Advances in Forest Fire Research

DOMINGOS XAVIER VIEGAS
EDITOR

2014

Modelling fine fuel moisture content and the likelihood of fire spread in blue gum (Eucalyptus globulus) litter

Anita Pinto[a], Juncal Espinosa-Prieto[a], Carlos Rossa[a], Stuart Matthews[b], Carlos Loureiro[c], Paulo M. Fernandes[a*]

[a] *Centro de Investigação e de Tecnologias Agro-Ambientais e Biológicas, UTAD, Quinta de Prados, Apartado 1013, 5000-801 Vila Real, Portugal.* *pfern@utad.pt
[b] *CSIRO Ecosystem Sciences and CSIRO Climate Adaptation Flagship, GPO Box 1700, Canberra, ACT 2601, Australia*
[c] *GIFF S.A.; Rua D. João Ribeiro Gaio, 9B-1ºE, 4480-811 Vila do Conde, Portugal.*

Abstract
The capabilities of accurately estimating dead fuel moisture content and predicting the likelihood of self-sustained fire spread are crucial to plan prescribed fire operations and achieve the treatment goals, among other fire management objectives. After analysis to determine whether some existing models could be adopted or adapted, we developed user-friendly equations to predict the moisture content of dead fine fuels in blue gum (*Eucalyptus globulus*) litter and examined their prediction ability. Models with vapour pressure deficit, the FFMC code of the Canadian FWI System (or the no. of days since last precipitation in alternative) and noon 10-m open wind speed from the nearest weather station as independent variables fitted the data suitably, as well as a physics based model. The probability of sustained fire propagation in experimental burns carried out in reconstructed blue-gum litter in the laboratory was described through fuel moisture content, litter depth and fire-spread direction (backward or forward). Both types of equations will be further tested in blue gum stands.

Keywords*: Fuel moisture, Eucalyptus globulus, fire behaviour, fire danger, prescribed burning*

1. Introduction

Blue gum eucalypt (*Eucalyptus globulus* Labill.) stands in Portugal are an important economic resource as well as inherently flammable, hence contributing to the extent of the fire problem. Treatment of fuels in highly flammable forest plantations is an essential component of their sustainable management to minimize burn probability, be able to suppress fire under unfavourable weather conditions, decrease its ecological impact and increase the value of salvaged wood. The advantages of prescribed burning as a fuel management technique warrant investigation of its feasibility in industrial eucalypt plantations. The FIREglobulus project seeks to establish the scientific basis for the technological development of prescribed burning in blue gum plantations. This project studies the behaviour and severity of experimental outdoors fires carried out from autumn to spring, supplemented by laboratory trials data. Data analysis relates fire characteristics with fuel complex descriptors and other environmental factors, examines the performance of currently available fire-behaviour prediction models, and develops predictive relationships for the chain fire environment - fire behaviour - fire effects in blue gum stands.
The moisture content of dead and live fuels plays an important role in fire behaviour and fuel consumption. Usually referred to as 'fuel moisture content' FMC (Viney 1991) it significantly influences fuel flammability and ignition, fuel consumption and overall fire behaviour (Matthews 2006; Pyne *et al.* 1996). Over the past decades several authors have developed research in this area using different approaches. Viney (1991) and more recently Matthews (2014) reviewed the state-of-the art on modelling the moisture of dead fine fuels. The focus of our work is on user-friendly operational models for use in the field, falling inside the group of empirical models based on weather

conditions so that FMC can be expressed through functional relationships like those developed by Pook and Gill (1993), Marsden-Smedley and Catchpole (2001), Ferguson *et al*. (2002), Lin (2004), Sharples *et al*. (2009), Ray *et al*. (2005, 2010) or Sharples and McRea (2011).

Fuel moisture content has been shown to be the main variable determining the likelihood of sustained fire spread in distinct fuel types, but other environmental variables (wind speed, fuel accumulation and continuity, fire direction) further exert an effect (e.g. Fernandes *et al*. 2008; Leonard 2009; Anderson and Anderson 2010; Cruz *et al*. 2013). Prescribed burning is often carried out under marginal conditions, i.e. at the high-end of the fuel moisture range that allows a spreading fire, and so the operational abilities to assess dead fine fuel moisture content and the likelihood of sustained fire spread are critical to plan and carry out prescribed fire operations.

In this study we present modelling results for blue-gum litter concerning (i) estimation of the moisture content of fine litter from environmental variables, and (ii) fire spread sustainability.

2. Methods

2.1. Fuel moisture content

The fuel moisture content of fine surface litter was measured by destructive sampling. The samples were collected daily (*n*=127) in a forest stand in the UTAD campus (Vila Real, northern Portugal) at 15:00 hours, between August 2012 and December 2013, and were oven-dried for 24 hours at a temperature of 100ºC. The temperature and relative humidity at the time of litter collection were measured at a 1.8-m height and used to calculate vapour pressure deficit (VPD, kPa), which measures the drying power of the air as the difference between the amount of moisture in the air and how much moisture the air can hold when saturated.

Noon weather data from the nearest meteorological station (4 km) and the corresponding indices of the Canadian FWI System (Van Wagner 1987) were also recorded.

2.2. Sustainability of fire spread

The sustainability of fire spread was evaluated in indoor burn trials (*n*=134) for backing (Figure 1) and heading fires under a wide range of litter moisture and structure (load, depth, bulk density) and wind speed.

For each trial we have reconstructed a litter layer (1.5m x 2m) in the combustion table. We tried to cover the natural variation in litter thickness and loading, based in the national forest inventory (2005-2006) data. Fuel loading was estimated by oven drying the material within a randomly-located 0.073 m^2 square. Fuel depth was determined from nails (*n*=8) inserted in the litter and flushed with its top. Fuel sampling for moisture content assessment proceeded immediately before ignition. Ambient temperature and relative humidity were monitored with a Davis weather station.

The fires were line-ignited (fire front width = 1.5 m) and allowed to propagate downslope with the slope fixed at 30%. The trials were either classified as sustained or non-sustained in case of self-extinction. If the fire failed to spread downslope the trial was repeated upslope with successive laminar-flow wind speeds of 0, 5, 10 and 15 km h^{-1} until attaining sustained fire spread.

Figure 1. A fire-spread sustainability trial in the combustion table.

2.3. Data analysis

We examined the prediction ability of eucalypt litter moisture content models (Gould *et al*. 2007; Sharples *et al*. 2009; Sharples and McRea 2011). FMC was empirically modelled from local weather (and related variables, e.g. vapour pressure deficit) and Canadian FWI moisture codes. FMC was log-transformed and regressed on both the untransformed and log-transformed independent candidate variables; the elected equations were back-transformed and corrected for bias. FMC was also derived through the physically-based model of Matthews (2006), for which hourly weather was estimated using the methods of Matthews *et al*. (2007). Model assessment was based on deviation statistics.

To predict the go/no-go status of fire spread we used two supplementary approaches, respectively CART (Classification and Regression Trees) and logistic regression, which estimates the continuous and non-linear probability P of an event (successful fire spread in this case, coded as 1). The logistic equation has the form (Hosmer and Lemeshow 2000):

$$P = 1 / [1 + \exp(-(b_0 + b_1 x_1 + \ldots + b_i x_i))] \quad (1)$$

where x_1 to x_i are the independent variables and b_0 to b_i are the regression coefficients.

Besides FMC we considered fuel structure (litter depth, load, and bulk density) and fire-spread direction as potential independent variables; the number of upslope trials with varying wind speed did not warrant assessment of its effect. The direction of fire spread was coded 0 for backward spread (the downslope back fire) and 1 for forward spread (the upslope head fire). To evaluate model predictions we used concordance analysis and the area under the ROC (receiver operating characteristic) curve, which is independent of an arbitrary decision.

3. Results and discussion

3.1. Fine fuel moisture content

Weather data at the moment of fuel sampling varied in the ranges of 7.0 - 35.8 ºC for ambient temperature, 16.5 - 100% for relative humidity and 0 - 25 km h^{-1} for wind speed. In general, the existing models for eucalypt litter FMC produced underestimates (Table 1), essentially because they were developed to predict the moisture content of fuels unaffected by precipitation. However, multiplying Gould *et al*. (2007) predictions by a factor of 1.5 succeeded in explaining 77% of the observed variation when FMC <35%. The physical model generally produced better predictions because it included precipitation effects. The best-fitting empirical model (Table 2) explained 92% of the observed variation and included the VPD, noon 10-m open wind speed and the FFMC of the Canadian FWI as independent variables (equation A). An alternative, more user-friendly equation (B) that included the number of days since precipitation instead of the FFMC had a poorer fit to data. The performance of both models was comparable to the more complex physical model.

Table 1. Evaluation of the models for estimating the moisture content (%) of fine surface litter.

Model	*n*	FMC range	RMSE	MAE	MAPE
Gould *et al*. (2007)	60	6.1 - 29.2	5.4	4.4	31.5
Sharples *et al*. (2009)	127	6.1 - 193.0	25.1	10.1	24.6
Sharples and McRae (2011)	127	6.1 - 193.0	33.6	15.3	45.3
Matthews (2006)	127	6.1 - 193.0	20.8	8.8	25.1
Matthews (2006)*	107	6.1 - 35.0	4.3	3.1	18.7

RMSE - Root mean square error; MAE - Mean absolute error; MAPE - Mean absolute percent error.
*Subset of results with modelled and observed moisture content below 35%

Table 2. Equations for estimating the moisture content (%) of fine surface litter. Standard errors of regression coefficients appear below the equations by the same order. All independent variables are significant at p<0.001.

Model	Equation	R^2	MAE	MAPE
A	$77.707\ VPD^{-0,385} \exp(-0.018\ FFMC) \exp(-0.012\ U)$ (8.493; 0.001; 0.004; 0.029)	0.92	4.5	16.9
B	$28.701\ VPD^{-0,571}\ NDWR{+}1^{-0,157} \exp(-0.021\ U)$ (1.919; 0.032; 0.034, 0.005)	0.85	6.8	21.8

VPD – Vapour pressure deficit (kPa); FFMC- Fine Fuel Moisture Code; U – 10-m wind speed in the open (km h^{-1}); NDWR - Number of days since precipitation. R^2- Coefficient of determination; MAE - Mean absolute error; MAPE - Mean absolute percent error.

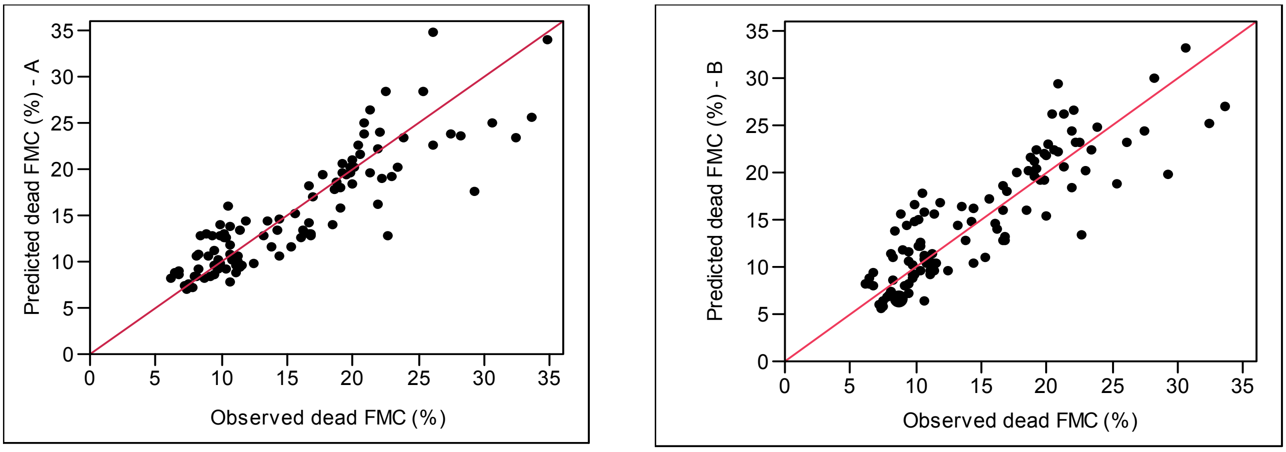

Figure 2. Observed versus predicted blue-gum litter moisture content using models A and B. The line of perfect agreement is overlaid.

3.2. Fire spread sustainability

FMC during the burn trials varied from 10.4 to 68%. The CART analysis indicates litter moisture content, its depth (which exerted the major effect) and fire-spread direction (forward or backward in relation to wind and slope) as the variables influent in the sustainability of fire spread (Table 3). When FMC is lower than 32.4% and litter depth is greater than or equal to 3.7 cm, sustained fire spread is virtually certain. In contrast, fire spread is highly unlikely for FMC above 32%, independently of other variables.

The model developed to predict the likelihood of sustained fire spread (Table 4 and Figure 3) has an area under the ROC curve of 0.925, which Hosmer and Lemeshow (2000) consider outstanding. Nevertheless, a comparison between Table 3 and Figure 3 indicates the logistic regression tends to be conservative, i.e. underestimates the fire-spread potential. In fact model predictions are quite sensitive to litter depth, e.g. the likelihood of fire spread increases substantially when LD changes from 3.0 (the data set average) to 3.5 cm. Litter depth probably expresses the effect of fuel continuity in addition to the effect of fuel loading, as the former tends to be partial at shallow depths due to the morphology of blue gum leaves. The fire-spread outcome was correctly predicted by the model in 85% of the experimental trials; out of the failed predictions 10% were underestimates and 5% were overestimates.

Table 3. CART analysis of the likelihood of sustained fire spread in blue gum litter.

<table>
<tr><td colspan="5">Variables and thresholds</td><td>Fire spread probability</td></tr>
<tr><td rowspan="5">FMC <32.4 %</td><td colspan="4">Litter depth ≥ 3.7 cm</td><td>1</td></tr>
<tr><td rowspan="4">Litter depth < 3.7 cm</td><td colspan="3">Forward spread</td><td>0.82</td></tr>
<tr><td rowspan="3">Backward spread</td><td rowspan="2">Litter depth ≥ 2.9 cm</td><td>FMC <28.2 %</td><td>1</td></tr>
<tr><td>FMC ≥28.2 %</td><td>0.20</td></tr>
<tr><td colspan="2">Litter depth < 2.9 cm</td><td>0.07</td></tr>
<tr><td colspan="5">FMC ≥32.4%</td><td>0.16</td></tr>
</table>

Table 4. Coefficients (standard errors) of the model for estimating the probability of sustained fire spread.

Intercept	FMC	LD	FD
3.0182 (0.9490)	0.1852 (0.0342)	-2.3181 (0.4799)	-2.7597 (0.6287)
p=0.0015	*p*<0.0001	*p*<0.0001	*p*<0.0001

FMC – Fuel moisture content (%); LD – litter depth (cm); FD – Fire-spread direction

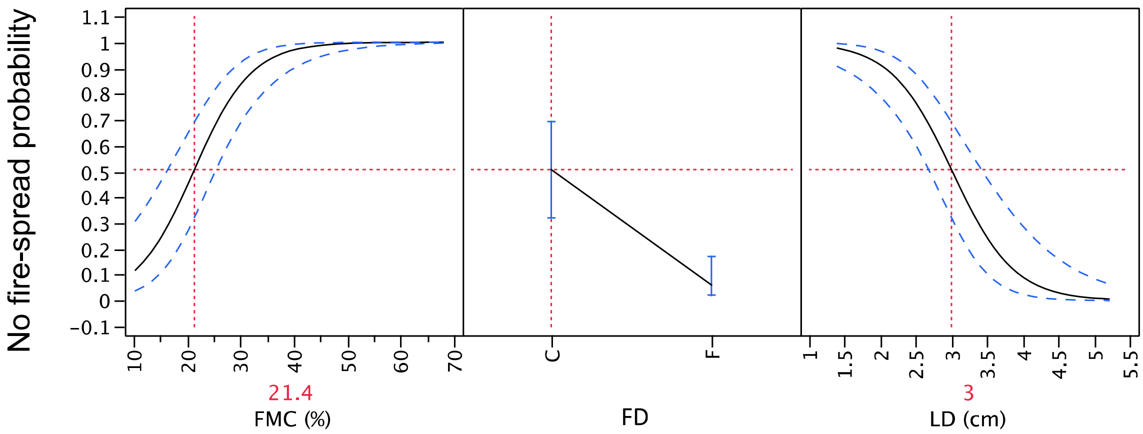

Figure 3. Fire-spread probability with confidence intervals as per the logistic model in Table 4. FMC = 21.4% is the threshold between go / no-go for a back fire and the mean observed litter depth.

4. Conclusions

Expedite and reasonably accurate estimation of the moisture content of fine surface litter for operational purposes is possible by using an empirical model based on temperature and relative humidity (in the form of the VPD), supplemented by other less relevant variables that account for the drying effects of time since last rainfall and wind speed. The physical model performs similarly, but its use by fire managers is not practical.

Fire-spread sustainability was highly influenced by fuel structure, which contrary to expectations (and because of the experimental design) exceeded the importance of FMC. The performance of the laboratory-base model for fire spread sustainability needs to be assessed during outdoors experimental fires. In case the results indicate good predictive ability, scaling problems will then be ruled out and it will be reasonable to extrapolate the lab-based results to the field and to management-ignited fires. The results will be part of the prescribed burning guide for blue gum plantations.

5. Acknowledgments

This study wass supported by FIREglobulus, I&DT co-promotion project no. 21555 in the frame of *Quadro de Referência Estratégico Nacional* (QREN), co-funded by the European Regional Development Fund (ERDF) through *Programa Operacional Regional de Norte*.

6. References

Anderson SAJ, Anderson WR (2010) Ignition and fire spread thresholds in gorse (*Ulex europaeus*). *International Journal of Wildland Fire* **19**, 589–598.

Cruz MG, McCaw WL, Anderson WR, Gould JS (2013) Fire behaviour modelling in semi-arid mallee-heath shrublands of southern *Australia.Environmental Modelling and Software* **40**, 21–34.

Ferguson SA, Ruthford JE, McKay SJ, Wright D, Wright C, Ottmar R (2002) Measuring moisture dynamics to predict fire severity in longleaf pine forests. *International Journal of Wildland Fire* **11**, 267–279.

Fernandes PM, Botelho HS, Rego FC, Loureiro C (2008) Using fuel and weather variables to predict the sustainability of surface fire spread in maritime pine stands. *Canadian Journal of Forest Research* **38**, 190–201.

Gould JS, McCaw WL, Cheney NP, Ellis PF, Matthews S (2007) Field Guide - Fuel Assessment and Fire behaviour Prediction in Dry Eucalypt Forest. Ensis-CSIRO, Canberra, ACT and Department of Environment and Conservation. (Perth, WA)

Hosmer DW, Lemeshow S (2000) Applied logistic regression. 2nd ed. John Wiley & Sons Inc. (New York)

Leonard S (2009) Predicting sustained fire spread in Tasmanian native grasslands. *Environmental Management* **44**, 430-440.

Lin CC (2004) Modeling fine dead fuel moisture in Taiwan red pine forests. *Taiwan Journal of Forest Science* **19**, 27–32.

Marsden-Smedley JB, Catchpole WR (2001) Fire modelling in Tasmanian buttongrass moorlands. III - Dead fuel moisture. *International Journal of Wildland Fire* **10**, 241–253.

Matthews S (2006) A process-based model of fine fuel moisture. *International Journal of Wildland Fire* **15**, 155–168.

Matthews S, McCaw WL, Neal JE, Smith RH (2007) Testing a process-based fine fuel moisture model in two forest types. *Canadian Journal of Forest Research* **37**, 23–35

Matthews S (2014) Dead fuel moisture research: 1991-2012. *International Journal of Wildland Fire* **23**, 78–92.

Pyne SJ, Andrews PL, Laven RD (1996) Introduction to Wildland Fire. John Wiley & Sons, Inc. (New York).

Pook EW, Gill AM (1993) Variation of live and dead fine fuel moisture in *Pinus radiata* plantations of the Australian Capital Territory. *International Journal of Wildland Fire* **3**, 155–168.

Ray D, Nepstad D, Moutinho P (2005) Micrometeorological and canopy controls of fire susceptibility in a forested Amazon landscape. *Ecological Applications* **15**, 1664–1678.

Ray D, Nepstad D, Brando P (2010) Predicting moisture dynamics of fine understory fuels in a moist tropical rainforest system: results of a pilot study undertaken to identify proxy variables useful for rating fire danger. *New Phytologist* **187**, 720–732.

Sharples J, McRae R, Weber R, Gill M (2009) Simple index for assessing fuel moisture content. *Environmental Modelling and Software* **24**, 637–646.

Sharples J, McRae R (2011) Evaluation of a very simple model for predicting the moisture content of eucalypt litter. *International Journal of Wildland Fire* **20**, 1000–1005.

Van Wagner CE (1987) Development and Structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Information Report 35. (Ottawa, ON).

Viney NR (1991) A review of fine fuel moisture modelling. *International Journal of Wildland Fire* **1**, 215–234.