Forest Ecology and Management 323 (2014) 47–56

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Natural establishment of *Eucalyptus globulus* Labill. in burnt stands in Portugal

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ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 5 March 2014
Accepted 6 March 2014
Available online 17 April 2014

Keywords:
Eucalyptus globulus
Wildfire
Post-fire management
Seed
Establishment
Naturalization

ABSTRACT

Exotic tree species are increasingly common in many regions of the world and at least some species are becoming naturalized in the regions where they were introduced. Disturbances like fire may be at the origin or accelerate the naturalization of these species. Portugal holds one of the largest areas of exotic *Eucalyptus globulus* plantations in the world and is one of the countries most affected by forest fires. These two facts have triggered the present research. This study aimed at characterising medium-term natural establishment of *E. globulus* plants originated from seeds under natural conditions in burnt planted forests (pure *E. globulus* stands, pure *Pinus pinaster* stands, and mixed stands of both species), and at analysing factors associated with this establishment. Occurrence, abundance and height of naturally established *E. globulus* plants were characterized in 284 sites distributed in burnt areas, across Central and Northern Portugal, 5–7 years after wildfire. Generalized linear models were used to assess the influence of stand type, regional productivity potential, and post-fire management practices on occurrence probability, density, and median height of sampled *E. globulus* individuals. The influence of these explanatory variables on the structure (in terms of size class distribution) of naturally established *E. globulus* cohort was examined using analysis of similarity and non-metric multidimensional scaling. Naturally established *E. globulus* plants were present in 93.1%, 19.0% and 98.6% of samples in pure *E. globulus*, pure *P. pinaster* and mixed stands, respectively. Cohort median density was 0.20 plants m^{-2} and maximum density was 4.55 plants m^{-2}. Median height of plants was 2.0 m and 95.3% of them had h >1.30 m and DBH $\leqslant$5 cm. Establishment probability, density and median height were highest in the most productive regions. Three post-fire management operations had a significant influence on the response variables: (i) salvage logging was associated with a higher density; (ii) tillage was associated with a lower density and a smaller median height; (iii) understorey removal was associated with a lower occurrence probability. Tillage was the only studied factor influencing the size structure of spontaneously established cohort, eliminating larger plants. This study showed that stand type, productivity region and post-fire management operations might have significantly influenced the natural establishment of *E. globulus* in burnt areas, and consequently the species naturalization process in Portugal. The implications of these findings for management are discussed.

1. Introduction

Given the expansion of exotic tree plantations in the world (MCPFE, 2007; FAO, 2010), the study of ecological processes associated with these forests is increasingly important. Some of the most relevant issues are related to naturalization or invasive potential of exotic tree species, since significant interactions with the native ecosystems are possible (Richardson, 1998). Disturbances in general and fire in particular are known to facilitate the recruitment of different exotic species (e.g. Anderson and Brown, 1980; Mandle et al., 2011; Arianoutsou and Vilà, 2012; Vallejo et al., 2012). Therefore, the fire-mediated naturalization of planted exotic trees is a relevant research topic (Silva and Marchante, 2012).

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http://dx.doi.org/10.1016/j.foreco.2014.03.012
0378-1127/

Eucalyptus globulus Labill. (Tasmanian blue gum) is one of the most widely planted and economically important hardwood species in temperate regions of the world (Potts et al., 2004). This eucalypt is native to SE Australia and it is planted in many regions around the world. Portugal is among the countries that have largest areas of planted *E. globulus* in the world (Potts et al., 2004). This species was introduced in Portugal in the middle of the 19th century (Radich, 2007) and is now the most widespread tree species in Portuguese mainland, representing 26% (812×10^3 ha) of its forest cover (ICNF, 2013).

E. globulus forests in Portugal are planted and mostly managed through a coppice system (10–12 year rotations) (Turnbull and Pryor, 1984; Soares et al., 2007). Their wood is almost exclusively used for pulp production. Water availability and episodic occurrence of temperatures below 0 °C are considered the main limiting climatic factors to *E. globulus* development in Portugal (Almeida et al., 1994; Ribeiro and Tomé, 2000; Alves et al., 2012), where wood yields are very variable due to site conditions and may exceed 30 m^3 ha^{-1} $year^{-1}$ in the very best sites (Tomé, 2000). However, the good adaptation of *E. globulus* to many Portuguese environmental conditions is having other implications, as the species has become naturalized. The species reproduces by seeds and naturally established plants are commonly found within or close to planted stands nowadays (Marchante et al., 2008; Silva and Marchante, 2012). Although the first reference to naturalization of *E. globulus* in Portugal dates from 1943 (Almeida and Freitas, 2006), we found no quantitative assessments of this process in the literature. Naturalization processes are known to have resulted in considerable economic and environmental costs for several alien species (Andreu et al., 2009). Naturally established plants may modify ecosystem/plantation dynamics and changes in forest management may be required to control them, since *E. globulus* grows fast (Silva et al., 2007a). Most of the literature concerning the seed regeneration from *E. globulus* plantations reports qualitative assessments in order to infer about the naturalization or the invasive status of the species (Ritter and Yost, 2009; Gassó et al., 2010; Gordon et al., 2012). The few references that provide quantitative data are not comparable due to differences on methods and on considered factors (Virtue and Melland, 2003; Calviño-Cancela and Rubido-Bará, 2013; Larcombe et al., 2013).

Fire is often related with eucalypt recruitment and establishment (Mount, 1964; Cremer, 1965; Mount, 1969; Ashton, 1981; Gill, 1997). Causes for fire facilitated recruitment/establishment of eucalypts are related with: increased seed shed from canopy (Cremer, 1965; Pryor, 1976; O'Dowd and Gill, 1984; Wellington and Noble, 1985b; Florence, 1996); seed-predator satiation (O'Dowd and Gill, 1984; Wellington and Noble, 1985b; Gill, 1997); increased light availability (Jacobs, 1955; Kirkpatrick, 1975; Gill, 1997); "ash-bed effect" (Pryor, 1976; Chambers and Attiwill, 1994); reduced competition (Wellington and Noble, 1985a; Whelam, 1995; Gill, 1997); removal of allelopathic substances (Pryor, 1976; Stoneman, 1994); and decreased predator activity (Whelam, 1995). Larcombe et al. (2013) demonstrated that fire was associated with higher recruitment levels of *E. globulus*, as it had been suggested earlier by Kirkpatrick (1975).

Portugal has the largest percentage of burnt forest area in Europe and one of the largest in the world (FAO, 2010; JRC, 2012) and the National Forest Strategy (DGRF, 2007) indicates that wildfires are a major threat to sustainable forest management in this country. Moreover, eucalypt stands are highly flammable in comparison to other forest systems in Europe and particularly in Portugal (Nunes et al., 2005; Moreira et al., 2009; Silva et al., 2009; Fernandes et al., 2011; Xanthopoulos et al., 2012).

Effects of post-fire operations on seedling establishment depend on how and when they are performed. Post-fire management of burnt forests often includes: salvage logging; tillage; and shrub removal. Post-fire salvage logging usually occurs before establishment of the next generation of trees and its major effects consist of environmental changes derived from removal of burnt trees. If it occurs after seedling establishment, significant seedling mortality can happen (McIver and Starr, 2000). *In situ* germination of seeds from logging eucalypt slash is common under favourable conditions (Fagg, 2001) and *E. globulus* plants may establish and grow normally or become dominated trees under coppice shoots (Skolmen and Ledig, 1990). Tillage is aimed at improving soil conditions for root development (Madeira et al., 1989), but in burnt areas can largely enhance erosion, if it is not performed with caution (Coelho et al., 1995; Shakesby et al., 1996). Established plants that were born after fire may be destroyed by tillage (Catry et al., 2010). Few years after fire, understorey is well developed in forests. Since *E. globulus* is very sensitive to competition with understorey plants especially in early years of life, and fuel load build up increases fire hazard, periodic understorey removal is performed in this species stands (Pereira, 2007; Soares et al., 2007; Moreira et al., 2009; Alves et al., 2012).

To our knowledge, a quantitative assessment of natural establishment of *E. globulus* in burnt areas has never been carried out in Europe. We chose to study the post-fire seminal regeneration of *E. globulus* because there were recurrent references to fire-induced eucalypt establishment (Jacobs, 1955; Cremer, 1965; Kirkpatrick, 1975; Pryor, 1976; O'Dowd and Gill, 1984; Chambers and Attiwill, 1994; Stoneman, 1994; Florence, 1996; Gill, 1997), as well as frequent observations of *E. globulus* saplings in recently burnt areas in Portugal (Silva et al., 2007a, 2007b; Silva and Marchante, 2012). Stands with *Pinus pinaster* were included in the study because this species is highly represented in Portuguese mainland (23% forest cover) (ICNF, 2013), and it has similarities to *E. globulus* on its ecological requirements and geographical range. Additional grounds were the common coexistence of these species in mixed stands (Silva et al., 2011) and the high fire proneness of *P. pinaster* stands (pure or mixed) (Moreira et al., 2009).

The study aimed at answering four questions related to medium-term establishment of *E. globulus* plants originated from seeds under natural conditions in burnt forests (pure *E. globulus* stands, pure *P. pinaster* stands, and mixed stands): (a) what is the likelihood of *E. globulus* natural establishment in burnt areas; (b) which are the most important factors related with site characteristics, stand type and post-fire management practices influencing this likelihood; (c) how do these variables affect the density of post-fire naturally established *E. globulus* cohort and the median height of its individuals; and (d) how do these variables influence the size structure (distribution of individuals among size classes) of post-fire naturally established *E. globulus* cohort.

2. Material and methods

2.1. Study areas

Forty areas that had burnt during 2005 and 2006 were selected in Central and Northern Portugal (Fig. 1), regions where *E. globulus* is common. Burnt areas were identified from existing fire maps created through semi-automated classification of remote sensing satellite data (Marques et al., 2011). Selection of burnt areas was based on time-since-fire (5–7 years), size (largest areas were preferred), accessibility and presence of pure or mixed stands of *E. globulus* and *P. pinaster* (pure stands corresponding to cover of target species $\geqslant$75%, and mixed stands to cover of either species <75%) (AFN, 2009). The selected areas ranged in size from 6 to 10924 ha, with an average of 2078 ha. The sampling grid (500 m $\times$ 500 m) created for the National Forest Inventory (NFI) (AFN, 2010) was used to define potential study sites within the