; Raymond and Peterson, 2005), but there is a lack of evidences from thinning experiments conducted in young thickets.

Ameliorating thicket structure through thinning is not profitable, especially in areas with low timber yields such as the Mediterranean Basin, and it relies largely on public funds. Thus, owing to the lack of commercial value, removed saplings are usually chopped and laid on the soil to reduce the costs of slash grinding, and to increase the possibility of thinning a larger area at a lower total cost (Llobet et al., 2008). Many studies report the importance of woody debris to forest functioning as a habitat and food resource for many species (Harmon et al., 2004), benefits for the germination and establishment of seedlings (Kuuluvainen and Kalmari, 2003) or the role as a carbon sink (Van Miegroet et al., 2007). In addition, in areas undergoing severe drought episodes such as Mediterranean climates, slash can act as a sort of "mulch", increasing soil moisture (J.M. Espelta, unpublished results). However, the effect on the fire behavior of woody debris in thinned thickets has been barely addressed although it may be critical when assessing the suitability of this type of forestry practices.

Fire behavior can be quantitatively predicted by means of mathematical models (Rothermel, 1972). These are powerful tools that allow forest managers to characterize and predict fire spread and behavior in order to evaluate the effectiveness of silvicultural treatments and to plan wildfire control strategies across a landscape, considering specific fuel types related to forest composition and structure (Fernandes, 2009). Yet although fuel models can provide an effective way to assess the potential effects of management on fire behavior, they need to be verified using field research in terms of fire severity on vegetation and calibrations from fire behavior observed in past wildfire events (Albini and Stocks, 1986). In recently thinned thickets, an important part of this modeling exercise will be to reproduce the process of woody residue decay, since one of the most important factors driving fire susceptibility is the presence of dead and down material (Bond and Van Wilgen, 1996) while the temporal dynamics of fuel accumulation and structure will influence the fuel treatment longevity (Gould et al., 2007). Dead fuel characteristics are very important in fire behavior because fine dead fuel moisture changes drastically with environmental conditions (Nolan et al., 2016). However, there is a lack of experimental studies on the relation between dead fuel dynamics and fire behavior. The amount of woody debris (dead fuel material) generated after thinning will change over time, especially during the first years, depending on woody debris size and climatic conditions such as temperature and moisture (Harmon et al., 2004). Moreover, under harsh climatic conditions for decomposition of woody debris, such as the Mediterranean climate, changes in precipitation and temperature predicted under a climate change scenario will probably alter woody debris decay (Russell et al., 2014).

The main aim of this study was to investigate how the thinning of young Aleppo pine (*Pinus halepensis* Mill.) thickets can affect fire behavior. Aleppo pine is one of the tree species with a post-fire obligate-seeder strategy more abundant in the Mediterranean Basin (ca. 2.5 million ha; see Daskalakou and Thanos, 1996) and also a successful invader of other Mediterranean-type areas (e.g. South Africa and Australia in Richardson, 2000). Successful regeneration of Aleppo pine after fire is based on the massive liberation of seeds from cones (partly serotinous) and their ability to germinate in exposed mineral seedbeds (De las Heras et al., 2012) resulting in high density thickets dominated by this species (González-Ochoa et al., 2004; Ne'eman et al., 2004; Pausas et al., 2004; Moya et al., 2007). The specific objectives of our study were: (i) to simulate the main parameters characterizing fire behavior in thinned and unthinned thickets and to compare the results obtained with field observations of fire severity recorded after a real wildfire event that occurred in the same study area, (ii) to assess the changes in fire behavior on thinned stands after one year taking into account the decay of woody debris experimentally measured under two precipitation levels (high and low). The results obtained may help to design management practices of overstocked thickets in order to reduce fire severity and spread. Moreover, simulations under different precipitation scenarios allow us to envision how the predicted increase in drought in Mediterranean-type climates owing to climate change (IPCC, 2013) may impact these practices.

2. Materials and methods

2.1. Study area

The data used in this study were obtained in a 29-year-old *P. halepensis* thicket (ca. 750 ha) grown from natural regeneration after a wildland fire event in 1986. We selected this particular forest age as representative of a large amount of current Aleppo pine forests established after the large wildfire episodes during the 1980s and 1990s in the Mediterranean Basin, and especially, on the eastern Iberian Peninsula (Espelta et al., 2002). The study site is located in El Bruc in the province of Barcelona (41°34′N, 1°46′E, Catalonia, NE Spain). Climate is dry-subhumid continental Mediterranean (according to the Thornthwaite index), characterized by mild winters and hot, dry summers. Mean annual temperature ranges from 14.1 to 16.3 °C and from 22.3 to 24.1 °C during summer. Precipitation varies from 550 to 650 mm annually and from 20 to 70 mm during the driest season (summer) (Digital Climatic Atlas of Catalonia; Ninyerola et al., 2010). Elevation ranges from 383 to 842 m and the site has a heterogeneous and irregular relief with slopes up to 56% (average of 18.9 ± 7.7%). According to García-Jiménez et al. (2017) forests in the area correspond to almost pure Aleppo pine thickets where density attains 11,579 ± 5083 trees ha^{-1} (mean ± standard deviation), basal area is 18.4 ± 4.9 $m^2\ ha^{-1}$ and mean DBH and tree height are 4.48 ± 1.34 cm and 5.2 ± 1.2 m, respectively (Fig. 1a).

2.2. Determination of forest structure and slash characteristics

During the spring of 2015, the local association of forest owners (Entorns de Montserrat) carried out an intensive manual thinning in ca. 400 ha, removing 90% of the established pines (Fig. 1). Woody residues generated during this operation were left in situ due to their nil commercial value and the difficulties of mechanically crushing them on these steep slopes (Fig. 1b). To increase their decomposition rate, they were cut ca. 0.75–1.5 m long, and laid down uniformly in contact with the ground to accelerate the degradation process. This resulted in an almost continuous and homogeneous layer of slash in the thinned areas (see Fig. 1b). To determine forest structure characteristics, in June 2015, we randomly established 22 circular plots (10 m radius) in thinned and unthinned areas (14 and 8, respectively). Each plot was geolocated to obtain elevation, aspect and slope, as the main topographic characteristics. Then we carried out a forest inventory of the tree layer (almost pure stands of *P. halepensis*) by measuring diameter at breast height (DBH), total tree height, crown base height (CBH) and crown-surface area (CSA). Crown-surface area was calculated after measuring two perpendicular diameters in order to estimate canopy cover fraction (FCC). *P. halepensis* live fuel biomass was estimated by developing allometries after randomly harvesting 26 pines from sites near the sampling plots. For each sampled tree, DBH and height were measured and we dissected all branches from the main stem. The branches were taken to the laboratory and separated into the following fractions following Brown (1978): needles, 0.0–0.63 cm (1 h time-lag fuel), 0.64–2.5 cm (10 h time-lag fuel), 2.5–7.5 cm (100 h time-lag fuel), > 7.5 cm (1000 h time-lag fuel). Needles were separated from other live fuels because their different chemical composition affects different combustion properties (Agee, 1983). The dry-weight of the samples was determined after being dried in a forced-convection oven