FUELS AND FIRE HAZARD IN BLUE GUM (*EUCALYPTUS GLOBULUS*) STANDS IN PORTUGAL

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Summary

Fast-growing, short-rotation forest plantations in Mediterranean-type ecosystems are vulnerable to wildfire. This study quantifies fuel characteristics over a wide range of stand characteristics in blue gum (*Eucalyptus globulus*) stands in Portugal, namely fuel loading by size class and fuel layer and bulk density. We combined destructive and non–destructive methods to estimate fuel loadings in both natural and activity (logging slash) fuels, and then built fuel models to predict fire behaviour characteristics. Classification of National Forest Inventory blue gum plots by fuel model showed that high-intensity fire threatens approximately half of the plots. Fire modelling indicates that wildfire control operations are made effective by treating hazardous fuels in these plantations, even under extreme weather conditions. Stand management against wildfire can greatly benefit from fuel and fire modelling.

Keywords: Fuel inventory, fire behaviour, fire simulation

Resumen: Combustibles y peligro de incendio en repoblaciones de *Eucalyptus globulus* en Portugal

Plantaciones forestales de crecimiento rápido y rotación corta en ecosistemas de tipo mediterráneo son vulnerables a los incendios forestales. Este estudio cuantifica las características del combustible (carga de combustible por clase de tamaño y estrato de combustible, densidad aparente) en masas de *Eucalyptus globulus* en Portugal con una amplia gama de características dasométricas. Se combinaron los métodos destructivos y no destructivos para estimar las cargas de combustible en ambos combustibles naturales y de actividad (residuos de explotación), y luego construyó modelos de combustible para predecir las características de comportamiento del fuego. A clasificación por modelo de combustible das parcelas do inventario forestal nacional ocupadas con *E. globulus* demostró que el fuego de alta intensidad amenaza a aproximadamente la mitad de las parcelas. La modelización del fuego indica que las operaciones de control de incendios forestales se hacen efectivas mediante el tratamiento de combustibles peligrosos en estas plantaciones, incluso en condiciones meteorológicas extremas. A prevención de incendios forestales puede beneficiar en gran medida de los modelos de combustible y de comportamiento de fuego.

Palabras clave: Inventario de combustibles, comportamiento del fuego, simulación de incendios.

I. Introduction

Owing to its fast growth and adaptability, blue gum (*Eucalyptus globulus* Labill.) is extensively planted worldwide, especially in Mediterranean climate regions. In Portugal, blue gum plantations occupy approximately one fifth of the afforested land, being especially important in the NW and CW regions, and represent a significant fire problem. The extremely flammable nature of the leaf and bark litter fuel complex makes eucalypt forests fire-prone, a distinctive feature being the potential for long-distance fire spotting by species with long ribbons of bark, such as blue gum (Luke and McArthur 1978).

Eucalypts managed as short-rotation coppices to optimize biomass production are inherently fire sensitive, which recommends mandatory treatment of accumulated fuels whenever the chance of destructive fire is high (Cheney and Richmond 1980). The objectives of fuel management are to reduce fire hazard by limiting surface fire spread and intensity and avoiding crown fire, thus allowing wildfire suppression under severe weather conditions, decreasing the ecological impacts of fire and increasing the salvage value of wood. Maintenance of low fire hazard in blue glum plantations implies that fuels are treated on a short rotation (Agee *et al*, 1973).

Fire behaviour models are at the core of decision support systems for fire management. Tables, graphs and meters have been developed from field data to rate fire danger from weather conditions and predict fire characteristics in eucalypt forest (McArthur 1967; Sneeuwjagt and Peet 1985) and were later translated into equations (e.g. Noble *et al*, 1980). Concerns with the underestimation of wildfire spread (e.g. McCaw *et al*, 2008) led to further experimentation on a larger spatial scale and under more severe weather, resulting in the VESTA model (Gould *et al*, 2007). Alternatively, the fire spread model of the U.S. Forest Service (Rothermel 1972) and companion models can be used to estimate fire behaviour in eucalypt stands, provided that vegetation is described as a fuel model.

Blue gum is less prone to crown fire than other eucalypts (Luke and McArthur 1978). However, fire behaviour has not been documented or studied in plantations of the species, apart from a few wildfire case studies (e.g. Braun 2006) and experimental fires of low-intensity (Vega 1985; Boness and Van Etten 1998; Cruz and Viegas 2001) or in post-logging slash (Cruz and Viegas 2001; Vega *et al*, 1993). Despite the worldwide importance of eucalypt plantations - around 20 million ha and growing – the fire behaviour knowledge base required by their effective protection against wildfire is lacking. The quantitative appraisal of fuel properties is required to predict fire behaviour, regardless of the system used. This study describes and typifies (through fuel models) blue gum fuels in Portugal and uses forest inventory data to assess the nationwide distribution of fire hazard.

II. Materials and methods

We characterized fuels in blue gum plantations by sampling stands that were perceived as representing the structural and physiognomic variation occurring in Portugal. Destructive quadrat sampling (0.5 – 4 m^2) individualized the fuel layer, i.e. litter (including its woody component and excluding humus) and understorey vegetation (shrubs, forbs, ferns, herbs). Additionally, we collected the suspended bark up to a 2-m height along eucalypt stems. Non-destructive assessments consisted of structural descriptors (litter depth, vegetation height, cover of each layer) measured along transects and for each quadrat sampled. Oven-dry weights of the fuel samples were obtained after separation by size class, respectively <6, 6-25 and >25 mm, which for dead fuels correspond to the 1-hour, 10-hour and 100-hour time-lag classes (Rothermel 1972). We arrived at plot-level estimates of fuel loading by fuel layer and category by combining results of the application of destructive and non-destructive procedures.

We characterized post-logging slash fuels at three locations in Central Portugal. Destructive sampling to characterize fuel structure and quantify fine fuel loading was based on 1-m^2 quadrats (n=21). Downed woody fuels >6 mm were estimated by linear interception as per Van Wagner (1968) and McRae *et al*,1979, using 20- and 30-m long transects for 10-h and 100-h fuels, respectively.

To describe the flammability of blue gum stands in Portugal we estimated fine fuel loadings for the 2005-2006 National Forest Inventory (NFI) plots occupied or dominated by blue gum, using our fuel data plus published and on-file data as the basis. As part of a general fuel modelling effort for the Portuguese vegetation types (Fernandes *et al*, 2009), we analysed the NFI data to define blue gum fuel models, which were built with the BehavePlus software (Andrews *et al* 2005). The fire behaviour data required to fine-tune the fuel models to real-world conditions (e.g. Cruz and Fernandes 2008) was almost non-existent. Hence, we adjusted the fuel models parameters such that the predicted fire characteristics would mimic the output of the VESTA fire spread model (Gould *et al,* 2007) for structurally similar fuel complexes. Then, we assigned a fuel model to each NFI plot and (i) simulated fire behaviour with BehavePlus for three summer weather scenarios, respectively mild, typical and extreme, and (ii) classified the respective fire hazard as a function of fire suppression difficulty as inferred from fire intensity (Hirsch and Martell 1996).

III. Results and Discussion

Fuel characteristics

A wide range in stand characteristics characterized the blue gum stands (n=30) subjected to fuel sampling, with stand height, density and basal area ranging from 4.4 to 36.5 m, 553 to 3567 trees ha^{-1} and 4 to 30 m^2 ha^{-1}, respectively. As a result, fuel inventories are expected to depict the existing variation, but the north-western (and more productive) part of Portugal is less represented in the collected data (Fig. 1).

Litter bulk density of the fuel samples, calculated with leaves and other fine (<6 mm) components, averaged 23.6 kg m^{-3}, with a standard deviation (SD) of 10.6 kg m^{-3}, and decreased with litter depth as $y = 54.716\ x^{-0.590}$ (R^2=0.42, n=61), indicating a more aerated litter than in *Pinus pinaster* stands (Fernandes *et al*, 2002). The decomposing layer accounted for 36.6% (SD =14.8 %) of the litter amount, and coarser (10-h+100-h) fuels further added 38.9% (SD = 5.8 %) of the fine litter loading to the forest floor.

Averages for the stand-level distribution of fuel loading by fuel category were 44.5, 25.8, 25.3 and 4.4% for fine litter, coarse litter components (i.e. 10-h+100-h fuels), understorey vegetation and suspended bark in the trees, respectively. Fuels generated by eucalypts, i.e. the forest floor plus suspended bark, increased with stand basal area (p<0.001, R^2=0.35, n=30) (Fig. 2). We did not attempt to relate fuel quantities and stand age. However, if a decomposition rate (k) of 0.37 (Ribeiro *et al*, 2002) is assumed, then fine litter loading will reach 95% of its maximum (3/k) after 8 years of accumulation, representing a faster build-up than in *P. pinaster* (Fernandes *et al,* 2002). Stand rotation did not affect fuel loadings or fuel distribution among categories, with one exception: a Tukey-Kramer test showed that 10-h+100-h downed woody fuels were higher in 2nd and 3rd rotation stands (5.4 Mg ha^{-1}) than in 1st rotation stands(1.8 Mg ha^{-1}).

Destructive sampling in the clear-felled stands indicated an increase of total slash load with slash depth (p=0.030, R^2=0.22). The bulk density of the slash fuel complex was quite variable (mean = 34.4 kg m^{-3}, SD = 30.2 kg m^{-3}) but the existing variation was unrelated (p=0.11) with slash depth. Fine fuels dominated the complex (on average, 63.8% of total slash load), followed by 10-h (27.9%) and 100-h (8.3%) fuels; note however that the 1-h fraction is overestimated, as all bark was included in this category. Total slash loading for the three study sites was estimated at 49.1, 81.7 and 89.9 Mg ha^{-1}, the first value corresponding to a site where slash had been partially removed and the other values corresponding to very recent logging. Vega et al. (1993) reported a quite similar mean load of 85.2 Mg ha-1 for blue gum slash in Galicia, NW Spain, but where fuels >6 mm comprised 61% of the total slash load.

Fire hazard

Figures 3 and 4 provide statistical information on the fine fuel loadings estimated for the NFI plots. In contrast with our previous findings, the shrub component tends to prevail over the litter component (Fig. 3), possibly because our sampling program emphasized litter and litter-shrub dominated fuel complexes. Fuel accumulation in the majority (65.2%) of NFI plots (Fig. 4) is below the 12 t ha-1 threshold for fuel treatment (Cheney and Richmond 1980), which is a natural outcome of the economic value of eucalypt plantations. Fire hazard mitigation in blue gum stands in Portugal is achieved by using mechanized equipment (disc harrowing or shrub cutting) in-between tree rows. Nonetheless, this is an optimistic assessment of stand vulnerability to wildfire as it is based on fine fuels loading only.

Estimates of fire behaviour characteristics based on fuel models can provide a more realistic assessment of fire hazard. Table 1 displays the fuel models parameters for blue gum stands in Portugal, including a previous fuel model for slash fuels (Cruz 2005). Three fuel models correspond to fuel complexes distinct in composition and structure, respectively stands either too young to have more than 2/3 of the ground covered by litter or disturbed by mechanical treatment (M-EUCd), dominated by litter (F-EUC), and composed by a mix of litter and shrubs (M-EUC). Fire behaviour potential increases from M-EUCd to M-EUC. These fuel models account for 65.4% of the NFI blue gum plots, M-EUCd being the most common as expected from a short-rotation forest system. Fuel models where the understorey vegetation controls fire behaviour represent the remaining plots (Fernandes *et al*, 2009).

Table 2 distributes the NFI plots by fire intensity class. For the respective interpretation in terms of fire suppression difficulty and requirements see Hirsch and Martell (1996). The lower and upper-intensity classes tend to be more populated, except for milder weather. Control of the forward section of a fire is very difficult or impossible when fire intensity exceeds 4000 kW m^{-1} and, because of spotting, even more so in eucalypt forest. For the weather scenarios considered, inefficient fire suppression is expected in 29 to 56% of the NFI plots. Table 2 results are quite illustrative of the benefits of fuel management in flammable forest types.

This study represents the state-of-the-art on fuel characterization and modelling in blue gum stands in Portugal. However, the results are still based on a relatively low sampling effort on a reduced number of locations. Further and more in-depth work is required to better understand and quantify the relationships between fuel dynamics, stand characteristics and silvicultural activities. This will improve the scheduling process of fuel treatments and its integration with stand management. The blue gum fuel models are useful to classify fire hazard and to estimate fire behaviour characteristics for broad purposes, but their development was not assisted by fire behaviour data. Hence, the fuel models may be unsatisfactory for planning and operational uses related with fire use or fire control. In this regard, and similarly to what has been achieved for *P. pinaster* (Cruz and Fernandes 2008; Fernandes *et al*, 2008; Fernandes *et al*, 2009), a thorough experimental fire behaviour program would significantly expand the scientific and technical basis for fire management in blue gum stands.

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Table 1: Blue gum fuel model parameters.

Model (% NFI plots)	Fuel depth	Fuel loading (Mg ha^{-1})				SVR (m^{-1})		PC	Mx
	(m)	1-h	10-h	100-h	live shrubs	1-h	live shrubs	(J g^{-1})	(%)
F-EUC (6.0%)	0.32	4.63	2.96	1.27	1.12	4200	5000	21000	26
M-EUC (22.9%)	0.64	8.37	3.81	0.00	4.51	4700	5000	21000	32
M-EUCd (36.5%)	0.40	1.37	2.89	1.59	1.84	4500	5000	21000	26
*RESE-01	0.30	7.00	7.00	5.00	0.00	5500	-	22000	30

* Fuel model for logging slash (Cruz 2005).

Table 2: Distribution (%) of the NFI blue gum plots by fire intensity class for three summer weather scenarios.

Fire intensity (kW m^{-1}) class	*Weather scenario		
	Mild	Typical	Extreme
<500	38.1	37.7	0.0
500-2000	16.1	6.4	38.1
2000-4000	17.3	10.1	6.0
4000-10000	25.5	42.8	12.7
>10000	3.0	3.0	43.2

* Defined by different fuel moisture content (%) sets (1-h, 10-h+100-h, live shrubs): extreme = 4, 5, 75; typical = 7, 8, 85; mild = 10, 11, 100. Wind speed and terrain slope fixed at 10 km h^{-1} and 30%, respectively.

Figure 1: Fuel sampling locations. Black circles = stands, white circles = post-logging slash.

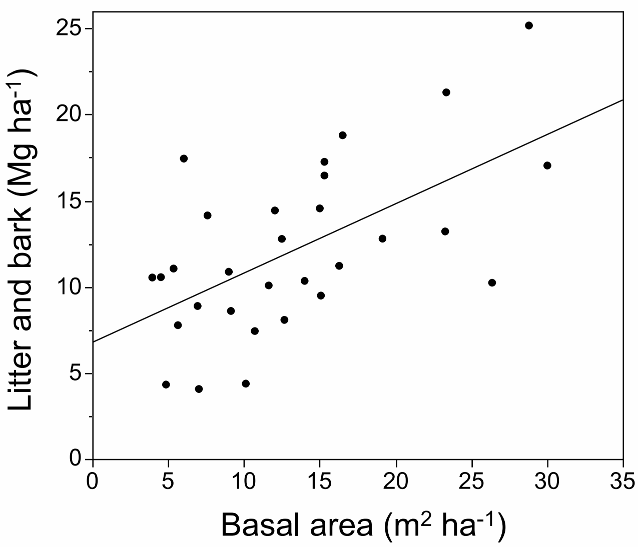

Figure 2: Relationship between accumulated blue gum fuels and stand basal area.

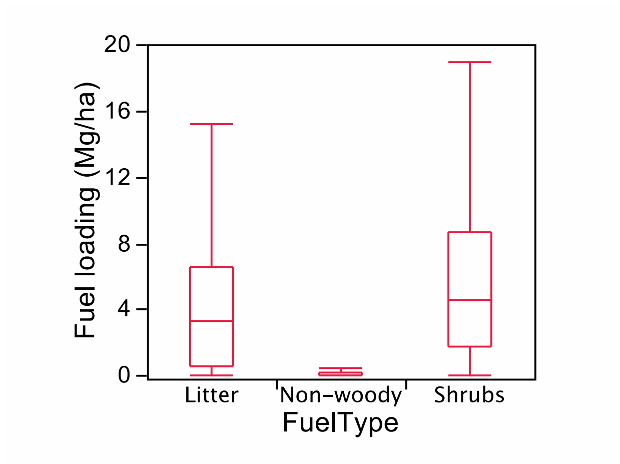

Figure 3: Maximum, 75th percentile, median, 25th percentile, and minimum values of fine fuel loadings per fuel layer for the NFI blue gum plots (n=1095).

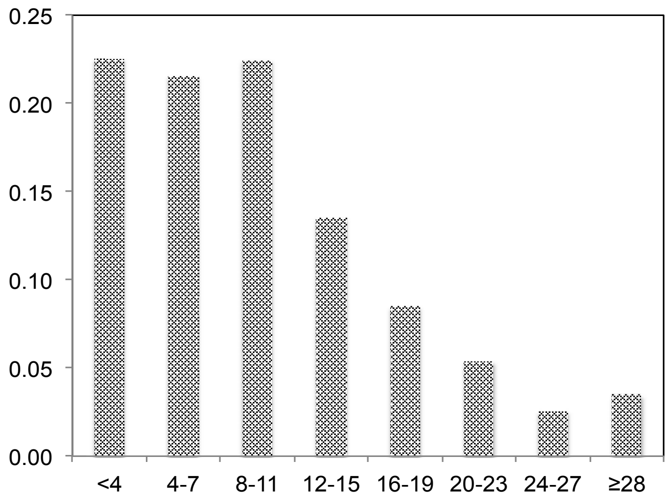

Figure 4: NFI plots distribution by fine fuel loading class (Mg ha^{-1})