Forest Ecology and Management 260 (2010) 1184–1192

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Post-fire tree mortality in mixed forests of central Portugal

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ARTICLE INFO

Article history:
Received 26 February 2010
Received in revised form 2 July 2010
Accepted 6 July 2010

Keywords:
Wildfires
Fire effects
Tree survival
Modelling
Mediterranean ecosystems
Resprouting

ABSTRACT

Wildfires are a recurrent disturbance in the Mediterranean Basin. However, managers from this region are confronted with a lack of information on the effects of fire on most woody species, which is required for defining sustainable forest management strategies. Following a large wildfire in central Portugal (2003), we surveyed the area during the first year and assessed the vegetative condition of 1040 burned trees from 11 different species. Among those trees, 755 individuals were selected and monitored annually for 4 years. At the end of the study, almost all the broadleaved trees survived, while most coniferous died. In spite of the low mortality observed in broadleaves, most were top-killed and regenerated only from basal resprouts, which implies a slow recovering process. *Quercus suber*, however, showed vigorous post-fire crown resprouting and was the most resilient species. We fitted logistic regression models to predict the probability of individual tree mortality and top-kill from fire injury indicators and tree characteristics. Besides the differences between the two main functional groups (coniferous, broadleaved), bole char height and crown volume scorched or consumed were important predictors of tree responses. Additionally, the main factor determining crown mortality on broadleaved species was bark thickness. The selected models performed well when tested with independent data obtained on four other wildfires. These models have several potential applications and can be useful to managers making pre-fire or post-fire decisions in mixed forest stands in the western Mediterranean Basin.

1. Introduction

Wildfires are a recurrent disturbance in the Mediterranean Basin. Prediction of post-fire tree mortality and top-kill (i.e., crown mortality) is essential to plan logging or to evaluate recovery options (e.g. reforestation, wildlife habitat, soil erosion) in burned areas (Ryan and Reinhardt, 1988; Regelbrugge and Conard, 1993). However, authorities and managers from the Mediterranean Basin confront with a lack of published information on the effects of wildfire on most woody species (e.g. Ordóñez et al., 2005), and especially on broadleaved ones. Even for European pines, which are relatively well studied, recent reviews indicate that most studies are based in low-intensity dormant season burns and only reflect short-term (1–2 years post-fire) mortality (Fernandes and Rigolot, 2007; Fernandes et al., 2008).

Much of the variation in plant response to burning can be attributed to varying sensitivity to heat of the different tissues and species. The time required to kill plant tissue decreases exponentially with the exposure time to a given temperature (Bond and van Wilgen, 1994). Tree resistance to fire depends largely on the presence of morphological traits that protects critical tissues and on the food reserves for successful recovery (Whelan, 1995; DeBano et al., 1998). The tissues important for post-fire recovery can be protected from lethal temperatures in several ways; for instance, cambium and stem buds may be protected from radiant heat by a thick bark, while below-ground stems and buds may be shielded by the overlaying soil (Whelan, 1995; DeBano et al., 1998). Fire injury on trees includes crown-kill, bole-kill and root-kill, crown damage being the most readily observed whereas root injury is seldom quantified. Variables such as bole char height and the percentage of crown scorched or consumed are often used as tree-level fire injury descriptors (e.g. Peterson, 1985; Stephens and Finney, 2002).

Crown injury has been identified as the primary cause of post-fire mortality in most conifers (e.g. Ryan and Reinhardt, 1988; Rigolot, 2004) but the response to defoliation by fire varies considerably among species. Many species are extremely sensitive and are killed if defoliation is above some threshold value, while others although completely defoliated will regenerate the crown by issuing shoots from epicormic (Bond and van Wilgen, 1994) or leaf buds (e.g. Thies et al., 2006).

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doi:10.1016/j.foreco.2010.07.010

Bole damage consists of injury to phloem, cambium, or functional xylem (Ryan, 1998), and has been correlated with tree mortality and top-kill through the use of parameters like bark thickness, bole diameter, bole char height or char depth (Regelbrugge and Conard, 1993; Hély et al., 2003; McHugh and Kolb, 2003). Bark thickness has been a widely employed morphological variable to account for fire resistance (Peterson and Ryan, 1986; Pausas, 1997; Rigolot, 2004), as small differences in bark thickness produce large differences in fire resistance (Bond and van Wilgen, 1994; Moreira et al., 2007). The time taken for cambial cells to reach lethal temperature is a function of both bark thickness and thermal properties of the bark, although the former plays a more important role (Hare, 1965; Peterson and Ryan, 1986).

Post-fire tree survival and regeneration capacity are mainly influenced by factors related to both fire injury and individual tree characteristics, although additional factors of stress in the pre and post-fire environment like drought, herbivory or pests can also be relevant (Whelan, 1995; DeBano et al., 1998; Miller, 2000; McHugh and Kolb, 2003; Dylan et al., 2006).

In this paper we hypothesize that the most important factors determining the initial and delayed tree mortality and top-kill in Mediterranean mixed forests are fire injury, and bark thickness or tree size; because closely related species tend to share similar traits, we also predict that the differences within taxonomic group (coniferous, broadleaved) will be lower than between groups. Higher mortality is expected in trees apparently more injured by fire, on smaller or thinner barked individuals, and in coniferous rather than in broadleaved species, because most species from the former group are not able to resprout when the entire canopy is burned. Ungulate herbivory is also hypothesized to be an additional factor of stress affecting delayed mortality in top-killed broadleaves. A large wildfire which occurred in 2003 in a mixed forest of central-west Portugal provided an opportunity to evaluate these hypotheses in a range of tree species affected by the same fire and under similar ecological conditions. The study includes species for which there was no previous information on post-fire responses.

2. Methods

2.1. Study area

The study area (Tapada Nacional de Mafra, 885 ha) is a public fenced area located in central-west Portugal (western Iberian Peninsula), 8 km from the sea. Elevation ranges from 80 to 360 m and soils are predominantly humic cambisols derived from sandstone. Climate is Mediterranean, with a mean annual precipitation of 850–950 mm and a mean annual temperature ranging from 13 to 15 °C (IA, 2003). Before the fire, the vegetation was dominated mainly by forests (48%), including both broadleaved and coniferous species, and by shrublands (46%).

2.2. Sampling and measurements

In September 2003, 70% of the Tapada Nacional de Mafra burned during a large wildfire that occurred in the region. Fire weather was extreme and the crown of most trees was affected, although in different degrees. Following the fire, the study area was mapped and divided into a regular 500-m grid using a GIS (geographic information systems); 20 points (centers of each grid) were randomly selected in the burned area as starting locations for field plots. Points that fell in treeless areas were moved to the nearest burned forest stand. Each plot was about 100-m long and 20-m wide, and all the trees found within it were coded, marked and geographically located (with both GPS and terrain measurements) for monitoring in the subsequent years. Elevation, aspect and slope were derived for each tree location from a digital elevation model at 1:10,000 scale. We did not sample trees with broken stems or identified as being already dead before the fire (evaluation based e.g. on bark condition or advanced degree of decay).

The first field sampling was performed 3 months after the fire (December 2003) and included 1040 burned trees of 11 of the more representative species in the area over a range of tree sizes that were differently affected by fire (Table 1). The studied species were: *Castanea sativa* Mill. (chestnut), *Crataegus monogyna* Jacq. (weissdorn), *Eucalyptus globulus* Labill. (bluegum eucalyptus), *Fraxinus angustifolia* Vahl. (narrowleaf ash), *Olea europaea* L. var. *sylvestris* Brot. (wild olive), *Pinus pinaster* Ait. (maritime pine), *Pinus pinea* L. (stone pine), *Pistacia lentiscus* L. (evergreen pistache), *Quercus coccifera* L. (kermes oak), *Quercus faginea* Lam. ssp. *broteroi* (Portuguese oak), and *Quercus suber* L. (cork oak). All the studied broadleaved species are resprouters and the coniferous species are non-resprouters (Paula et al., 2009). Most of the studied species have a wide distribution in the Mediterranean Basin and are within their natural area of distribution, except *E. globulus* (introduced species native to southeast Australia). In the study area *C. sativa* can be also considered as an old introduction (González, 2001; Krebs et al., 2004).

Table 1
Characteristics of the trees (n = 1985, 11 species) used to develop and validate models to predict post-fire tree response.

Species (scientific name)	n	DBH (cm)		TH (m)		BT (cm)		TCD (%)		PCH (%)	
		$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range
Castanea sativa	30	21.0	10–38	7.5	4–11	1.2	0.6–2.1	99.7	90–100	30.9	6–75
Crataegus monogyna	133	17.8	5–41	4.0	2–8	0.9	0.4–1.6	100	100	94.9	17–100
Eucalyptus globulus	60	14.0	5–24	11.5	6–16	0.9	0.4–1.4	100	100	36.4	10–100
Fraxinus angustifolia	82	41.4	10–76	11.3	5–18	2.0	0.6–3.4	89	65–100	58.9	7–100
Olea europaea sylv.	127	21.3	5–54	4.5	2–10	1.0	0.4–1.7	100	100	98.6	25–100
Pinus pinaster	56	50.9	23–101	17.3	8–25	5.4	2.9–9.2	87.6	50–100	78.9	32–100
Pinus pinea	78	47.7	16–92	12.4	3–17	4.7	1.7–9.0	92.2	50–100	69.4	20–100
Pistacia lentiscus	113	7.8	3–20	2.4	1–5	0.5	0.2–1.1	100	100	97.2	33–100
Quercus coccifera	120	12.8	4–30	3.8	2–8	0.6	0.2–1.2	99.6	60–100	99.0	42–100
Quercus faginea	129	39.3	17–94	8.9	3–17	1.9	1.3–3.1	99.3	75–100	91.1	29–100
Quercus suber	112	47.0	15–140	8.8	3–16	4.9	1.9–14	99.3	60–100	79.9	28–100
Validation dataset											
Eucalyptus globulus	388	10.0	5–60	13.6	6–31	0.7	0.4–3.0	–	–	54.1	0–100
Pinus pinaster	397	22.7	7–49	13.7	5–25	2.8	1.2–5.9	–	–	54.1	0–100
Quercus faginea	98	17.9	10–51	8.9	4–19	1.3	1.0–2.2	–	–	58.2	0–100
Quercus suber	62	20.6	10–45	8.3	4–14	2.0	0.2–4.8	–	–	98.0	18–100

DBH, diameter at breast height; TH, total tree height; BT, bark thickness (BT for all the species but *Q. suber* is based on the equations presented in Table 2), TCD, percentage of crown volume damaged (crown scorched + crown consumed); PCH, maximum bole char height expressed as percentage of tree height; n, total number of sampled trees; $\bar{x}$, mean.