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Post-fire live residuals of maritime pine plantations in Portugal: Structure, burn severity, and fire recurrence

Paulo M. Fernandes [a,b,*], Manuel M. Fernandes [b,1], Carlos Loureiro [a]

[a] Centro de Investigação e de Tecnologias Agro-Ambientais e Tecnológicas (CITAB), Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-801, Portugal
[b] Departamento de Ciências Florestais e Arquitetura Paisagista, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-801, Portugal

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ABSTRACT

The drivers, characteristics and impacts of surface fire regimes in the Mediterranean Basin are poorly understood. We describe the post-fire structure of residual maritime pine (*Pinus pinaster* Ait.) patches in frequent-fire mountain landscapes of northern Portugal and relate it with burn severity and fire history. Live trees within each plot were measured and cumulative burn severity metrics were assessed at the tree and plot levels. Plot fire recurrence and fire intervals (mean, MFI; minimum, MinFI; and maximum, MaxFI) were calculated from a digitized fire atlas. Fire thinned from below, with a 15.5-cm diameter at breast height corresponding to 50% survival probability. Bole char and crown kill (or live crown base) heights (CKH) were correlated with live tree height; crown ratio averaged 0.38. Each patch burned 1–9 times since 1975, with a MFI range of 1.7–16 years in multiple-fire plots. We found wide variation in stand height (7.8–22.5 m), basal area (1.4–47.9 m^2 ha^{-1}) and tree density (14–2199 ha^{-1}) but single-storied structures prevailed. Higher fire recurrence was associated with lower stand density and higher percentage of fire-scarred trees, indicating cumulative thinning and cambium damage effects. Bole char height and CKH increased with longer fire intervals, i.e. with fuel accumulation and potentially higher fire intensity. MFI (accounting for 70% of the explanation), terrain aspect, and MaxFI explained 55% of plot-level variation in CKH using regression tree analysis. MFI <4.2 years generated the lowest CKH. For stands with MFI $\geqslant$4.2 years, CKH increased on slopes facing east or south (drier and warmer) and was highest when MaxFI $\geqslant$4.8 years. Active crown fire was less likely in forest patches stocked at <20 m^2 ha^{-1} and <200 ha^{-1}, which should decrease crown fire hazard and limit high-severity fire if combined with adequate pruning and surface fuel treatments every 3–5 years. The study indicates that patches surviving a first-entry wildfire are likely to persist under a frequent fire regime, adding to the understanding of Mediterranean pines resilience to fire and providing quantitative empirical evidence useful to guide the management of fire-prone forests.

1. Introduction

Residual live trees are an important biological legacy of disturbance regimes that create heterogeneity in structure, composition, and function (Franklin et al., 2007), with benefits to carbon recovery and biodiversity (Seidl et al., 2014). Differential tree survival to wildfire is dependent on fire behaviour variability and the associated variation in the severity of fire effects. Even large and severe fires are characterized by variable fire behaviour (Oliveras et al., 2009; Cruz et al., 2012), resulting in a gradient of fire effects across the landscape, including unburned islands (Boer et al., 2008; Lee et al., 2009; Román-Cuesta et al., 2009; Fernandes et al., 2010; Madoui et al., 2010; Kolden et al., 2012).

The environmental factors that drive fire spread and fuel consumption – wind, fuel moisture, vegetation type, fuel accumulation and structure, and topography – interact to determine fire severity (Broncano and Retana, 2004; Oliveras et al., 2009; Fernandes et al., 2010; Clarke et al., 2014; Lecina-Diaz et al., 2014; Viedma et al., 2014). All these factors are spatially and temporally heterogeneous, so there is ample room for burn severity variation within any given fire. As an example, low-, moderate-, and high-severity fire were attributed to 6.8%, 33% and 60.2% of the 12,697 ha burned in a maritime pine (*Pinus pinaster* Ait.) forest in central Spain

* Corresponding author at: Centro de Investigação e de Tecnologias Agro-Ambientais e Tecnológicas (CITAB), Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-801, Portugal. Tel.: +351 259 350861; fax: +351 259 350480.

E-mail addresses: pfern@utad.pt (P.M. Fernandes), mmfernand@gmail.com (M. M. Fernandes), carlos.a.r.loureiro@gmail.com (C. Loureiro).

[1] Present address: CEGOT – Centro de Estudos de Geografia e Ordenamento do Território, Faculdade de Letras da Universidade do Porto, Via Panorâmica, s/n, 4150-564 Porto, Portugal.

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(Viedma et al., 2014). On-the-ground assessment and classification of fire severity typically individualizes the existing strata (soil, understorey, overstorey) through specific indicators (Morgan et al., 2014). Although correlation is often assumed, substantial variation in fire severity can occur among fuel strata (Jain and Graham, 2007; Halofsky and Hibbs, 2009; Fernandes et al., 2010), depending on the interaction between fire, fuels, biota, and the biophysical setting (Sikkink and Keane, 2012).

Disturbance by fire in conifer forests ranges from non-lethal, non-scorching surface fires to high-severity crown fires, corresponding to a gradient in fire effects and tree mortality (Franklin et al., 2007) where increasingly larger trees are killed as burn severity rises (Peterson and Ryan, 1986; Fernandes et al., 2008). The contribution of crown scorch to tree death depends essentially on surface fire intensity, tree height, and forest type (Van Wagner, 1973; Peterson and Ryan, 1986). Fire-thinned forests are typically open and heterogeneous at small spatial scales, forming mosaics of isolated trees, canopy gaps and tree clusters variable in size and shape (Larson and Churchill, 2012; Kane et al., 2013a; Lydersen et al., 2013; Fry et al., 2014). Frequent surface fire in USA conifer forests is associated to fire resiliency, even when fire occurs under severe weather and drought conditions (e.g. Stephens et al., 2008), in part because fuel loadings are kept low and constrain fire size and severity (Collins et al., 2009; Malone et al., 2011; van Wagtendonk et al., 2012).

Research on the fire ecology of Mediterranean Basin pines has been focused on the dynamics of post-fire regeneration, probably because of the contemporary prevalence of high-intensity fire, and much less is known about forest persistence under surface fire regimes (Fernandes et al., 2008). Fire history reconstructions at centennial or multi-centennial time scales from the analysis of fire-scarred trees in Mediterranean conifer forests support low- or mixed-severity fire regimes in maritime pine (Vega, 2000), *Pinus nigra* (Fulé et al., 2008; Touchan et al., 2012; Christopoulou et al., 2013), *Pinus halepensis* (Fournier et al., 2013) and *Cedrus atlantica* (Slimani et al., 2014). However, no study has explicitly examined the linkages between fire history, burn severity, and stand structure in frequently-burned Mediterranean forests.

Crown fire development and behaviour is dependent on surface fire behaviour, the existence of vertical fuel continuity, and canopy bulk density (Van Wagner, 1977; Cruz et al., 2004, 2005, 2006), and this supports the basic principles for creating fire-resistant conifer forests through fuel treatments such as thinning and prescribed burning (Agee and Skinner, 2005). Simulation modelling suggests that stand density management is crucial to decrease the likelihood of severe fire (e.g., Fernández-Alonso et al., 2013; Gómez-Vázquez et al., 2014), but empirical evidence of fire-resistant stand structures in Europe is still scarce and in debate (Oliveras et al., 2009; Román-Cuesta et al., 2009; Fernandes et al., 2010; Alvarez et al., 2012, 2013; Viedma et al., 2014). Ongoing efforts to decrease burned area and protect forest resources through local and landscape-scale fuel treatments (e.g., Loureiro et al., 2006) would benefit from a sounder evidence-based approach.

Large-scale afforestation with maritime pine in the western Mediterranean Basin proceeded throughout the 20th century, especially in the mountains of Portugal, where most forest cover disappeared during the mid-late Holocene (Connor et al., 2012). The resulting dense, even-aged, and flammable plantations have been implicated in the 1970s fire regime shift towards substantially greater fire extent (Fernandes et al., 2014). Wildfire is the major factor in the decline of maritime pine occupation in Portugal, which has diminished 27% between the forest inventories of 1995 and 2010 (ICNF, 2013). Extensive tracts of the Portuguese mountain landscapes planted with maritime pine are now shrub-dominated, but fires commonly leave behind fragments of the former afforestation. While the ability of maritime pine to survive surface fire is well documented (Fernandes and Rigolot, 2007; Fernandes et al., 2008), scarce attention has been given to tree survival after wildfire in relation to fire severity (Pimont et al., 2011; Vega et al., 2011; Catry et al., 2013).

This study addressed maritime pine patches that had survived one or more wildfires in northern Portugal. The general goal was to examine the links between fire history, cumulative burn severity, and stand structure. We identify size thresholds for tree survival and describe burn severity at the tree- and plot-level, using field data from 50 plots. Correlations between burn severity metrics are examined. Stand structure and burn severity variables are related with fire history variables, and the determinants of crown fire hazard are inspected as a function of stand density and fire history. Our hypothesis is that the structure of post-fire pine remnants should reflect some degree of fire-induced thinning and pruning, increasing the likelihood of tree survival to subsequent reburning.

2. Methods

2.1. Study location and design

The study area (41°03′–41°27′N, 7°26′–7°50′W) encompasses the mountain ranges of Alvão, Marão, and Montemuro in the northeast of Portugal. Soils are shallow and derived from granite or schist. Climate is Mediterranean with an oceanic influence (Csb sub-type). Mean temperatures in January and July are 7–9 and 24–26 °C, respectively, and precipitation occurs mostly from October to April and varies between 800 and 1400 mm year^{-1} (Ribeiro et al., 1988).

On average, 2.5% of the region burns annually and the median fire return interval is 24 years (Oliveira et al., 2012), but in the southern part of the study area decreases to 13 years where fire has occurred twice or more since 1975 (Fernandes et al., 2012). We identified potential sampling areas by overlaying the Landsat-based digitized fire atlas of Portugal with the location of maritime pine remnants identified in 2005 aerial photography. The atlas spatial resolution and minimum mapping units are 80 m and 35 ha, respectively (1975–1983), and 30 m and 5 ha (1984-present) (Oliveira et al., 2012). In areas where forest remnants were conspicuous we selected nine 25-km^2 squares for field sampling, each including a range in fire recurrences.

We carried out the field work in 2007 and 2008, excluding recently (<3 years) burned patches where pine mortality caused by *Scolytidae* insects could occur in the future (e.g., Vega et al., 2011). Upon field inspection, conditional on accessibility, we chose a total of 50 sampling plots representative of variation in stand structure within the selected 25-km^2 areas. Distance between plots was variable but always >50 m. Variability in the size and structure of forest patches guided the selection of plot size from three options: (1) plot area equal to patch area in isolated clumps (<0.05 ha) of trees; (2) 0.05-ha circular plots within relatively dense stands; and (3) 0.1–0.5 ha circular plots within relatively open stands.

2.2. Data collection and processing

2.2.1. Site characteristics and fire history

Understory on each plot was qualified as shrub- or grass-dominated and the dominant species were registered. We assessed plot elevation (m), aspect (°), slope (%), and slope position, categorized as valley or lower slope, upper slope, ridge, or plateau. Plot aspect (θ, 0–360°) was transformed as a continuous index (Wu et al., 2014):

$$\text{Aspect index} = -\cos(\theta \times 2 \times \pi/360) \qquad (1)$$

which ranges from −1 to 1, with higher values implying higher exposure to solar radiation and hence warmer and drier conditions; level terrain was equalled to south aspect.