CSIRO PUBLISHING

International Journal of Wildland Fire **2015**, *24*, 443–460
http://dx.doi.org/10.1071/WF14130

A generic, empirical-based model for predicting rate of fire spread in shrublands

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Abstract. A shrubland fire behaviour dataset was assembled using data from experimental studies in Australia, New Zealand, Europe and South Africa. The dataset covers a wide range of heathlands and shrubland species associations and vegetation structures. Three models for rate of spread are developed using 2-m wind speed, a wind reduction factor, elevated dead fuel moisture content and either vegetation height (with or without live fuel moisture content) or bulk density. The models are tested against independent data from prescribed fires and wildfires and found to predict fire spread rate within acceptable limits (mean absolute errors varying between 3.5 and 9.1 m min^{-1}). A simple model to predict dead fuel moisture content is evaluated, and an ignition line length correction is proposed. Although the model can be expected to provide robust predictions of rate of spread in a broad range of shrublands, the effects of slope steepness and variation in fuel quantity and composition are yet to be quantified. The model does not predict threshold conditions for continuous fire spread, and future work should focus on identifying fuel and weather factors that control transitions in fire behaviour.

Additional keywords: fire behaviour, fire prediction.

Received 24 July 2014, accepted 2 December 2014, published online 12 February 2015

Introduction

Heathlands, shrublands and woodlands with a prominent shrub understorey comprise a significant component of the vegetation of subtropical and temperate climates (Specht 1979; di Castri 1981; Gillison 1994; Specht 1994). Shrub vegetation types are particularly relevant as one of the dominant elements of the landscape in Mediterranean-type climates (Keeley *et al.* 2012). Such vegetation is found in a wide range of environments, from coastal dunes to mountainous uplands, often where soils are either shallow or sandy, and of low nutrient status. Prominent features of such heath/shrubland communities, particularly in Australia and South Africa, are their high levels of floristic diversity (see van Wilgen 2013), their propensity for recurrent fire (Gill and Groves 1981; Keith *et al.* 2002) and the importance of fire for plant reproduction (Bradstock *et al.* 1997). Management of fires to maintain floristic diversity is therefore a primary objective in such shrubby vegetation. Equally significant, management of fires for pastoral purposes and protection of people and their property are issues of great importance (Fernandes *et al.* 2013). Heaths, shrublands and shrubby woodlands comprise a considerable proportion of the remaining natural vegetation in the most heavily populated parts of New Zealand, Australia and South Africa. Thus, there are strong imperatives for sound, scientifically based fire management in these vegetation types.

Throughout the last five decades, empirically based fire behaviour models and corresponding prescribed burning guides have been developed for many prominent vegetation types including forests (e.g. McArthur 1967; Sneeuwjagt and Peet 1985; Forestry Canada Fire Danger Group 1992; Fernandes *et al.* 2009; Cheney *et al.* 2012), perennial and ephemeral grasslands (e.g. McArthur 1966; Cheney *et al.* 1998), hummock grasslands (Burrows *et al.* 1991) and mallee-heath woodlands (Cruz *et al.* 2013). Nonetheless, there is still a significant gap in our understanding of fire behaviour in shrublands. A few fire behaviour field studies have been carried out in European, North American and South African shrubland types, essentially under moderate to high fire danger rating conditions and based on a limited number of experimental fires (Lindenmuth and Davis 1973; van Wilgen *et al.* 1985; Vega *et al.* 1998; Fernandes *et al.* 2000; Fernandes 2001; Davies *et al.* 2009). Shrubland fuel types are notorious for their high flammability due to several intrinsic physical and chemical characteristics such as high proportion of dead fuel component in the shrub canopy (Rothermel and Philpot 1973; Countryman 1982; Baeza *et al.* 2011), high porosity (Papió and Trabaud 1991), the existence of low-temperature volatiles (Philpot 1969; Rothermel 1976) and the direct exposure to wind. Thus, fires in such vegetation tend to be characterised by high rates of spread and intensities, even under moderate burning conditions. There is a pressing need for a comprehensive understanding of fire behaviour in heathlands, shrublands and shrubby woodlands to inform fire-management decision-making and better manage the threat of fire to human populations and natural resources.

In Australia, shrubland vegetation types tend to be located in protected areas, such as national parks, and are somewhat fragmented (see Keith *et al.* 2002). Opportunities to conduct experimental burning programs on a large enough scale to allow the development of a robust fire spread model are limited by fire regulations, availability of homogeneous experimental sites, and the expense of field experiments. In addition, shrubland vegetation varies considerably in structure and species composition between bioclimatic regions.

To overcome these issues, fire behaviour researchers from several states of Australia and from New Zealand formed a working group in the mid-1990s with the objective of sharing their limited datasets and agreeing on common methodologies to conduct experimental fires and measure variables associated with shrubland fire behaviour. Based on the compilation of this early dataset, a simple interim fire behaviour model was created (Catchpole *et al.* 1998). The model predicted fire spread rate in terms of wind speed and vegetation height. A deficiency with the model was that no dead (or live) fuel moisture content effect could be found in the dataset for which the lowest dead fuel moisture content was 10%. Since the development of the interim fire spread model by Catchpole *et al.* (1998), additional data have become available from Portugal (Fernandes 2001; Vega *et al.* 2006), Spain (Vega *et al.* 1998) and South Africa (van Wilgen *et al.* 1985), and from a recent experimental burning program in semiarid vegetation of southern Australia (Cruz *et al.* 2010).

The present paper extends the previous work of Catchpole *et al.* (1998) using an expanded experimental dataset in order to develop a generic rate of fire spread model applicable to a wide range of shrubland types around the world.

Methods

The premise behind the present study was that sufficient field research into the fire behaviour of shrubland vegetation exists that will permit the development and evaluation of a generic rate of fire spread model for shrubland fuel complexes. A suitable fire spread rate database was assembled from published and unpublished data on fire environmental variables and associated fire behaviour characteristics in shrubland fuels collected in several unrelated research projects and wildfire documentation case studies in Australasia, Europe and Africa. Data were originally collected by land-management and research organisations for distinct purposes (e.g. development of fire danger rating systems, production of guidelines for prescribed burning, and investigation of the effects of fire on biodiversity). As a consequence, the level of detail on fuel characteristics varied considerably. Some organisations conducted detailed sampling of the fuel complex structure, including sorting of fuel components into size classes and dead and live condition, whereas others only provided a coarse description of the fuel complex (e.g. fuel height and cover). However, all researchers collected observations of the key weather variables and fire behaviour characteristics. Based on the data available, namely fuel description, the dataset was divided into two major groups: (i) model development, and (ii) model evaluation.

Model development subset

The model development subset comprised data from 79 fires collected over a broad range of fuel structures, fire environment variables and fire behaviour characteristics. Table 1 lists the sources of the experimental and prescribed fire data and their respective study locations. The main features of this data subset were the quality of the fuel data and the assumption that fires were spreading near their quasi-steady rate of advance. Three primary constraints, related to slope steepness, ignition line length and fuel moisture, were imposed on the data used in the analysis to ensure this expectation was met. As a result, not all published data sources assembled for possible inclusion in the analysis were used (e.g. Bilgili and Sağlam 2003; Streeks *et al.* 2005; Viegas *et al.* 2006; Sağlam *et al.* 2008; Stephens *et al.* 2008; Davies *et al.* 2009; Fontaine *et al.* 2012).

Table 1. Sources of data groups
Australian heath classifications follow Keith *et al.* (2002)

Source	Code	Country	Number of fires	Use	Dominant vegetation	Main reference
Jonkershoek Forestry Research Centre	ZA	South Africa	14	Model development	Fynbos	van Wilgen *et al.* (1985)
University of NSW	WC	Australia	3	Ignition line length	East coast dry and temperate wet heath	Catchpole (1987)
National Parks and Wildlife Service of NSW	NSW	Australia	10	Model evaluation	East Coast dry heath AND woodland	Bradstock and Auld (1995)
Tasmania Parks and Heritage	BGM	Australia	34	Model evaluation	Temperate wet heath (buttongrass)	Marsden-Smedley and Catchpole (1995*b*)
Forestry Research Centre of Lourizan	SP	Spain	19 + 13	Model development, ignition line length	Mixed heathland	Vega *et al.* (1998)
University of Trás-os-Montes and Alto Douro	PT	Portugal	8 + 25	Model development, ignition line length	Mixed heathland	Fernandes (2001); Vega *et al.* (2006); unpublished data
CSIRO	SA	Australia	10	Model development	Central lowland heath	Cruz *et al.* (2010)
Scion	NZ	New Zealand	28	Model development	Mixed heath–shrubland	Anderson (2009)
Tasmania Parks and Heritage	Tas.	Australia	11	Model evaluation	Mixed heathland and moorland	Unpublished data
Department of Environment and Primary Industries, Victoria	VGM	Australia	11 + 1	Model evaluation, ignition line length	East Coast temperate wet heath	Unpublished data

The behaviour of fires on slopes brings in many complexities due to gradients in fuel structure and moisture content, and issues with the interaction of wind and slope. To limit these effects, the data selected for analysis were restricted to slopes of <5°. No attempt was made here to develop a statistical parameterisation for the effect of slope steepness on fire spread in shrublands.

Ignition line lengths, and the ensuing head-fire widths are known to affect fire propagation, with narrower fires failing to attain quasi-steady rates of spread observed in free-burning fires. This topic is discussed further in Cheney and Gould (1995) for grassland and in Wotton *et al.* (1999) and Luke and McArthur (1978) for forests. To overcome this possible confounding factor, the data used for modelling were restricted to ignition line lengths of ≥50 m. The effect of ignition line length was also considered in the analysis. A limited set of fires with smaller ignition line lengths were used to develop an ignition line length correction.

One final constraint was imposed. The fires selected for analysis had to have a measured dead fuel moisture content below the assumed fibre saturation point of 35% (Berry and Roderick 2005). A summary of the site characteristics, plot size and layout, vegetation types, fuel characteristics, weather and fire behaviour assessment methods, and main study references associated with each experimental burning program selected for inclusion in the analysis dataset is given in the Supplementary Material (available online only).

Model evaluation subset

A model evaluation subset was assembled from two main data types. The first type comprised data from the datasets given in Table 1 that lacked appropriate vegetation variables, namely measured fuel loading (amount of fine fuel per unit area) and percentage of dead fuel, to allow its inclusion in the model development analysis. Buttongrass moorland was not included in the model development set, even though the vegetation variables were available, because it is a fuel complex where grasses of the family *Cyperaceae* (sedges) dominate the overall fuel structure. Only the high-productivity moorland (see Marsden-Smedley and Catchpole 1995*b*) and the oldest low-productivity moorland (20 years or over) were used in the model evaluation dataset, as the fuel structure in the younger low-productivity moorland is similar to a grassland.

The second evaluation data type comprised fire spread rates from well-documented wildfire reconstructions and observations. Weather and fire spread data in the evaluation dataset were classified for their reliability, as per Cheney *et al.* (2012). Models were assessed using scatterplots and the same goodness-of-fit statistics used in the model development process. Wind speed in the wildfire dataset was measured at 10 m in the open at nearby weather stations as per World Meteorological Organisation standards (WMO 1983). A conversion factor was needed to make these data consistent with the experimental data, which mostly have wind speed measured at 2 m.

The ratio of 10- to 2-m wind speed measured in the open (i.e. no canopy cover present) depends on the stability of the atmosphere and thermal turbulence, and the surface roughness (Albini 1981; Campbell and Norman 1998). In the absence of detailed vegetation and turbulence measurements, a simplified relationship between the wind speeds at these heights was sought. Simultaneous field measurements of 10- and 2-m wind speeds above shrublands by Tran and Pyrke (1999) and Marsden-Smedley and Catchpole (1995*b*) yielded a wind reduction factor of 0.667 (i.e. the wind speed at a height of 2 m above the shrub canopy is ~67% of the 10-m open wind). For the fuel types where the shrub component was below a woodland (a woodland ecosystem is defined by a low stature open forest with tree canopy cover varying between 10 and 30%, and limited shading of the understorey fuel layer), a wind reduction factor of 0.35 was used to convert the 10-m wind to the 2-m wind speed height (from Tran and Pyrke 1999).

Most of the wildfire data did not include measured fuel load or structure and dead fuel moisture content. In the absence of measurement data for vegetation height and fuel load, estimates of these quantities were derived from standard fuel accumulation curves based on fuel age when available (e.g. Keith *et al.* 2002), or equations with shrub height and cover as independent variables (e.g. Fernandes and Rego 1998; Pearce *et al.* 2010). To estimate dead fuel moisture content, a function derived from a process-based fuel moisture model (Matthews *et al.* 2010) parameterised to elevated dead fuels in shrub canopies was used (Cruz *et al.* 2010). The model performance for shrub fuels was tested with the fuel moisture data from Tas., VGM, SA (see Table 1), Catchpole (1987), and unpublished data from heathland and mallee in South Australia.

Statistical methods – fire spread rate modelling

Wind speed and fuel moisture content exert a large effect on the rate of fire spread in all vegetation types. A review of empirical fire spread rate models by Sullivan (2009) showed that all models contain these variables either explicitly (e.g. Cheney *et al.* 1998, 2012), or implicitly through air temperature, relative humidity and long-term drying (e.g. McArthur 1973). The effect of fuel structure is usually present in some form, as fuel loading (McArthur 1973), bulk density (Thomas 1971), percentage of dead fuel (McArthur 1966), fuel age (Marsden-Smedley and Catchpole 1995*b*), fuel height (Catchpole *et al.* 1998; Fernandes *et al.* 2000) or through visual ratings of the fuel bed composition (Cheney *et al.* 2012). Thus, wind speed and fuel moisture content were included in the statistical model, together with those fuel descriptor variables that proved to have sufficient predictive power.

To make sure that fast-spreading fires were predicted with maximum accuracy, a non-linear model was used. The model incorporates well-accepted functional forms for the two key environmental variables, namely a power function of wind speed and an exponential decay function of dead fuel moisture content as in Cheney *et al.* (1998) and Cruz *et al.* (2013):

$$R = aU_2^b \exp(-cM_d)\Phi_1(V_1)\ldots\Phi_p(V_p) \quad (1)$$

where R is the rate of spread, a, b and c are constants, U_2 is the wind speed at 2 m, M_d is the dead fine fuel moisture content, $\Phi_1(V_1)\ldots\Phi_p(V_p)$ is the product of functions of p variables $V_1\ldots V_p$, and p is the number of statistically significant variables in the model. The functions Φ_i were either power or exponential functions, depending on the most sensible formulation (e.g. as the effect of the live fuel moisture content (M_l) and proportion of live fuels (p_l) both tend to a value of 1.0 as these variables tend to zero, so an exponential decay function was used). Table 2 contains a list of variables that were tested for significance.

To account for correlated observations within each data group, the error was split into between-group and within-group error and a non-linear mixed effect model (Pinheiro and Bates 2000) was used in the analysis; as a consequence, in Eqn 1, a can be regarded as the mean of a random variable that varies over the data groups. The data were analysed using the packages *nlme* (Pinheiro *et al.* 2014) and *nls* in the software *R* (R Core Team 2014). The models were assessed using several goodness-of-fit measures, namely the root-mean-squared error (RMSE), the mean absolute error (MAE), the mean bias error (MBE) and the mean absolute percentage error (MAPE) (Willmott 1982). Normal quantile plots were made of the residuals and tests of normality were carried out using the Anderson–Darling test (Anderson and Darling 1952).

Table 2. Variables, symbols and units

Variable	Symbol	Units
Rate of fire spread	R	m min^{-1}
Wind speed measured at 2-m height	U_2	km h^{-1}
10-m open wind speed	U_{10}	km h^{-1}
Dead fine fuel moisture content	M_d	%
Live fine fuel moisture content	M_l	%
Vegetation height	h	m
Fine fuel load	w	kg m^{-2}
Vegetation cover	C	%
Vegetation bulk density	ρ_b	kg m^{-3}
Percentage of live fuel	p_l	%
Ignition line length	L	m
Wind reduction factor	w_f	–

Statistical methods – fireline width effect

Several fires ($n = 40$) from the sources listed in Table 1 had ignition line lengths less than 50 m. Although not used for model development and evaluation, these fires were used to investigate the effect of line ignition length on fire spread rates. The ratios of the observed values to the predicted values from a model based on Eqn 1 were obtained for fires with ignition line lengths less than 50 m, and plotted against ignition line length. Various asymptotic equations were considered and the best-fitting equation was chosen to represent the ignition line length effect.

Results

Dataset characteristics

Table 3 contains a summary of the means and ranges of the variables broken down by data type: model development, model evaluation – controlled fires, and model evaluation – wildfires. Ranges in rate of fire spread, 2-m wind speed and dead fuel moisture content in the model development dataset varied between 2 and 60 m min^{-1}, 4 and 25 km h^{-1}, and 2 to 30% respectively. Overall, the model evaluation – controlled fires data subset had similar ranges of the variables to the model development subset, except for fire spread rate, for which average and maximum values were much less than a half. The wildfire dataset had data ranges for the key variables similar to the model development data. The range of the wildfire data 10-m wind speed in Table 3 was equivalent to the 2-m wind speed range in the model development dataset. Fig. 1 illustrates the ranges of rate of fire spread versus 2-m wind speed for the

Table 3. Summary of the means, medians (in square brackets) and ranges (in round brackets) of the variables by data type: model development, controlled fires and wildfires datasets

Refer to Table 2 for definitions of terms

	n	R (m min^{-1})	U_2 (km h^{-1})	U_{10} (km h^{-1})	M_d (%)	M_l (%)	h (m)	w (kg m^{-2})	C (%)	ρ_b (kg m^{-3})	p_l (%)	L (m)
Model development	79	18.6 [16.9] (2–60)	10.6 [10.8] (4–25)		13.7 [13.6] (2–30)	107 [90] (58–236)	1.3 [0.9] (0.3–4.8)	2.0 [1.7] (0.3–5.2)	77 [86] (43–100)	1.8 [1.5] (0.5–6.1)	51.4 [49.2] (19–86)	81 [70] (50–200)
Control fire evaluation	67	7.5 [6.6] (1–34)	7.3 [7.2] (1–19)		16.9 [15.8] (8–33)	102^{A} [97] (76–158)	1.0 [0.5] (0.2–3.0)	1.1^{B} [1.0] (0.1–3.0)	74^{C} [73] (45–100)	3.1^{A} [3.6] (0.1–5.8)	59^{D} [63] (38–67)	105 [75] (50–350)
Wildfires evaluation	32	28.9 [19.6] (5–100)		20.4 [18.3] (5–54)	10.5 [9.3] (3–31)		1.34 [1.5] (0.4–2.0)	1.5^{E} [1.5] (0.4–3.6)	88^{F} [93] (60–100)	1.7^{E} [1.2] (0.4–4.0)		

$^{A}n=45$; $^{B}n=42$; $^{C}n=52$; $^{D}n=34$; $^{E}n=12$; $^{F}n=16$.

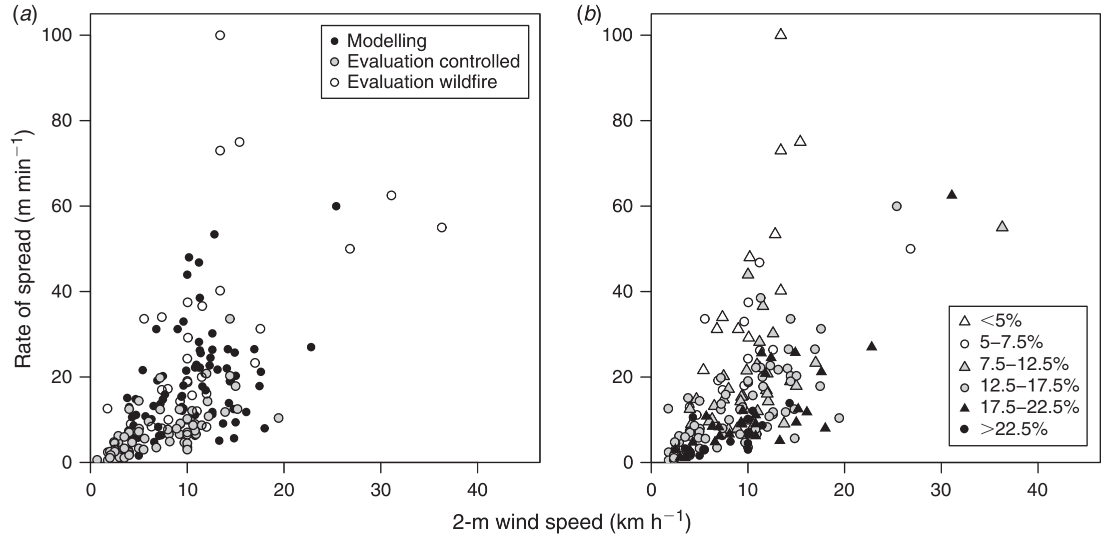

Fig. 1. Scatterplot of rate of spread versus wind speed for the full dataset (*a*) grouped by data usage (model, controlled evaluation and wildfire); and (*b*) by dead fuel moisture content (%) classes.

full dataset grouped by data usage (model, controlled evaluation and wildfire evaluation) and by moisture content class. The data used in the analysis are given in Appendix A (Table A1).

A model for rate of spread based on 2-m wind speed, dead fuel moisture content and vegetation-related variables

Model development data (which contained five groups with a total of 79 observations) were analysed to determine which fuel variables most affected rate of fire spread. Table 4 provides the intercorrelation between the various variables used in the analysis. Correlation coefficients above 0.20 are significant (at the 5% level), and shown in this table in bold font. The results show a strong correlation between rate of fire spread and 2-m wind speed and dead fuel moisture content ($r=0.43$ and -0.46 respectively). There were some reasonably strong correlations between possible predictor variables that might limit some of the modelling analysis. For instance, live fuel moisture content and height were highly correlated ($r=0.52$), thus if height were included in the model, live fuel moisture content may not show its correct contribution to the fire spread rate in terms of significance and its associated regression coefficient (Meyers 1990).

A model was created using non-linear regression analysis with 2-m wind speed and dead fuel moisture content in the form of Eqn 1, but without incorporating any fuel variable. Both wind speed and dead fuel moisture content were highly significant ($P<0.00005$). The other variables (including htco = height × cover) were then added in turn. The significant variables were height ($P=0.002$), htco ($P=0.02$) and fine fuel load ($P=0.04$). Bulk density, based on live and dead fine fuels, was almost significant, with $P=0.08$. Height was included in the model and the remaining variables were then added in turn. For this third iteration, only live fuel moisture content was significant ($P=0.008$). No other significant variables could be added to the model using height and live fuel moisture content. The final model is given as Eqn 2:

$$R = aU_2^b h^c \exp(-k_d M_d)\exp(-k_l M_l) \quad (2)$$

where h is fuel bed height, and a, b, c, k_d and k_l are regression coefficients that minimise the summed square of residuals. These coefficients and their standard errors are given in Table 5. The error statistics for this and the following models are summarised in Table 6.

Table 4. Pearson correlation coefficient, r, between the variables in the model development dataset

$n = 79$. Significant correlations are shown in bold font

	R	U_2	M_d	M_l	h	w	C	ρ_b	p_l	L
R	1	**0.43**	**−0.46**	0.14	**0.22**	0.14	−0.09	**−0.19**	−0.08	−0.01
U_2		1	0.18	**0.30**	0.19	**0.31**	**−0.21**	**0.13**	**−0.30**	0.13
M_d			1	0.08	**0.23**	**0.29**	**−0.21**	**0.25**	**−0.22**	0.06
M_l				1	**0.52**	**0.55**	−0.05	**−0.13**	**−0.44**	0.08
h					1	**0.69**	−0.19	**−0.30**	**−0.28**	−0.04
w						1	0.14	**0.38**	**−0.32**	−0.03
C							1	**0.48**	**0.65**	**−0.52**
ρ_b								**1**	0.06	−0.12
p_l									1	**−0.47**
L										1

Table 5. Coefficients and standard errors (in parentheses) for the models given in Eqns 2–4

	Constant (a)	U_2 (b)	M_d (k_d)	h (c)	ρ_b (c)	M_l (k_l)
Eqn 2	6.4211	0.9942	0.0761	0.3722		0.003131
	(1.8327)	(0.1297)	(0.0075)	(0.0790)		(0.001148)
Eqn 3	5.6715	0.9102	0.0762	0.2227		
	(1.6975)	(0.1336)	(0.0082)	(0.0681)		
Eqn 4	3.8320	1.0927	0.0721		−0.2098	
	(1.2182)	(0.1425)	(0.0094)		(0.1189)	

Table 6. Error statistics for the models given in Eqns 2–4 for the model development dataset

RMSE, root-mean-squared error; MAE, mean absolute error; MBE, mean bias error; MAPE, mean absolute percentage error

	n	RMSE	MAE	MBE	MAPE
Eqn 2 (h and M_l) model development set	79	6.7	5.0	0.2	38
Eqn 3 (h) model development set	79	7.0	5.3	0.2	40
Eqn 4 (ρ_b) model development set	79	7.4	5.8	0.3	42

Estimation of live fuel moisture content would constitute an added layer of complexity to the operational use of the model, and its inclusion added little to the predictive ability of the model using height alone. The fit of the model with height as a vegetation descriptor is given as Eqn 3:

$$R = aU_2^b h^c \exp(-k_d M_d) \tag{3}$$

with coefficients and their standard errors given in Table 5. In Table 6, we can see that the error statistics are only marginally improved by adding live fuel moisture content as an input variable. Fig. 2*a* presents the observed versus predicted rate of fire spread values using Eqn 3. Notably, all fires with an observed rate of fire spread higher than 35 m min^{-1} are underpredicted.

A residual plot showed that the two outliers in the SA group that had much higher rates of fire spread than those predicted by the model also had fairly low bulk densities (0.74 and 1.0 kg m^{-3}). Because there are physically based reasons for bulk density to decrease the rate of fire spread (Thomas 1971; Rothermel 1972), a model was fitted using bulk density ρ_b instead of height. The model is given in Eqn 4:

$$R = aU_2^b \rho_b^c \exp(-k_d M_d) \tag{4}$$

The variables live fuel moisture content (M_l), percentage of live fuel (p_l), vegetation cover (C) and ignition line length (L) were added to the model in Eqn 4, but none of them was significant. M_l and ρ_b had a low correlation ($r = -0.14$), and it can safely be said that if bulk density is included in the model, M_l has no effect. Coefficients and their standard errors for Eqn 4 are given in Table 5. Error statistics for this model were slightly higher than found for the models represented by Eqns 2 and 3 (Table 6). The observed versus predicted rate of spread values for the model represented by Eqn 4 are shown in Fig. 2*b*. Although the error statistics are somewhat poorer than those for Eqn 3, the outliers are less pronounced.

For both models, the variance of the random effect, a, was extremely small compared with the residual variance ($<10^{-7}$); thus, there was no significant variation in a from group to group, and a simple non-linear fit to the data would have given similar results. Non-random effect models were used in the analyses. Normal quantile plots and significance tests of normality of the residuals showed no deviation from normality for any of the models.

Operational model

The models using 2-m wind speed, elevated dead fine fuel moisture content and either vegetation height or bulk density could be used to predict fire spread rate potential in an operational setting. Nonetheless, the inclusion of bulk density in any model will add an extra layer of uncertainty as it will require knowledge of fuel load. The prediction of moisture content is discussed later. In practice, only the 10-m wind speed would be available, so the models in Eqns 3 and 4 were modified to include the 10-m wind speed and a wind reduction factor w_f (0.67 and 0.35 for heath-shrublands and woodlands respectively).

To avoid the problem of predicting zero spread rate in no-wind conditions, the model was modified below a 10-m wind speed of 5 km h^{-1} to decrease linearly to a spread rate depending only on height (or bulk density) and dead fuel moisture content (see also Cheney *et al.* 1998). The resulting two-step model including height is:

$$R = \begin{cases} [R_0 + 0.2(a(5w_f)^b - R_0)U_{10}]h^c \exp(-k_d M_d), U_{10} < 5 \\ a(w_f U_{10})^b h^c \exp(-k_d M_d), U_{10} \geq 5 \end{cases} \tag{5}$$

where U_{10} is the 10-m open wind speed, w_f is the wind reduction factor, and R_0 is the rate of spread in zero-wind at a moisture content of zero and height of 1.0 m. The constants a, b, c and k_d are those given in Table 5 for Eqn 3. When $U_{10} = 5$ km h^{-1}, the two parts of the equation are equal. In the following equation, R_0 was taken as 5 m min^{-1}, which was in reasonable agreement with field observations.

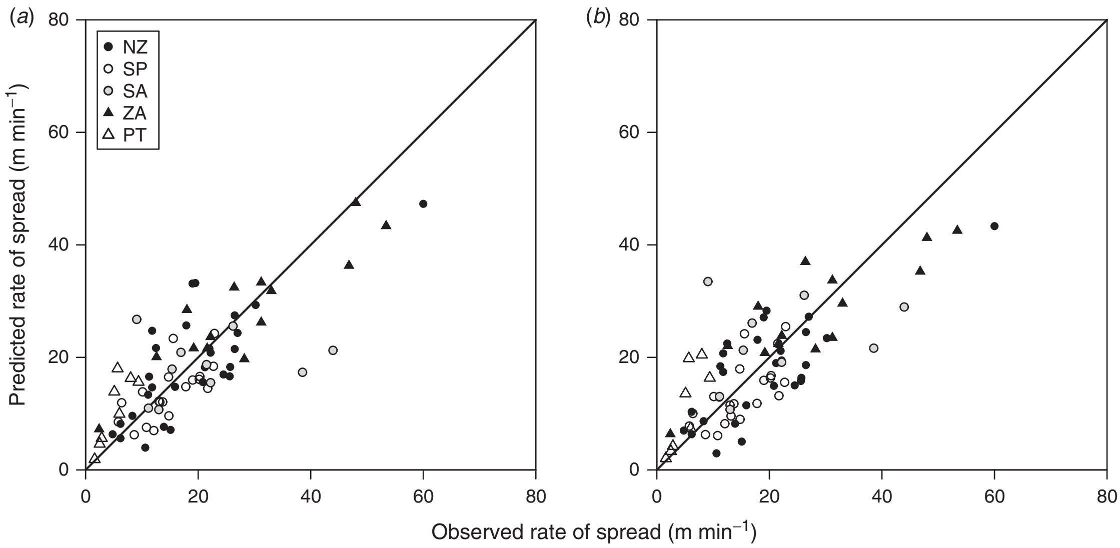

Fig. 2. Observed rate of fire spread values from the model development dataset versus predictions given by (*a*) Eqn 3 (vegetation height model); and (*b*) Eqn 4 (bulk density model) marked according to source. Sources: NZ – Scion, New Zealand; SP – Forestry Research Center of Lourizan, Spain; SA – Commonwealth Scientific and Industrial Research Organisation, Australia; ZA – Jonkershoek Forestry Research Centre, South Africa; PT – University of Trás-os-Montes and Alto Douro, Portugal.

Table 7. Error statistics for the models given in Eqns 5 and 6 for the experimental and controlled fire evaluation dataset and wildfire dataset
RMSE, root-mean-squared error; MAE, mean absolute error; MBE, mean bias error; MAPE, mean absolute percentage error

	n	RMSE	MAE	MBE	MAPE
Eqn 5 experimental and controlled fire validation set	67	4.9	3.5	−1.9	77
Eqn 5 wildfire evaluation set	32	13.7	9.1	1.5	33
Eqn 6 experimental and controlled fire validation set	43	6.3	4.5	−3.5	85
Eqn 6 wildfire evaluation set	17	7.5	5.4	−3.8	27

For bulk density, the model becomes:

$$R = \begin{cases} [R'_0 + 0.2(a(5w_f)^b - R'_0)U_{10}]\rho_b^c \exp(-k_d M_d), U_{10} < 5 \\ a(w_f U_{10})^b \rho_b^c \exp(-k_d M_d), U_{10} \geq 5 \end{cases} \quad (6)$$

The constants a, b and k_d are those given in Table 5 for Eqn 4. Here R'_0 is the rate of fire spread in zero wind at a moisture content of zero and a bulk density of 1.0 kg m^{-3}. Again, a suggested value for R'_0 would be 5 m min^{-1}.

Evaluating Eqn 5 against the controlled fire data

The performance of the rate of fire spread model with height (Eqn 5) could be assessed with the model evaluation – controlled fire subset. The model predicted these data with an MAE of 3.5 m min^{-1} (77% error) and an overprediction bias of −1.9 m min^{-1} (Table 7; Fig. 3*a*). The performance of the rate of fire spread model with bulk density (Eqn 6) was not evaluated against the controlled fire evaluation subset because this variable was only available for the buttongrass moorland data.

Evaluating Eqn 5 against the independent wildfire dataset

The wildfire dataset comprised 32 fire spread rate observations from 24 wildfires from Australia, New Zealand and Portugal (Table 8), and spanned several distinct vegetation types over a broad range of climates (Mediterranean, semiarid, maritime temperate). Table 8 contains the fuel, weather and fire behaviour variables for the wildfire data along with the source reference and reliability rating. Dead fuel moisture contents for the wildfires dataset were predicted from the model presented in Appendix B.

Rates of spread for the wildfire dataset were predicted from the models in Eqns 5 and 6 (Fig. 3*a* and 3*b*). Mean absolute errors for these models were 9.2 and 6.6 m min^{-1} respectively, with an overprediction bias, in particular for Eqn 6 (Table 7). As a percentage of absolute error, the errors were 36% for Eqn 5 and 32% for Eqn 6.

Ignition line length

Predictions were made, using the height model (Eqn 5), for 42 fires from the data sources in Table 1 whose ignition line length were <50 m. All of these were from the same or similar vegetation to the model development or evaluation datasets. These predictions resulted in an overprediction bias with a mean bias error of −4.4 m min^{-1}. This was a substantial departure from the 0.2 m min^{-1} bias for the model development dataset and −1.9 m min^{-1} bias for the controlled fire evaluation dataset (Tables 6 and 7). This overprediction bias arises presumably owing to the shorter ignition line length, which limits the attainment of the quasi-steady rate of spread for the prevailing environmental conditions.

Various forms of asymptotic models were tested to explain the reduction in the potential rate of fire spread with decrease in ignition line length and 2-m wind speed. The models

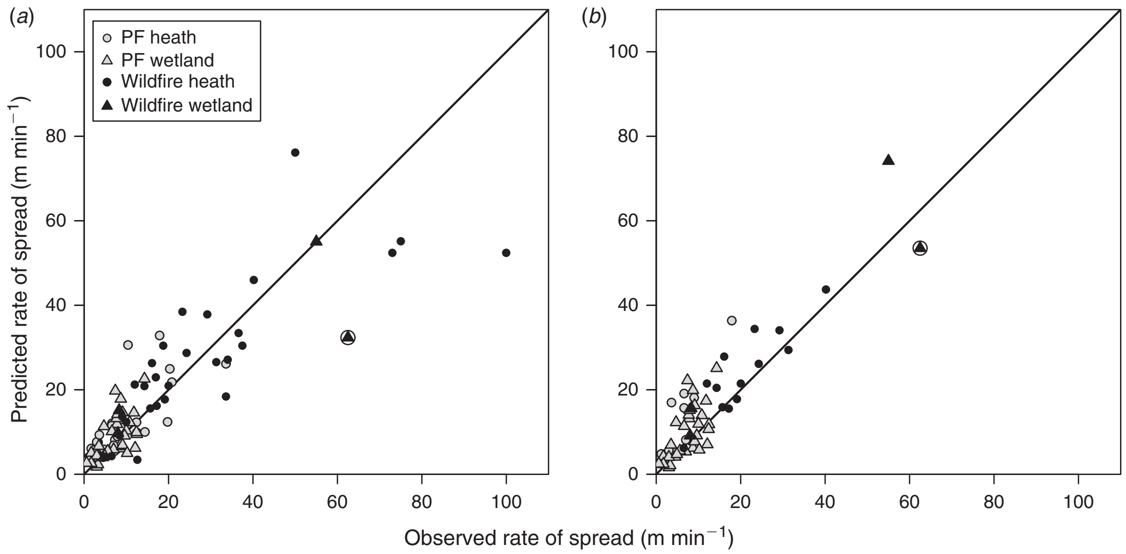

Fig. 3. Observed rates of fires spread (ROS) versus predictions for the prescribed fire (PF) and wildfire datasets given by (*a*) Eqn 5 (vegetation height model) and (*b*) Eqn 6 (bulk density model). Prescribed fire data shown as grey, wildfire data shown as black. Heathlands are shown as circles, buttongrass and wetlands are shown as triangles. The Awarua wetland wildfire is shown circled (see Discussion).

incorporated an arbitrary constraint that resulted in a prediction of rate of fire spread, R, for a point source fire to be a tenth of the quasi-steady rate of spread, R_{ss}. The best asymptotic model relating R to R_{ss} for varying ignition line length, L, was chosen and is given below as Eqn 7:

$$R = \frac{R_{ss}}{1 + 9\exp(-0.00316L^2)} \tag{7}$$

Using this correction reduced the bias to 0.11, and gave an RMSE of 3.0 m min^{-1}. The model is shown overlaid on a plot of the ratio of observed values to predicted values versus ignition line length in Fig. 4*a*. A scatterplot of the observed versus predicted values is given in Fig. 4*b*. This formula represents the correction needed for the spread rate of experimental fires with ignition line lengths of less than 50 m.

Discussion

Model development

A first assessment of the adequacy of the models developed in this study can be obtained by comparing parameters obtained in the present analysis with those found by other authors in different vegetation types. The coefficient b determines the form of the wind function. The fits for the various models developed here resulted in estimates of b close to values of 1.0 (Table 5), indicating fire spread rate to be proportional to wind speed. Similar results have been found in other fire behaviour studies over a range of fire intensities and vegetation complexes including grasslands (Cheney *et al.* 1998), surface fires in eucalypt forests (Cheney *et al.* 2012) and crown fires in conifer forests (Cruz *et al.* 2005).

The decay constant, k_d, in the exponential decay function for dead fuel moisture content was 0.076 for the height model and 0.072 for the bulk density model. A similar modelling approach resulted in decay constants of 0.10 for grassland (Cheney *et al.* 1998), between 0.024 and 0.1 for various different shrublands (Marsden-Smedley and Catchpole 1995*b*; McCaw 1997; Fernandes *et al.* 2000; Fernandes 2001), and 0.19 for crown fires in conifer forests (Cruz *et al.* 2005). These results seem to suggest a smaller effect of dead fuel moisture content in shrublands than found in other vegetation types. However, parameter estimates of the decay constant can be quite sensitive to the range of moisture contents in the data.

The coefficient, c, of the fuel variable was 0.22 for the height model and −0.21 for the bulk density model. The similarity between the two coefficients is probably due to the negative correlation between these variables ($r = -0.3$ from Table 4). The dependence on height is thus weaker than the coefficient of 0.49 estimated for the previous model developed for heathland with a more limited dataset (Catchpole *et al.* 1998). Experiments carried out in Europe also suggested a stronger effect of vegetation height or bulk density (Vega *et al.* 1998; Fernandes *et al.* 2000; Fernandes 2001). Indeed, the effect of vegetation structure in the model is relatively small compared with the 2-m wind speed and dead fuel moisture content variables. The 2-m wind speed and dead fuel moisture content parameters caused a drop in log-likelihood of 34.3 from the model with just a single fitted constant for all fires, whereas the addition of vegetation height and bulk density caused an extra drop of only 5.2 and 1.4 respectively.

Fine fuel load was a significant variable, but with less predictive power than vegetation height. These variables were also significantly correlated ($r = 0.69$; Table 4). Given the added difficulty in estimating or measuring fuel loading, it is easy to reason that there is no advantage to using it in a model. Height × cover was also significant, but less so than height alone, and its significance was through its relationship with height, as cover was not significant.

Table 8. Fuel, weather and fire behaviour variables for the wildfire evaluation dataset
See Table 2 for definitions of terms

Fire name	Country	Location	Date	Period (hhmm)	Vegetation[A]	R (m min^{-1})	U_{10} (km h^{-1})	w_f	T (°C)	RH (%)	m_d (%)	h (m)	w (kg m^{-2})	ρ_b (kg m^{-3})	Reliability (see Cheney *et al.* 2012) (weather/fuel/spread)	Source[B]
Awarua	New Zealand	Southland	Oct 1986	1322–1522	Wetland	62.5	46.4	0.67	12	76	18	1	0.4	0.4	1/2/2	1
Birch's Inlet	Australia	Tasmania	Nov 1986	1000–1800	BGM	55.0	54.2	0.67	21	46	10	0.5	1.1	3.1	5/1/2	8
Phh1	Australia	Tasmania	Jan 1991	1400–1430	BGM	8.3	17.9	0.67	28	43	14	0.5	1.6	4.1	1/1/1	8
Phh2	Australia	Tasmania	Jan 1991	1430–1500	BGM	8.0	16.4	0.67	28	43	14	0.5	1.6	4.1	1/1/1	8
Heywood	Australia	Victoria	Feb 1991	0822–1300	CL	31.3	26.2	0.67	17	62	15	1.5	1.5	1.0	2/2/3	2
Interview River	Australia	Tasmania	Nov1992	1300–1330	Coastal	6.5	14.9	0.67	26	40	31	1	0.4	0.4	1/2/1	4
Royal NP	Australia	Sydney, NSW	Jan1994		Coastal	40.2	20.0	0.67	35	10	5	1.5	2	1.3	1/1/3	4
Bell Range	Australia	Blue Mountains	Jan1994	1410–1610	HS	29.2	28.8	0.35	35	10	5	2	2	1	1/1/3	5
Ryland (a)	Australia	Sydney, NSW	Jan 1994		HS	12.6	5.0	0.35	18	63	15	2			1/1/3	6
Ryland (b)	Australia	Sydney, NSW	Jan 1994		HS	4.8	6.9	0.35	18	72	17	2			1/1/3	6
Wildflower	Australia	Sydney, NSW	Jan 1994		HS	8.4	18.0	0.35	22	81	18	2			1/1/3	6
Calanden	Australia	Sydney, NSW	Jan 1994		HS	36.6	33.0	0.35	32	32	8	2			1/1/3	6
Central Track	Australia	Sydney, NSW	Jan 1994		HS	33.6	15.8	0.35	32	25	7	2			1/1/3	6
Westhdrd	Australia	Sydney, NSW	Jan 1994		HS	9.0	11.9	0.35	31	28	8	2			1/1/3	6
Lousã	Portugal	Lousã	Aug 1998		DH	17.3	11.9	0.67	28	37	8	0.5	1.4	2.9	1/1/1	7
Friumes	Portugal	Penacova	Aug 2008		DH	23.3	25.4	0.67	26	42	10	1.5	3.6	2.4	1/2/2	7
Paipenela	Portugal	Meda	Aug 2008		CS	16.1	18.0	0.67	27	40	10	1.0	1.2	1.2	1/2/2	7
Sicó	Portugal	Sicó	Sept 2007		QC	24.3	14.9	0.67	35	30	7	1.5	2.0	1.4	1/2/2	7
Contos	Australia	WA	6 April 2006	1900–2400	Coastal	10.0	12.0	0.67	15	70	17	2			2/2/4	9
Ellen Brook	Australia	WA	23 Nov 2011	1145–1445	Coastal	50.0	40.0	0.67	30	25	7	2			2/3/3	9
Boorabin	Australia	WA	28 Dec 2007	1500–1640	SK_A	34	11	0.67	36	20	4.5	1.5			3/2/3	10
Boorabin	Australia	WA	29 Dec 2007	1030–1900	SK_P	17	11	0.67	30	24	5.5	1.0			3/2/4	10
Boorabin	Australia	WA	30 Dec 2007	1100–1140	SK_A	75	23	0.67	37	13	4	1.5			3/2/3	10
Boorabin	Australia	WA	30 Dec 2007	1155–1430	SK_P	100	20	0.67	42	6	3	1.0			3/2/3	10
Boorabin	Australia	WA	30 Dec 2007	1950–2045	SK_A	73	20	0.67	39	9	3	1.5			3/2/3	10
Boorabin	Australia	WA	31 Dec 2007	1100–1900	SK_P	19	15	0.67	30	24	5.5	1.0			3/2/4	10
Boorabin	Australia	WA	4 Jan 2008	1100–1420	SK_P	38	15	0.67	35	24	5.5	1.0			3/2/4	10
Snake Island	Australia	Vic.	3 Mar 2008	1242–1414	WH-SH	14.3	18.5	0.67	28	38	9	0.9	1.4	1.6	2/1/3	11
Cathedral	Australia	Vic.	10 Feb 2009	1430–1649	WH	19.1	20.0	0.67	15.5	58	13	1.2	1.4	1.2	2/1/3	11
Cathedral	Australia	Vic.	14 Feb 2009	0900–1328	WH	12.0	22.0	0.67	20	52	12	1.2	1.5	1.2	1/1/2	11
Cathedral	Australia	Vic.	14 Feb 2009	1328–1610	WH	20.0	23.0	0.67	21	58	12.5	1.2	1.5	1.2	1/1/2	11
Cathedral	Australia	Vic.	14 Feb 2009	1610–1710	WH/SH	15.7	21.0	0.67	20	65	15	1.2	1.5	1.2	1/1/2	11

[A]CL, Central Lowland; HS, Hawkesbury sandstone; DH, dry heathland; CS, *Cytisus striatus*; QC, *Quercus coccifera*; BGM, buttongrass moorland; SK_P, sandplain kwongan with Proteaceous shrubs; SK_A, sandplain kwongan with *Allocasuarina* and *Acacia*; WH, wet heathland; SH, sand heathland.

[B](1) Pearce *et al.* (1994); (2) Wouters (1993); (3) Jon Marsden-Smedley, unpubl. data; (4) Keith *et al.* (2002); (5) Speer *et al.* (2001); (6) Ross Bradstock, unpubl. data; (7) Paulo Fernandes, unpubl. data; (8) Marsden-Smedley and Catchpole (1995*b*); (9) Lachie McCaw, unpubl. data; (10) De Mar (2008); (11) Greg Mattingley, unpubl. data.

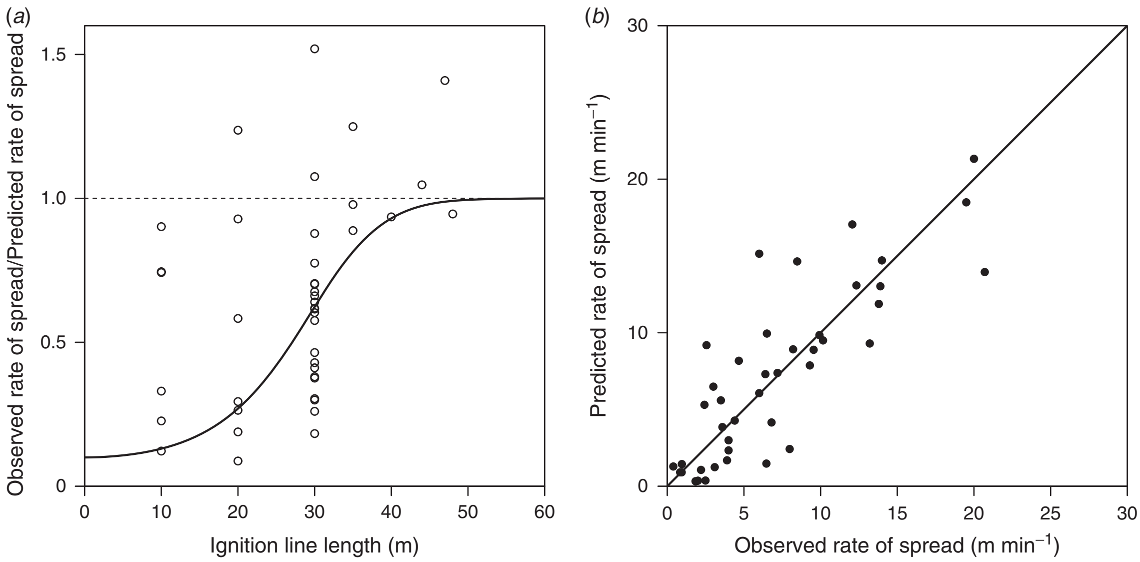

Fig. 4. Graphs of (*a*) Eqn 7 overlaid on the ratio of the observed values to the predicted rate of fire spread values from Eqn 5 (vegetation height model) for experimental fires with ignition line lengths less than 50 m; and (*b*) observed rates of fire spread versus predictions from Eqn 5 (vegetation height model) for fires with ignition line lengths less than 50 m with the ignition line length correction factor in Eqn 7 applied.

The analysis found a significant effect of live fuel moisture in a model with height. However, live fuel moisture content was quite strongly correlated with height ($r = 0.52$ in Table 4), and this may be part of the reason for its significance in a model with height. Alexander and Cruz (2013) reviewed the empirical evidence from 14 distinct studies of shrubland fire behaviour in relation to the effect of live fuel moisture content on fire spread rates. Counterintuitively, none of the studies found the moisture of live fuels to be significantly correlated with rate of fire spread (e.g. Lindenmuth and Davis 1973; van Wilgen *et al.* 1985; Marsden-Smedley and Catchpole 1995*b*; Sağlam *et al.* 2008; Davies *et al.* 2009).

Model evaluation

The Awarua wetland wildfire, in New Zealand (Pearce *et al.* 1994), was underpredicted badly by the height model (see circled triangle in Fig. 3*a*). This fire occurred under conditions of low air temperature (12–13°C), high relative humidity (76–82%) and strong surface winds (43–50 km h^{-1}). Its spread rate is predicted to be low, partly because of the predicted moisture content (18%), and partly because the vegetation height was low (0.9 m). It also had significant fuel discontinuities due to areas of open water. However, its spread rate is better predicted by the bulk density model (Fig. 3*b*) as the bulk density was low (0.44 kg m^{-3}). Similarly, the two outlying underpredicted experimental fires from SA (Fig. 2*a*) were better predicted by the bulk density model (Fig. 2*b*). These were fires with low vegetation height (0.43 m) and low bulk density (0.74 kg m^{-3}). This indicates that the effect of bulk density is important. However, it is difficult to estimate in the field, and the relatively poor evaluation results may reflect this. The fuel height model badly underpredicted the spread rate of the fastest-moving fire in the wildfire evaluation dataset (100 m min^{-1}) that came from a fire burning in mature scrub-heath under extreme fire danger conditions (Table 8). Reliability scores for weather, fuel and spread observations were similar for this fire, as for others from the same incident and we are unable to identify an obvious reason for the underprediction. We alert model users to the possibility of very fast spread under extreme weather conditions, and recommend that predictions be verified and if necessary adjusted regularly against field observations.

Seven of the wildfires were in woodland areas characterised by low canopy height (<10 m) and low cover (<20%). The model represented by Eqn 5 predicted these wildfires with a MAPE of 33% (equally well as the fires in open heath), showing that the change in wind-reduction factor from 0.67 to 0.35 was reasonable. The dead fuel moisture content in woodland may be underestimated by the model of Matthews *et al.* (2010) because of the reduction of solar radiation by the canopy, but overall, the model fit shows the potential of the model developed in the current study to be extrapolated to predict the fire spread rate in open woodlands with a shrub understorey.

The ratios of observed to predicted values for the vegetation height and bulk density in the models in Eqns 5 and 6 for the wildfire evaluation dataset were plotted against the three reliability measures for wind speed, fuel and fire spread rate data. Linear regressions were then performed to see whether these ratios increased with decreasing reliability. No significant change in these ratios was found with reliability.

Ignition line length effect

Rates of spread for fires with ignition line lengths less than 50 m were clearly slower than expected for quasi-steady-state fires. The results obtained in our analysis must be seen as exploratory in nature as the present study did not investigate this aspect of fire dynamics. One of the limitations of the present analysis is that, contrary to Cheney *et al.* (1993) who used fireline width as their explanatory variable, only ignition length was available as a metric of fire size. After ignition of a set length, the fireline width may increase or decrease depending on the burning conditions. Cheney *et al.* (1993) also found a significant effect of wind speed on the fireline width required to reach an asymptotic rate of fire spread. The characteristics of the present dataset did not show this effect, which would be expected from theoretical reasoning (Wotton *et al.* 1999). Despite the perceived limitations of the analysis, the ignition line length effect given in Eqn 7 is useful in the planning of prescribed burning ignitions. Further work is needed to verify this correction factor.

Evaluation against other published heathland data

In order to extend the evaluation of the models represented by Eqns 5 and 6, their predictive capacity was tested in distinct fuel types where fires were conducted in small plots in maquis vegetation (varied species including *Quercus coccifera*, *Arbutus andrachne*, *Pistacia lentiscus* and *Sarcopoterium spinosum*, *Phillyrea latifolia* and *Cistus creticus*), given in Bilgili and Sağlam (2003) and Sağlam *et al.* (2007, 2008) and in heather (*Calluna vulgaris*), given in Kayll (1966), Ascoli (2007) and Davies *et al.* (2009). These fires had short ignition line lengths (15–20 m) so the correction given by Eqn 7 was used. Both models slightly underpredicted the spread rates for the fires given in Bilgili and Sağlam (2003), overpredicted somewhat the fires in Sağlam *et al.* (2007), and badly overpredicted the fires in Sağlam *et al.* (2008). For the vegetation height model (Eqn 5), the MBEs were 0.96, -1.5 and -4.7 m min^{-1} respectively. The vegetation in the latter two studies was taller and less dense than for the former, but had very little dead fuel. Fires burned more slowly for the same wind speed than those described in Bilgili and Sağlam (2003), where the mean live fuel moisture content was also much lower. Fire spread rate in young low-productivity buttongrass moorland (less than 20 years old) was also badly overpredicted by the height model (MBE $= -5$ m min^{-1}). The percentage of dead fuel is low for these younger moorlands (Marsden-Smedley and Catchpole 1995*a*), which is not reflected in the models. This suggests that the models presented here may overpredict in situations where there is little dead fuel.

With regard to the fire spread rate data in heather vegetation, the height model (Eqn 5) predicted the Scottish fires given in Kayll (1966) and Davies *et al.* (2009) quite well, with an MBE of -0.35 and an RMSE of 1.8 m min^{-1}. Compared with the Scottish data, the Italian fires (Ascoli *et al.* 2007) had much higher spread rates for the same wind speeds, and the vegetation height model severely underpredicted the observed rates of fire spread, with an MBE of 5.9 m min^{-1}. However, the Italian heather fires had a high proportion of grass (above 35%) in the vegetation complex (see Ascoli 2007), which might explain the higher rates of fire spread.

A note on uncertainty and model limitations

To answer the question of how well the fire spread models performed, the error statistics obtained in our study were compared with the findings of Cruz and Alexander (2013), who analysed the error measured in a large number of fire spread model evaluation studies. The MAPEs for the model development set, using Eqns 2, 3 and 4, varied between 38 and 42% (Table 6). This is consistent with findings in other field-based studies (e.g. Marsden-Smedley and Catchpole 1995*b*; Fernandes *et al.* 2009; Cheney *et al.* 2012). The MAPEs for the experimental fire and controlled fire evaluation set using Eqns 5 and 6 were higher at 76 and 85% (Table 7), but the MAPEs for the wildfire evaluation dataset were noticeably lower, 33 and 27% respectively (Table 7), which is a good result for validation against wildfire data (Cruz and Alexander 2013).

The results from our evaluation against independent wildfire data and from other published studies (e.g. Cheney *et al.* 2012; Cruz *et al.* 2013) provide evidence that empirical models based on well-accepted functional forms can be applied beyond the bounds of the data on which they are based. In our studies and those mentioned above, the prediction errors for the wildfire validation datasets had no bias; this is despite the wildfire datasets having average rates of spread almost double that of the model development sets.

However, there are some potential limits to the applicability of the models developed here, notably to shrubland fuel types with a physical structure that depart considerably from the ones used in model development. As noted above, application of the model to open shrublands characteristic of semiarid and arid areas should be preceded by verification of the model validity. Similar care should precede the application of the model to shrublands with a substantial cover of grass fuels.

A simplified sensitivity analysis looking at the proportional change in output given input uncertainty indicates that errors in the wind speed, vegetation height and bulk density input variables, e.g. a 10% error in the wind speed or vegetation height input, result in a smaller (i.e. $<$10%) or proportional (i.e. $\sim$10%) variation in the predicted rate of spread. This is the result of the functional forms used to describe the effects of these variables. The model sensitivity to variation in the fuel moisture content input changes depending on where in the fuel moisture range the variations occur. The exponential decay function used to describe the effect of this variable results in lower model sensitivity (smaller than the perturbation) in the lower range of fuel moisture. For high fuel moisture content values, the variation in the output will be larger than the input perturbation.

A note on slope steepness effect

As indicated earlier, no attempt was made to incorporate the effect of slope steepness in the fire rate of spread models developed in the present study. Slope steepness is a variable with a dramatic effect on fire propagation. Fires spreading on positive slopes aligned with the wind are known to increase their rate of spread several fold (McArthur 1967; Van Wagner 1977; Viegas 2004). Although there have been several studies attempting to describe the effect of slope on shrubland fire propagation (Catchpole *et al.* 1998; Vega *et al.* 2006; Viegas *et al.* 2006), its quantification has not been conclusive. One of the issues associated with the slope effect in outdoor fire propagation is that its influence is not restricted to solely the mechanical effect on fire spread, as is normally achieved in a laboratory setting (Rothermel 1972; Van Wagner 1977).

Wind flows in outdoor fires also tend to change with position on the slope, with stronger winds occurring closer to ridge lines and lighter winds occurring at the valley bottom (Schroeder and Buck 1970; Forthofer *et al.* 2014). Fuel structure also tends to change with position in the slope. The lower levels of a slope tend to be wetter and of higher productivity, causing fuels in these areas to have higher fuel loads, bulk densities and fuel moisture contents (e.g. Potts *et al.* 1986; Raaflaub *et al.* 2012). Shrub fuels near ridge tops tend to be more open (and mixed with grassy understorey) and of lower height than fuels at lower elevations. Furthermore, it is difficult to determine in outdoor experiments when a fire has reached a steady state. Viegas (2006) showed an almost continuous acceleration in rate of spread for several experimental fires on slopes. Such fires can then reach very high rates of spread, as documented by Butler *et al.* (1998). This is at odds with results from Catchpole *et al.* (1998) and Vega *et al.* (2006), who have suggested a slope effect for shrubland fires lower than observed for forests (e.g. McArthur 1967).

Taking into account that both the slope correction factors of Catchpole *et al.* (1998) and Vega *et al.* (2006) might not capture some of the very high rates of spread observed in shrublands, we suggest the use of the McArthur (1967) slope effect function when using the models in Eqns 5 and 6 for slopes up to a steepness of 20°. This slope effect will result in higher spread rates, and hence a more conservative result from the point of view of fireline safety, than the two shrubland slope effect functions of Catchpole *et al.* (1998) and Vega *et al.* (2006) mentioned above. Above slope angles of 20°, flame attachment processes are expected to induce even higher spread rates, so the extrapolation of this function to steeper slopes should be carefully exercised. The effect of negative slope on fire propagation is still poorly understood. Sullivan *et al.* (2014) provide a review of this topic and suggest a downslope correction factor.

Future research needs and knowledge gaps

The current study focussed on developing a generic rate of spread model for shrubland fuels in flat terrain. As with other empirical-based fire spread rate models that use a single fuel structure input as a surrogate for fuel complex structure, the models developed here might not capture well the fire spread dynamics in all possible shrub fuel structures. For example, shrubland fuel complexes with a low or very high dead fuel component might exhibit fire behaviour distinctly different from that predicted by the models presented here. Similarly, the effect of very high live fuel moisture contents might not be captured in the models. Therefore, future research into identifying the separate effects of changes in particular shrub fuel variables could improve the applicability of the models.

One of the limitations to the accurate prediction of fire propagation in temperate shrublands is our lack of understanding of the conditions suitable for sustained propagation, 'go or no-go' (Weise *et al.* 2005). In particular, for prescribed burning applications with ignitions conducted under a somewhat marginal burning environment, the knowledge of threshold conditions for sustained fire propagation constitutes the most important fire behaviour quantity (Anderson and Anderson 2010; Cruz *et al.* 2013). At the low-intensity end of the spectrum, fire behaviour will be most sensitive to small changes in fuel complex structure and fuel moisture, and fire spread thresholds may vary between vegetation types and depend on time since last fire – mostly because of fuel continuity and proportion of fine dead fuel. Research focussed on this aspect of fire dynamics should be extended to several distinct shrubland types to capture the effects of fuel complex structure, and will require careful characterisation of the lower levels of the fuel complex, especially with respect to dead suspended fuels.

As discussed above, the characterisation of a definitive effect of slope steepness on shrubland fire rate of spread is still a major knowledge gap. This issue acquires greater significance owing to many shrublands areas being located in hilly to mountainous terrain, such as in southern Europe, California and New Zealand. The difficulty in isolating the effect of fuel structure, fuel moisture and wind speed from a pure slope steepness effect has limited the suitability of field-based studies to determine the slope effect on shrubland fire propagation. Further research into this topic will likely require a combination of physical modelling and carefully conducted field experiments, where a comprehensive quantification of the heat transfer processes is conducted.

Acknowledgements

The authors thank the Department of Environment and Primary Industries, Victoria, Australia, for financial support in completing this work. New Zealand data collection was conducted as part of the Rural Fire Research Program (grant no. C04X0403) funded by the Ministry for Business, Innovation and Employment and New Zealand Rural Fire Authorities. The financial support of the following projects: 1FD97–122-C06 and AGL2001–1242-C04 (Ministry of Science and Technology, Spain); EGV1-CT-2001–00041(DG XII, European Commission) and INIA-RTA 2009–00153-C03 (Ministry of Science and Innovation, Spain) is greatly appreciated. Miguel Cruz is grateful to the Department for Environment and Heritage (South Australia) and the Bushfire Cooperative Research Centre for supporting the Ngarkat Natural Park experimental burning experiments. Appreciation is also extended to the many landowners who provided sites, and rural fire agencies that provided in-kind support for the conduct of experimental burns. The authors wish also to thank Matt Plucinski (CSIRO, Australia), Marty Alexander (University of Alberta, Canada) and two anonymous referees for their critical review of an early version of the manuscript.

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Appendix A. Database of shrubland fire spread data used in model development and evaluation

Table A1. Fire source, fuel, weather and fire behaviour data used in model development and evaluation
EB, experimental burn; PB, prescribed burn; refer to Table 1 for code correspondence

Code	Country	Fire type	Veg. height (m)	Veg. cover (%)	Fine dead fuel load (kg m^{-2})	Fine live fuel load (kg m^{-2})	Total fuel load (kg m^{-2})	Air temp. (°C)	Relative humidity (%)	2-m wind speed (km h^{-1})	Slope (%)	Moisture content dead elevated fuels (%)	Moisture content live fuels (%)	Ignition length (m)	Rate of spread (m min^{-1})
NZ	New Zealand	EB	1.3	83	0.6	1.2	2.36	23	67	15	0			50	12.5
NZ	New Zealand	EB	1.8	83	0.82	1.08	5.37	23	67	7	0	18	87.6	50	8.3
NZ	New Zealand	EB	1.3	43	1.22	0.7	4.29	20	89	14	1.5	28.6	88.2	100	13.9
NZ	New Zealand	EB	1.9	47	1.3	0.92	5.51	23	70	19	3	36.1	116.8	100	25
NZ	New Zealand	EB	1.6	47	1.45	0.77	5.23	19	82	18	1.5	20.3	119.7	100	21.2
NZ	New Zealand	EB	1.1	45	1.26	0.7	3.42	21	67	23	2	18.5	85	100	27
NZ	New Zealand	EB	1.8	47	1.31	0.9	5.25	21	71	11	−2	13.6	97.1	100	22.2
NZ	New Zealand	EB	2	56	1.29	0.94	5.61	21	64	12	−1	18.2	95.8	100	20.8
NZ	New Zealand	EB	2	55	1.3	0.92	5.37	22	78	14	−2	16.1	87	100	22
NZ	New Zealand	EB	0.6	48	0.88	0.28	1.34	23	60	13	0	14.7	124.7	60	11.3
NZ	New Zealand	EB	0.6	56	0.83	0.33	1.35	23	67	16	0	19.2	107.5	80	11.8
NZ	New Zealand	EB	4.8	64	2.05	1.73	12.15	24	66	8	0	16.4	130.4	50	15.9
NZ	New Zealand	EB	4.7	69	2.1	1.72	12.27	17	77	15	0	21.4	103.6	50	25.7
NZ	New Zealand	EB	3.4	65	2	1.5	9.24	21	71	4	0	25.7	112.4	60	10.6
NZ	New Zealand	EB	2.9	72	1.78	1.56	9.09	13	73	12	0	18.8	102	80	24.5
NZ	New Zealand	EB	3.6	60	1	1.07	6.69	18	45	11	0	20.9	105.6	100	11.1
NZ	New Zealand	EB	3.3	60	1.1	1.1	7.24	18	46	11	0	18.4	119.2	100	25.6
NZ	New Zealand	EB	3.1	58	3.43	1.38	10.99	20	62	13	0	12	185.9	100	30.2
NZ	New Zealand	EB	3.1	58	3.43	1.38	10.99	20	61	14	0	12	185.9	100	19
NZ	New Zealand	EB	3.1	58	3.43	1.38	10.99	19	60	25	0	14.1	166.8	100	60
NZ	New Zealand	EB	2.4	63	2.4	0.91	7.58	22	66	4	0	15.5	175.1	100	15.1
NZ	New Zealand	EB	2.73	75	2.61	1.42	7.65	17	56	15	0	11.7	219.5	100	19.5
NZ	New Zealand	EB	2.36	86	2.61	1.42	7.65	17	56	13	0	13.4	219.5	100	11.8
NZ	New Zealand	EB	2.2	92	2.61	1.42	7.65	17	64	17	0	16.6	236.4	100	17.9
NZ	New Zealand	EB	2.31	85	2.61	1.42	7.65	17	66	14	0	16.7	236.4	100	26.5
NZ	New Zealand	EB	2.37	87	2.61	1.42	7.65	16	70	17	0	15.6	236.4	100	26.5
NZ	New Zealand	EB	0.4	47	0.52	0.12	0.64	22	59	11	0	20.9	144.5	100	6.2
NZ	New Zealand	EB	0.5	48	0.61	0.16	0.77	23	63	7	0	21.5	132.1	100	6.2
NZ	New Zealand	EB	0.5	48	0.61	0.16	0.77	21	69	7	0	19	128	100	4.8
WC	Australia	EB	0.7	90	1.04	1.43	6.26	24	61	6	4	14	80	30	3.5
WC	Australia	EB	0.25	90	0.33	0.52	1.89	19	60	15	0	15	106	30	6.5
WC	Australia	EB	0.45	90	0.58	0.82	2.5	23	62	15	4	21	106	30	6.4
Tas.	Australia	PB	1	100				12	63	3	0	32		75	4.5
Tas.	Australia	PB	1.5	100				12	63	3	0	32		75	3
Tas.	Australia	PB	1.5	100				13	60	4	0	28.2		75	7
Tas.	Australia	PB	1	60				16	68	4	0	16		75	2.4
Tas.	Australia	PB	2.5	60				14	81	3	0	17		75	3
Tas.	Australia	PB	3	50				13	90	4	0	17		75	4.7

(*Continued*)

Table A1. (Continued)

Code	Country	Fire type	Veg. height (m)	Veg. cover (%)	Fine dead fuel load (kg m^{-2})	Fine live fuel load (kg m^{-2})	Total fuel load (kg m^{-2})	Air temp. (°C)	Relative humidity (%)	2-m wind speed (km h^{-1})	Slope (%)	Moisture content dead elevated fuels (%)	Moisture content live fuels (%)	Ignition length (m)	Rate of spread (m min^{-1})
Tas.	Australia	PB	1.5					15	82	3	0			200	1.2
Tas.	Australia	PB	0.5					16	70	11	0	18		200	6.6
Tas.	Australia	PB	0.3					15	75	10	0	18		200	3.6
Tas.	Australia	PB	2					15	77	9	0	18		200	9
Tas.	Australia	PB	2.5					15	80	8	0	19		200	6.6
VGM	Australia	PB	1	50				19	51	12	0	12	120	300	20.8
VGM	Australia	PB	2	70				24	56	2	0	12	120	50	2.5
VGM	Australia	PB	1.2	80				16	82	4	0	17	111	70	6
VGM	Australia	PB	1.3	90				17	83	4	0	10	158	100	12.5
VGM	Australia	PB	1.2	50				22	60	3	0	15	120	50	2.5
VGM	Australia	PB	1.2	70				19	75	5	0	16	124	100	3.3
VGM	Australia	PB	0.4	80				18	76	5	0	17	135	70	7.2
VGM	Australia	PB	1.3	80				24	58	5	0	12.5	135	100	14.4
VGM	Australia	PB	0.75	75				26	56	5	0	15.5	126	50	3
VGM	Australia	PB	0.95	65				23	70	6	0	19	120	40	6
VGM	Australia	PB	1.8	70				16	66	7	0	15	109	50	19.8
VGM	Australia	PB	3	90				17	66	14	0	15	109	300	33.6
VGM	Australia	PB	1					17	73	7	0	13			1.25
VGM	Australia	EB	2.2	90				21	52		0	11.6		350	17.9
PT	Portugal	EB	0.25	85	0.09	0.52		10	56	3	0	37.5	113	50	1.2
PT	Portugal	EB	0.52	86	0.39	0.95		14	56	10	2	20.5	76.4	30	2.4
PT	Portugal	EB	0.57	91	0.52	0.91		15	43	15	0	15.4	74.8	50	5.7
PT	Portugal	EB	0.39	77	0.15	0.73		18	54	2	2	17.5	86.7	10	2.5
PT	Portugal	EB	0.4	73.4	0.15	0.73		16	57	2	2	18	86.7	10	2
PT	Portugal	EB	0.34	62.2	0.08	0.57		15	60	2	2	18.5	86.7	10	1.9
PT	Portugal	PB	0.3	50	0.04	0.49		22	31	6	0	10.6	108.5	30	3
PT	Portugal	PB	0.8	80	0.11	1.35		22	31	12	0	10.6	108.5	30	6
PT	Portugal	PB	1.9	90	1.05	1.74		14	62	13	0	35	96	30	4
PT	Portugal	PB	1.2	95	1.02	1.69		19	35	4	0	10.3	84.1	100	6
PT	Portugal	PB	1.3	95	0.75	1.07		22	30	2	0	10.2	78.3	30	6.8
PT	Portugal	PB	0.8	90	0.74	1.65		7	55	13	0	18.5	78	100	5.1
PT	Portugal	PB	0.28	95	0.13	0.7		12	93	5	2	30	85	50	1.6
PT	Portugal	PB	0.35	90.3	0.18	0.8		22	69	18	0	17.6	85	50	8
PT	Portugal	PB	1.82	100	1.22	2.44		13	78	4	3	21	85	50	2.5
PT	Portugal	PB	1.39	65	0.89	1.98		12	73	4	3	17.6	85	50	2.7
PT	Portugal	PB	0.4	95	0.25	0.9		8	50	8	0	15.4	76.7	10	3.1
PT	Portugal	EB	0.65	65	0.06	0.5		18	54	7	0	19.6	93.5	10	0.8
PT	Portugal	EB	0.5	100	0.44	1.06		13	97	25	0	24.9	85	20	3.6
PT	Portugal	EB	0.21	70	0.04	0.44		12	51	10	0	17.6	101.2	50	0.9
PT	Portugal	PB	1.3	95	0.75	1.07		22	30	15	0	10.2	78.3	30	20
PT	Portugal	PB	0.3	90	0.13	0.71		8	50	16	0	14.4	76.7	10	4
PT	Portugal	PB	0.8	70	0.55	1.12		8	85	15	0	40	85	20	2.5
PT	Portugal	PB	0.7	90	0.72	1.19		14	65	15	0	18	87	100	9.4
SP	Spain	EB	0.98	100	1.95	1.55	3.84	16	53	9	0	16.1	118.8	30	9.3
SP	Spain	EB	0.6	100	1.54	1.28	3.11	26	47	11	0	14.2	154.4	30	9.9

SP	Spain	EB	0.9	98	2.58	1.32	4.65	23	41	6	0	11.1	183	30	7.2
SP	Spain	EB	0.75	99	1.53	1.36	3.09	15	48	12	0	12.4	95.9	30	12.3
SP	Spain	EB	0.89	93	1.78	1.64	3.83	24	39	6	0	10.9	166	30	4.7
SP	Spain	EB	0.96	92	1.83	1.39	3.66	25	39	10	0	9.2	149.4	30	8.5
SP	Spain	EB	1.18	98	1.95	1.34	4.04	19	41	14	0	12.3	144.1	30	12.1
SP	Spain	EB	0.9	100	1.87	1.17	3.59	25	38	7	0	11.2	165.9	30	10.2
SP	Spain	EB	1.29	96	1.82	1.51	4.04	12	62	8	0	14.2	134	30	9.5
SP	Spain	EB	0.9	100	1.38	1.42	3.23	23	40	5	0	7.4	117.4	30	2.6
SP	Spain	EB	1.5	100	1.95	1.55	4.37	18	53	9	0	15.9	160.1	30	8.2
SP	Spain	EB	0.88	100	1.24	1.69	3.13	16	65	6	0	20	116	30	4.4
SP	Spain	EB	0.75	100	0.97	1.69	2.92	16	45	7	0	13.2	98.5	200	6.4
SP	Spain	EB	1.16	100	1.34	1.89	3.86	18	73	3	0	24.2	108	30	3.9
SP	Spain	EB	0.45	100	0.29	0.8	1.18	18	62	0	0	11.4	72.4	20	0.4
SP	Spain	EB	0.32	100	0.23	0.84	1.09	17	72	3	0	15.9	69.8	20	0.9
SP	Spain	EB	0.7	100	0.39	1.13	1.73	16	76	3	0	16	87.8	20	2.2
SP	Spain	EB	1.28	99	1.76	0.99	3.47	18	56	6	0	17.7	108.3	57	10.8
SP	Spain	EB	0.85	100	1.59	1.43	3.41	21	40	7	0	12	92.2	80	13.2
SP	Spain	EB	0.4	90	0.19	0.63	0.93	11	53	9	0	21.4	76.1	60	12.1
SP	Spain	EB	0.61	100	0.95	1.03	2.1	14	66	9	0	15.3	89.9	70	13
SP	Spain	EB	0.68	100	2.3	1.78	4.38	19	42	12	0	13.4	84.1	65	22.7
SP	Spain	EB	0.63	100	0.92	1.32	2.3	9	61	15	0	16.9	88.6	50	20.3
SP	Spain	EB	0.63	97	1.79	1.47	3.7	12	51	13	0	17.1	75.1	70	21.7
SP	Spain	EB	0.63	100	1.04	1.26	2.56	10	62	14	0	16.9	91.7	50	19
SP	Spain	EB	0.47	98	0.49	0.74	1.26	10	65	13	0	15.9	73.8	48	14
SP	Spain	EB	0.86	100	3.25	1.97	5.95	13	53	12	0	16.2	81.7	50	17.8
SP	Spain	EB	0.6	92	0.96	1	2.06	12	53	9	0	13.4	77.1	35	13.8
SP	Spain	EB	0.67	98	0.72	0.95	1.73	15	57	15	0	13.1	77.1	35	19.5
SP	Spain	EB	0.6	97	0.71	0.92	1.68	12	52	10	0	14.8	67.1	44	13.9
SP	Spain	EB	0.67	100	1.18	0.98	2.25	9	56	15	0	16.7	71.8	35	20.7
SP	Spain	EB	0.76	78	0.39	0.9	1.45	10	54	7	0	12.9	75.1	70	13.7
SP	Spain	EB	0.73	95	0.15	0.58	0.8	22	28	7	0	9.1	70.6	70	14.7
SP	Spain	EB	0.88	87	0.25	0.83	1.36	18	36	9	0	7.9	73.9	70	15.6
SP	Spain	EB	0.53	96	0.29	0.73	1.21	20	18	7	0	8.5	69.3	70	20.2
SP	Spain	EB	0.66	96	0.09	0.62	0.77	15	42	5	0	10.9	71	47	13.2
SP	Spain	EB	0.79	89	0.22	0.81	1.18	21	16	5	0	10.8	75.7	70	14.8
SP	Spain	EB	0.74	99	0.39	0.86	1.5	11	52	5	0	12.7	72	55	5.8
SP	Spain	EB	0.39	83	0.11	0.66	0.83	11	48	4	0	13.8	71.3	70	8.6
SP	Spain	EB	0.77	93	0.38	0.76	1.39	18	34	4	0	10.2	68.5	20	8
SP	Spain	EB	0.86	94	0.33	0.72	1.25	12	43	4	0	15.8	71.8	20	6.5
SP	Spain	EB	0.54	87	0.11	0.73	0.85	21	36	0	0	10.5	76.1	20	1
SP	Spain	EB	0.57	90	0.42	0.84	1.47	21	35	6	0	8.6	82.1	70	10.1
SP	Spain	EB	0.76	86	0.39	0.79	1.38	17	30	11	0	8.7	73.7	70	22.9
SA	Australia	EB	0.43	45	0.17	0.15	0.32	32	26	10	0	7.71	72	120	43.9
SA	Australia	EB	0.43	45	0.17	0.15	0.32	29	32	5	0	7.36	72	120	11.2
SA	Australia	EB	0.57	56	0.42	0.18	0.6	20	48	10	0	10.02		120	21.5
SA	Australia	EB	0.57	56	0.42	0.18	0.6	23	40	9	0	9.94		120	15.4
SA	Australia	EB	0.57	56	0.42	0.18	0.6	33	22	11	0	7.49	72	120	26.2
SA	Australia	EB	0.57	56	0.39	0.25	0.64	24	37	14	0	9.3		120	9.1
SA	Australia	EB	0.57	56	0.3	0.29	0.59	20	37	11	0	12.67		120	38.5
SA	Australia	EB	0.57	56	0.3	0.29	0.59	21	33	12	0	10.83		120	16.9
SA	Australia	EB	0.57	62	0.4	0.19	0.59	32	24	4	0	6.48	72	120	13
SA	Australia	PB	0.57	56	0.37	0.24	0.61	22	60	11	0	13.6		200	22.2

Appendix B. Model for estimating dead fuel moisture content in heathlands

Elevated dead fuel moisture content was found to be best predicted with an equation based on the nomograms in Cruz *et al.* (2010), which is given in simplified form as:

$$M_d = 4.37 + 0.161H - 0.1(T_a - 25) - 0.027H\delta \qquad \text{(B.1)}$$

where T_a and H are respectively the air temperature (°C) and relative humidity (%). The radiation factor, δ, is 1.0 for a solar radiation intensity greater than $\sim$500 W m^{-2} (clear skies in early afternoon in summer) and zero otherwise. As the time of day and cloud cover was not always known, δ was set to be 1.0 if H was less than or equal to 60%. Of the models tested, this model provided the lowest error and bias, particularly when the moisture content was low (i.e. less than 10%), which is generally the case for wildfire data. The fit of the fuel moisture content model is shown in Fig. B1. Error statistics for this model were: MAE = 0.87%, RMSE = 1.1%, MBE = 0.12% and MAPE = 12%.

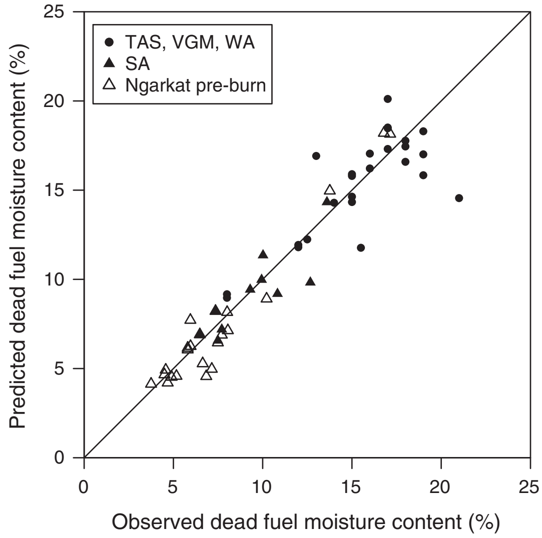

Fig. B1. Dead fuel moisture content predictions using equations derived from nomograms from Cruz *et al.* (2010). Symbols denote data from Tas., VGM, Catchpole (1987) (filled circles), SA (filled triangles) and Ngarkat pre-burn data (empty triangles).