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Post-fire survival and regeneration of *Eucalyptus globulus* in forest plantations in Portugal

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ABSTRACT

Eucalyptus globulus is one of the most important pulpwood plantation species in the world, and nowadays it is present in most continents. Some of the regions where *E. globulus* plantations have been expanding have a high incidence of wildfires; therefore, knowing the factors affecting the fire resistance and resilience of this species is particularly important for forest management. This is the case of Portugal, where nearly 1.4 million ha of land burned in the last decade and where *E. globulus* has become the most widespread tree species. In this paper we assessed the short-term post-fire responses of *E. globulus* trees in four sites affected by wildfires, and investigated their potential relationships with fire severity descriptors and with tree and stand characteristics. One year after fire, individual tree mortality was low (3.9%) but most trees (79.2%) were top-killed (i.e. had stem mortality). Both post-fire tree mortality and top-kill increased with fire severity (expressed by maximum char height and/or char severity rating). Moreover, top-kill was positively related with vegetation cover and the proportion of pine trees in the stand, and was negatively related with tree diameter and the proportion of other broadleaved trees in the stand. The most common post-fire regeneration type among the sampled trees was basal resprouting (89.2%), though 20.9% had epicormic resprouting. The number of basal resprouts increased with char height, top-kill and diameter of the parent tree, and decreased with slope. In terms of post-fire growth, the height of the dominant resprout increased with the number of resprouts and with char severity, while it decreased in drier southern aspects. Results showed that *E. globulus* is a fire-resilient species with a very high probability of surviving fire; however, in forest plantations where trees are usually felled in short rotations (thus with limited size), individuals have a high probability of being top-killed. The presented models may be useful to help managers on the assessment of post-fire production losses and regeneration potential in *E. globulus* plantations.

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1. Introduction

Eucalypts are native to Australasia but some species have been widely planted in many countries, mainly because of their fast growth, wood characteristics and ability to withstand dry and low nutrient conditions (Florence, 1996). One of these species, *Eucalyptus globulus* Labill. (Tasmanian blue gum), is nowadays one of the most important pulpwood plantation species in the world, having great economic importance (Potts, 2004). This eucalypt is native to south-eastern Australia (Tasmania and southern Victoria; Dutkowski and Potts, 1999) and was introduced in all continents except Antarctica (in Europe introduction occurred more than 150 years ago; Goes, 1977). In 2004 there were estimated to be over 2.5 million hectares of *E. globulus* planted worldwide, with the main concentration of plantations occurring in the Iberian Peninsula (Potts et al., 2004). According to the Portuguese Forest Inventory, *E. globulus* is now the most widespread tree species representing 26% (812 000 ha) of the total forest cover (ICNF, 2013). In Portugal this species is cultivated through a coppice system (10–12 year rotations) and the wood is almost exclusively sold to pulp mills which in turn supply papermaking industries in different parts of the world; however, rotation cycle and main uses varies among countries (e.g. Pohjonen and Pukkala, 1990).

Some of the regions where *E. globulus* has been expanding also present a high incidence of wildfires. This is the case of Portugal and Spain in the Iberian Peninsula; in Portugal alone nearly 1.4 million ha of land burned in the last decade (JRC, 2012). Moreover, the perspectives under a climate change scenario indicate a very significant increase of the annual burned area in these and other countries (Flannigan et al., 2009; Amatulli et al., 2013). Planted stands dominated by *E. globulus* are known for being highly

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fire-prone in comparison to other forest systems (Nunes et al., 2005; Moreira et al., 2009b; Silva et al., 2009; Fernandes et al., 2011; Xanthopoulos et al., 2012). Therefore the impact of wildfires on *E. globulus* plantations is an important issue to address, both from economic and ecologic perspectives.

Most eucalypt species in their native range are subject to fires and many have characteristics indicative of adaptation to a particular regime of fire intensity, frequency and season (Florence, 1996; Gill, 1997). However, mortality and regeneration type of eucalypt species are known to be quite variable (Gill, 1997). Although various studies assessed the post-fire responses of several eucalypt species (e.g. Strasser et al., 1996; Vivian et al., 2008; Waters et al., 2010), there are still many (including *E. globulus*) for which post-fire responses remain poorly known; furthermore, very few studies investigated eucalypt responses in forest plantations beyond their native range.

Whether trees survive or die after fire and the type and extent of recovery, will depend on the type and extent of damage (e.g. Gill, 1997). Post fire tree responses may vary with fire behaviour characteristics as these are directly related with the level of tree damage. Fire behaviour variables like fire intensity or flame height are a direct consequence of surface and crown fuels (Van Wagner, 1977; Rothermel, 1983); therefore the assessment of fuel-related variables like shrub cover and tree cover can be of interest for the establishment of relationships with tree responses (e.g. Moreira et al., 2007). Additionally, topographic conditions, such as slope and aspect, have a direct influence on fire behaviour (Rothermel, 1983), but also on the vegetative conditions of each tree and surrounding vegetation, particularly in Mediterranean-type ecosystems (Kutiel and Lavee, 1999; Sternberg and Shoshany, 2001; Catry et al. 2009). Post-fire tree responses may also vary with species (which possess different regeneration and fire-resistance traits), individual tree characteristics important for fire resistance or avoidance (e.g. size, bark thickness), tree physiological condition when the fire occurs (e.g. availability of energy reserves to fund regrowth), and management factors (Whelan, 1995; DeBano et al., 1998; Catry et al., 2013).

Although several eucalypt species are sensitive to fire and are killed after full crown scorch (depending on seed for regeneration; classified as obligate seeders), the vast majority are fire-resistant and will recover from damages by vegetative regeneration (classified as resprouters) (Florence, 1996; Strasser et al., 1996; Gill, 1997; Burrows, 2013; Clarke et al., 2013). Indeed, less than 10% of the more than 900 eucalypt taxa have been classified as obligate seeders (Nicolle, 2006). The principal mechanisms of recovery in fire-resistant eucalypt species are resprouting from epicormic strands (i.e. regeneration from meristem strips, usually extending from the inner to outer bark on aboveground branches and stems, which produce buds), and/or from basal buds (i.e. regeneration from a lignotuber or the root collar, at or just below soil level) (Gill, 1997; Waters et al., 2010; Burrows, 2002, 2013).

E. globulus is known by strong resprouting capacity after disturbance, which may be explained by high epicormic bud initiation potential and the presence of a lignotuber (Burrows, 2002; Whittock et al., 2003). Although some mortality may occur in burned plantations, many trees are likely to survive by resprouting. In one of the few studies on post-fire survival of *E. globulus*, Catry et al. (2010) found 100% survival in a sample of 60 burned trees, monitored over 4 years. In another study, Marques et al. (2011) reported 47% of dead trees, but these results most likely refer to stem mortality instead of individual mortality. This is the only study to our knowledge that attempted to relate mortality with other factors, although no fire characteristics were used. However, we could not find any references for *E. globulus*, relating the different types of post-fire tree response with stand and tree characteristics, nor with fire severity descriptors.

In this paper we analyse data collected in several sites that burned in the same fire season. We aimed to: (1) characterise the post-fire responses of *E. globulus* in terms of individual tree survival and resprouting behaviour; (2) investigate through modelling which are the main fire, tree and stand characteristics influencing these responses at the tree-level. Both fire, tree and stand characteristics can be partly managed, which enables some control on mortality and regeneration of burned trees. Therefore, the identification of these factors and forecasting of tree responses may allow minimizing fire damage through adequate planning and management of *E. globulus* plantations.

2. Methods

2.1. Study sites

We used data from four different locations in central Portugal, western Mediterranean Basin (Fig. 1). Each of these locations was affected by a wildfire in the summer of 2006 (July through September; Table 1), which corresponds to the normal fire season (dry season). The climate in the four study sites is Mediterranean, with mean annual temperatures ranging from 15 to 17.5 °C and precipitation ranging from 700 to 1400 mm (IA, 2003; Table 1). Elevation ranges from 120 to 580 m.

2.2. Sampling and data collection

In the four wildfire sites we used a regular grid (300 m) of points covering the burned area and defined a circular plot (50 m radius, 7850 m^2) around each point. We overlaid these plots with land cover maps (scale 1:25000) and selected those located in eucalypt areas and where no post-fire interventions occurred. In total, 22 plots were sampled (Table 1). In plots with 20 *E. globulus* trees or less, all individuals inside the plot were assessed; otherwise, we laid out up to four 50-m strip transects (20 m wide) and sampled trees (starting from north and proceeding clockwise) until obtaining 20 individuals per plot. Only trees with at least 5 cm diameter at breast height were sampled, and overall we sampled 388 *E. globulus* individuals. Data collection was performed 12–14 months after fire occurrence (12 months in all sites but Atouguia).

We recorded several tree characteristics, fire severity indicators and environmental variables (Table 2). We assessed whether each tree was dead or alive (trees were considered dead when no green foliage was present regardless of its location), and the regeneration type if alive, that is, if trees were resprouting from belowground organs (root collar or lignotuber, hereafter named basal resprouting) and/or from aboveground organs (crown or stem, hereafter named epicormic resprouting). As a result, the post-fire regeneration status of each tree (RS) was recorded as dead (no regeneration), basal resprouting only, simultaneous basal and epicormic resprouting, or epicormic resprouting only, following a decreasing gradient of fire-inflicted damage (Moreira et al., 2009a). Additionally, we classified the number of basal resprouts per tree into 5 frequency categories (0, 1–5, 6–10, 11–20, >20), and measured the height of the dominant (tallest) resprout (HDR, measured with a laser hypsometer to the nearest 0.1 m).

Tree size measurements included total tree height (*H*, measured with a laser hypsometer to the nearest 0.1 m) and diameter at breast height (DBH, measured at 1.30 m above ground level to the nearest 1 cm). Bark thickness (BT) was not measured on burned trees because the bark is often partially consumed by fire and may detach from the stem; alternatively, we measured BT and DBH on 60 nearby unburned trees (DBH range = 5.2–50.3 cm) and estimated BT for each burned tree from the derived allometric

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