

Existing fire behaviour models under-predict the rate of spread of summer fires in open jarrah (*Eucalyptus marginata*) forest

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Summary

Fire behaviour data from Project Vesta experimental fires were used to evaluate the fire behaviour relationship on the Forest Fire Danger Meter (FFDM), the Forest Fire Behaviour Tables (FFBT) for Western Australia and the fire spread model of Burrows (1999) for predicting the rate of spread of fires in jarrah (*Eucalyptus marginata*) forest under dry summer conditions. Experimental fires were conducted at two sites in south-western Australia under conditions of moderate to high forest fire danger with fine fuel moisture contents of 6–9% oven dry weight and wind speeds up to 20 km h⁻¹ (at 10 m in the open). Fuels ranged in age from 2 to 22 y since the last fire and had understorey shrub layers from 0.5 to 2.0 m tall. Mean rates of spread for experimental fires were 392 m h⁻¹ and 405 m h⁻¹ at the low and tall shrub sites respectively, with the fastest fires spreading at close to 1200 m h⁻¹. Fires spread two to three times faster than predicted by the FFDM and FFBT fire spread models, and up to five times faster than predicted by the spread model of Burrows. Both the FFDM and FFBT models predicted fire spread better at the low shrub fuel site and when wind speeds were <12.5 km h⁻¹. All models under-predicted fire spread at the tall shrub site and grossly under-predicted fire spread when wind speeds were >12.5 km h⁻¹. We argue that existing fire behaviour models under-predict because they were developed using data from fires that had not achieved a quasi-steady rate of spread, whereas the line ignition technique used during Project Vesta experiments resulted in fires travelling at a speed closer to their potential rate of spread for the prevailing conditions. Existing guides remain valid for predicting spread during the early stages of fire growth when fires are developing from a point ignition and the headfire remains narrow.

Keywords: forest fires; fire behaviour; model; fuel; weather; experiments; jarrah; *Eucalyptus marginata*; Western Australia

Introduction

Two fire danger rating systems are used in Australia to predict forest fire danger and rate of forward spread for fires burning in dry eucalypt forests:

- the Forest Fire Danger Meter (FFDM) of McArthur (1967, 1973)

- the Forest Fire Behaviour Tables for Western Australia (FFBT) of Sneeuwjagt and Peet (1985).

These guides were developed independently from measurements of small experimental fires lit in open eucalypt forests with fuels consisting of leaf litter and occasional low shrubs. Although designed primarily to predict the behaviour of fires for prescribed burning operations, the guides were extrapolated to predict the behaviour of high-intensity fires using observational reports of spread of wildfires.

Studies by McArthur (1962, 1967) and Peet (1965) suggested that the amount of available fuel on the forest floor (i.e. the fuel consumed by the fire) was the most significant fuel variable affecting the behaviour of fires in eucalypt forests. The authors stated that the rate of spread of the headfire (R) is directly proportional to the load of fine fuel (<6 mm diameter) consumed (w) and is expressed as a simple linear relationship:

$$R = aw, \quad (1)$$

where a is a constant defined by McArthur (1962) and Peet (1965). Both the FFDM and FFBT treat fuel load as a variable for fire behaviour prediction, with the FFBT also having provision to account for variation in the flammability of understorey shrubs associated with shrub foliage density and the proportion of dead fuel.

There is considerable uncertainty about how fuel characteristics affect fire behaviour, particularly under extreme fire weather conditions (Cheney 1996). Cheney *et al.* (1993) found that rate of spread of the headfire was not correlated with fuel load in uniform grass swards that had been harvested to different degrees to change fuel loads. Burrows (1994) concluded from a series of small experimental fires in jarrah forest that fuel load did not influence the rate of forward spread of the headfire. There is quite wide disagreement between fire spread models for dry forest fuels, and the difference in predicted rates of spread widens as the amount of available fuel increases (Table 1).

The 1985 edition of the FFBT included a revised table predicting rate of spread, based on preliminary analysis of summer fire experiments lit in 7-y-old jarrah forest fuels (Burrows 1983).

Table 1. Predicted rates of spread for different fuel quantities where air temperature = 30°C, relative humidity = 30%, wind speed at 1.5 m = 5.5 km h⁻¹, surface fuel moisture content = 5% and slope = 0°. Drought factor for FFDM is 10.

Fuel characteristics		Rates of spread predicted by dry forest fire spread models		
Age (y)	Load (t ha ⁻¹)	FFDM ^a (m h ⁻¹)	FFBT ^b (m h ⁻¹)	Burrows ^c (m h ⁻¹)
3	4.8	98	37	210
6	9.3	190	222	210
9	13.1	267	333	210
14	18.8	384	444	210

^aFFDM = Forest Fire Danger Meter Mark V (McArthur 1973)

^bFFBT = Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985)

^cBurrows (1999)

The functional relationships in these tables have been formulated as equations to facilitate their application in computer programs (Beck 1995). Burrows (1999) subsequently developed a new rate-of-spread model for jarrah forest following comprehensive analysis of his data. The new model did not include an effect of fuel quantity on forward rate of spread because there was little evidence in the experimental data for this relationship.

In 1996 the Department of Conservation and Land Management¹ and CSIRO Forestry and Forest Products² commenced Project Vesta, a comprehensive experimental study to investigate the behaviour of summer fires in dry eucalypt forests with fuel of different ages and with different understorey vegetation structures (Cheney *et al.* 1998; Gould *et al.* 2007). During the summers of 1998, 1999 and 2001 more than 100 experimental fires were lit at two sites in the jarrah forest in south-western Australia. Fire behaviour data collected during Project Vesta provided the opportunity to evaluate the performance of the FFDM, the FFBT and the fire spread model of Burrows (1999) for predicting the rate of spread of fires in jarrah forest under dry summer conditions.

Methods

Experimental sites

Experimental sites were at Dee Vee Road (33°06'S, 116°24'E) 40 km east of Harvey and at McCorkhill forest block (34°54'S, 115°46'E) 25 km west of Nannup, Western Australia (WA). The Dee Vee site was in open jarrah forest with a sparse shrub understorey and experimental plots were mostly located in vegetation complexes Dwellingup 1 and 2 with some limited areas of Goonaping complex on sandy soils (Mattiske and Havel 1998). Average annual rainfall at Dee Vee is slightly less than 900 mm with potential summer (December to February) evaporation of about 650 mm. The dominant understorey shrub (*Bossiaea ornata*) grows to around 0.5 m after 3 y then slowly senesces so that older fuels predominantly consist of leaf litter, bark and twigs with only a small proportion of shrubs. The vegetation and fuels at McCorkhill were representative of dry eucalypt forest

with a tall understorey shrub layer. The experimental site was located within the Blackwood and Kingia vegetation complexes described by Mattiske and Havel (1998). Average annual rainfall at the site is 1100–1200 mm with potential summer evaporation of about 500 mm. Jarrah and marri (*Corymbia calophylla*) form an overstorey with 30–50% canopy cover and a top height of 25–30 m. Intermediate canopy trees consist primarily of *Allocasuarina fraseriana*, *Xylomelum occidentale*, *Banksia grandis* and jarrah/marri saplings. The understorey is dominated by *Taxandria parviceps* which ranges in height from 0.2 to 3 m and in cover from sparse to near continuous depending on the time since the last fire. McCorkhill block was the site of previous high-intensity fire experiments conducted during Project Aquarius and Project Narrik in the summer of 1983 (Burrows 1983; Gould *et al.* 1996).

The terrain at both sites is gently undulating (average slopes <5°) with occasional steeper sections (up to 15°) at laterite breakaways or adjoining larger creeks. Plots for experimental burning were laid out on a grid oriented in the direction of the prevailing wind and selected for each site so that, as far as it was possible, the ground was level or had a positive slope in relation to the selected wind direction. Unavoidably, some plots included sections of slight negative slope (up to -2.5°).

Fuel description

Replicated plots were established in forest unburnt for between 2 and 22 y, with fuel of four ages at Dee Vee and five ages at McCorkhill. Plots were 200 m × 200 m and separated by bulldozed tracks. In the initial research project plan all experimental burning was scheduled for January–February 1998 and the site selection and preparatory prescribed burning was carried out to give a suitable range of fuel ages in 1998. However, extensive wildfires in south-western WA late in December 1997 forced the postponement of the experiments at McCorkhill until the following summer when burns were conducted from 11 January to 9 February 1999. Experiments at Dee Vee were spread over three summers in order to obtain the desired range of wind speeds, and this resulted in a spread of fuel ages. Fuels were allocated a nominal age in years reflecting the number of litter falls completed by the time that burning experiments commenced at each site (Tables 2 and 3). Litterfall in the jarrah forest takes place over the summer months (Hatch 1955) and by the time that experiments

¹In July 2006 the Department of Conservation and Land Management became part of the Department of Environment and Conservation

²In January 2008 CSIRO Forestry and Forest Products became CSIRO Forest Biosciences.

Table 2. Time since last fire for experiments at Dee Vee

Date of last fire	Fuel age in March 1998		Fuel age in March 1999		Fuel age in February 2001	
	(mo)	(y)	(mo)	(y)	(mo)	(y)
October 1995	28	3	40	4		
February 1998					36	3
October 1992	63	6	75	7		
October 1995					63	6
October 1990	87	8	99	9		
October 1979	219	19	231	20	255	22

Table 3. Time since last fire for experiments at McCorkhill

Date of last fire	Fuel age (mo)	Fuel age (y)
November 1996	25	2
March 1994	57	5
November 1991	85	7
November 1988	121	10
March 1983	187	16

commenced at Dee Vee in late February around 75% of the current season's litter fall had taken place, although in most cases this was 7–8 mo short of a full calendar year.

Fuel and vegetation characteristics were assessed at up to 32 sample points in each plot. Five fuel strata were recognised, as follows:

- overstorey canopy and bark
- intermediate canopy and bark
- elevated fuel — tall shrubs and other understorey plants without significant suspended material
- near-surface fuel — grasses, low shrubs and creepers, and collapsed understorey usually containing suspended leaf, twig and bark from the overstorey vegetation
- surface fuel — horizontally layered and consisting of leaf, bark and twigs.

Fuel characteristics assessed at each point included the depth, cover and loading of surface litter and near-surface fuel, and the height of elevated fuel. Each fuel stratum was assigned a percentage cover score and a hazard score that reflected increasing potential flammability on a scale from 0 to 4 judged according to a set of standard descriptions following the concept of Wilson (1992a,b, 1993) and McCarthy *et al.* (1999). Samples of surface litter and near-surface fuel were harvested from quadrats of 0.05 m² and 0.2 m² respectively and oven dried to determine loadings in tonnes per hectare (t ha⁻¹). Sampling intensity was designed to estimate the mean surface fuel loading with a standard error of less than ±15%. Elevated shrub fuel was also harvested from a small number of quadrats in each fuel age class to determine loadings of live and dead material <6 mm diameter.

Fuel loading and hazard score values were adjusted to account for changes that would have taken place in the period between

sampling and experimental burning. Measured mean values for individual plots were extrapolated to the time of burning using accumulation curves fitted to the data for each fuel stratum. Curves were based on non-linear equations of the form:

$$w = aA/(b + A), \quad (2)$$

where w is the fuel loading or hazard score, A is the number of months since last fire, and a and b are constants. The non-linear equation form provided a fit similar to that of the more commonly used exponential accumulation equation (e.g. Olsen 1963; O'Connell 1989) but did not limit fuel accumulation to a steady-state condition. In particular, we consider that the non-linear equation better represents the gradual increase in near-surface fuel load and fuel hazard score that takes place after 15 y without fire (Gould *et al.* 2007).

Experimental fires

Wind speed was measured during each fire using four sensitive cup anemometers suspended from portable aluminium towers at a height of 5 m above ground in the forest. Four towers were placed at 40 m intervals in a line upwind of each plot to be burnt, with the distance between the line of anemometers and the ignition line being about 40 m. This configuration of anemometers was expected to estimate the mean in-forest wind speed with an error of less than ±20% (Sullivan and Knight 2001). Wind speed data from these instruments were combined into 10-minute means for analysis of fire spread. Measurements of wind speed at 5 m were adjusted to meet the input requirements of the fire spread models using a multiplication factor of 0.85 to obtain equivalent in-forest wind speeds at 1.5 m for the FFBT and Burrows' models, and a factor of 2.5 to obtain equivalent 10 m open wind speeds for the FFDM. These adjustments were based on a study of wind profiles conducted at each experimental site (Gould *et al.* 2007).

Samples of the uppermost 5–10 mm of the litter layer on the forest floor were collected just before and after each experimental fire and oven dried at 105°C to determine moisture content. These measurements represent the surface moisture content (SMC) of Sneeuwjagt and Peet (1985).

Fires were ignited simultaneously in plots of each fuel age, using ignition lines 120 m long lit with drip torches on the upwind edge of each plot. Lighting teams worked outwards from the centre point of the ignition line to complete ignition in two minutes. Twelve sets of experiments were conducted at Dee Vee and

11 sets at McCorkhill, giving a total of 104 fires. Experiments at Dee Vee were conducted under prevailing easterly winds (ESE to ENE) that tended to be strongest in the late morning, several hours before the maximum temperature and minimum relative humidity normally occur. Experiments at McCorkhill were lit during mid-afternoon on a SSW sea breeze, except on Burn Day 6 when the wind was SE. Observers described fire behaviour, and forward rate of spread was determined by a range of methods including timers, thermo-loggers, tags and visual observations. Data were validated and checked for consistency between different methods. Where necessary, the distance travelled by the headfire was adjusted to take account of spread that was not parallel to the plot centre-line. Data from two sets of experiments at Dee Vee conducted after rain were not used in the analysis because the moisture content of the fuel bed (> 15% of oven dry weight) limited the consumption of surface fuel.

Predictions from fire spread models

Fire spread predictions from the FFDM were derived via the equations of Noble *et al.* (1980) using inputs of air temperature, relative humidity, drought factor, and wind speed at 10 m in the open to determine the Forest Fire Danger Index. Forward rates of spread were then predicted for the measured surface fuel load (FFDM_{sf}) and the combined load of surface and near-surface fuel (FFDM_{sf+nsp}). Near-surface fuel contributed 1.5–4.0 t ha⁻¹ to the total fine fuel load depending on the time since fire.

The rate of spread index for jarrah forest was calculated for each fire from the measured SMC and in-forest wind speed at 1.5 m using equations fitted to the 1985 edition of the FFBT by Beck (1995). This minimised variance resulting from the use of discontinuous index values taken from the original tables. Index values from the tabular FFBT and Beck's equations matched closely. Forward rates of spread were then determined for each fire by adjusting for fuel age (FFBT_{age}) or the measured loading of surface and near-surface fuel in each plot (FFBT_{load}) using the fuel quantity correction factor provided in the FFBT. Fuel loadings used to predict rate of spread from the FFBT also included an allowance for the loading and flammability of scrub fuel following the procedure described by Sneeuwjagt and Peet (1985). Shrub fuel loading and flammability were based on field measurements by Gould *et al.* (2007) and are presented for each fuel age class at each site in Table 4. Rates of spread from Burrows' (1999) model

were calculated with inputs of measured SMC and in-forest wind speed at 1.5 m.

Predicted rates of spread from all models were adjusted for slope using McArthur's slope function (Noble *et al.* 1980).

Evaluation of fire spread model performance

The performance of each model in predicting fire spread was evaluated by inspection of scatterplots and using statistical measures of agreement between predicted and observed values (Fox 1981; Willmott 1982; Janssen and Heuberger 1995). Comparative measures included the root mean square error (RMSE), mean absolute (MAE) and percent errors (MAPE), mean bias error (MBE), and an agreement index (*d*). This last index provides a measure of the degree to which the model's predictors are error free and varies between 0.0 and 1.0, where a value of 1.0 indicates perfect agreement between the observed and predicted values and 0.0 implies one of a variety of complete disagreements (Willmott 1981).

Results

Fire experiments

Experimental fires were conducted under conditions of moderate to high forest fire danger (Table 5) with fine fuel moisture contents of 6–9%. Half the experiments were scheduled for light winds (<12.5 km h⁻¹) and the other half for moderate winds (12.5–25 km h⁻¹). Fire behaviour ranged from low-intensity surface fires to fast-spreading fires (up to 1200 m h⁻¹) with sporadic crowning activity and intensities >10 000 kW m⁻¹. Mean rates of spread were not significantly different between the low shrub site at Dee Vee (392 m h⁻¹) and the tall shrub site at McCorkhill (405 m h⁻¹) (Table 6).

Observed rates of spread compared with McArthur fire spread predictions

Slope-adjusted rates of spread predicted by the FFDM ranged from 37 to 405 m h⁻¹ at Dee Vee and from 42 to 445 m h⁻¹ at McCorkhill. The FFDM under-predicted rate of spread by a factor of two or more (Table 6), regardless of whether the rate of spread observations were adjusted using the McArthur slope function or not (Fig. 1), particularly when observed rates of spread were >600 m h⁻¹. Predictions based on the sum of surface and near-surface fuel load were closer to observed values than those based on surface fuel load alone (Figs 2 and 3), and had smaller errors and an improved value of the agreement index *d* (Table 6). Error statistics indicated better agreement between predicted and observed rates of spread at Dee Vee than at McCorkhill, but overall the correlation between predicted and observed rates of spread was poor (Table 7).

Comparison of FFBT predictions based on fuel age and fuel load

Slope-adjusted rates of spread predicted by the FFBT ranged from 10 to 1386 m h⁻¹ at Dee Vee, and from 2 to 595 m h⁻¹ at McCorkhill. Predictions based on fuel age were strongly

Table 4. Shrub fuel loading and flammability factor for fuel age classes at each site

Site	Fuel age (y)	Scrub fuel load (t ha ⁻¹)	Scrub flammability factor
Dee Vee	3, 4	0.5	0.5
	6, 7	1.5	1.0
	8, 9	1.5	1.0
	19, 20, 22	1.5	1.0
McCorkhill	2	0.5	0.5
	5	1.0	1.0
	7	1.0	1.0
	10	1.5	2.0
	16	1.5	2.0

Table 5. Range of fire weather conditions during Project Vesta experimental fires

Variable	Site			
	Dee Vee 1998	Dee Vee 1999	Dee Vee 2001	McCorkhill
Temperature (°C)	22–32	23–31	24–25	21–33
Relative humidity (%)	28–54	17–39	37–40	26–50
Wind speed at 10 m (km h ⁻¹)	6–17	7–14	13–16	8–17
Soil dryness index (mm)	161–199	190–198	189	126–166
Forest fire danger index ^a	6–15	10–23	10–12	7–21
Jarrah forest rate of spread index ^b (m h ⁻¹)	56–474	50–113	108–375	16–199

^aForest Fire Danger Meter Mark V^bForest Fire Behaviour Tables for Western Australia**Table 6.** Quantitative evaluation of rate of spread predictions from fire behaviour models. Units are m h⁻¹ for all variables except MAPE which is per cent.

Site and model ^a	Mean (s.d.) $R_{observed}$	Mean (s.d.) $R_{predicted}$	$R_{predicted}/R_{observed}$	RMSE ^b	MAE ^c	MBE ^d	MAPE ^e	Agreement index (<i>d</i>)
Dee Vee <i>n</i> = 43	392 (240)							
FFDM _{sf}		153 (80)	0.50	331	240	-239	52	0.70
FFDM _{sf+nsf}		195 (85)	0.63	297	205	-197	44	0.75
FFBT _{load}		236 (203)	0.65	235	177	-177	45	0.86
FFBT _{age}		220 (242)	0.55	272	214	-214	54	0.85
Burrows		163 (125)	0.45	299	249	-249	60	0.73
McCorkhill <i>n</i> = 55	405 (289)							
FFDM _{sf}		120 (64)	0.53	337	293	-286	66	0.66
FFDM _{sf+nsf}		175 (89)	0.86	331	260	-232	80	0.72
FFBT _{load}		152 (109)	0.56	334	261	-254	62	0.71
FFBT _{age}		127 (114)	0.30	349	278	-278	69	0.68
Burrows		87 (124)	0.40	408	323	-320	72	0.63

^aFFBT = Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985); FFDM = Forest Fire Danger Meter Mark V (McArthur 1973); Burrows = Burrows (1999); sf = surface fuel load; nsf = near-surface fuel load; load = loading of surface and near-surface fuel adjusted using the fuel quantity correction factor^bRMSE = root mean square error^cMAE = mean absolute error^dMBE = mean bias error^eMAPE = mean absolute percent error

correlated with those based on measured surface and near-surface fuel load ($r = 0.89$, $P < 0.001$) reflecting the strong association between fuel load and time since fire in the jarrah forest. The relationship between predictions based on fuel age and measured fuel load was generally linear with a slope of 1.0 except for a group of slow-spreading fires that had predicted rates of spread less than 100 m h⁻¹ (Fig. 4). For this group, predicted rates of spread based on measured fuel loadings were consistently greater than those based on fuel age, indicating that there was more fuel present on these plots than expected by the fuel accumulation model in the FFBT.

Observed rates of spread compared with fire spread predictions from the FFBT

Experimental fires at both sites spread faster than predicted by the FFBT, and the model under-predicted to a greater extent for

fires at McCorkhill than at Dee Vee (Figs 5 and 6). At Dee Vee, mean predicted values were 236 m h⁻¹ (FFBT_{load}) and 220 m h⁻¹ (FFBT_{age}), representing about two-thirds of the mean observed value (Table 6). At McCorkhill the mean predicted values of 152 m h⁻¹ (FFBT_{load}) and 127 m h⁻¹ (FFBT_{age}) were less than half the mean observed rate of spread.

Predicted and observed rates of spread were more strongly correlated for fires at McCorkhill than at Dee Vee, but correlations were relatively weak in all cases (< 0.60 , Table 7). In contrast, error statistics for FFBT_{load} and FFBT_{age} indicated better agreement between predicted and observed rates of spread at Dee Vee than at McCorkhill (Table 6). The index of agreement *d* was also higher for FFBT predictions at Dee Vee than at McCorkhill. Overall, FFBT_{load} provided slightly better predictions of spread rate than did FFBT_{age}.

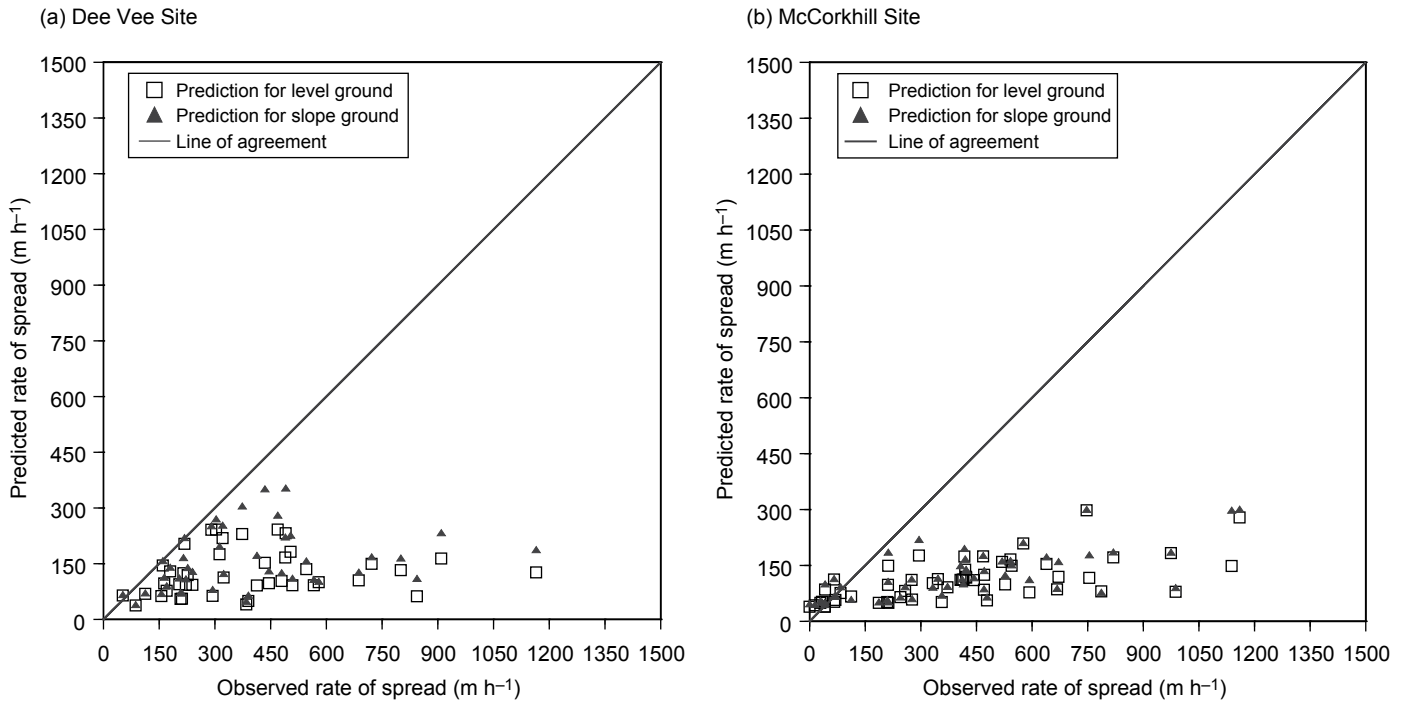


Figure 1. Observed rate of spread compared with predictions from the McArthur FFDM based on measured surface fine fuel load (FFDM_{sf}). Symbols identify the predicted rates of spread for level ground, and adjusted for slope. The line of agreement is shown.

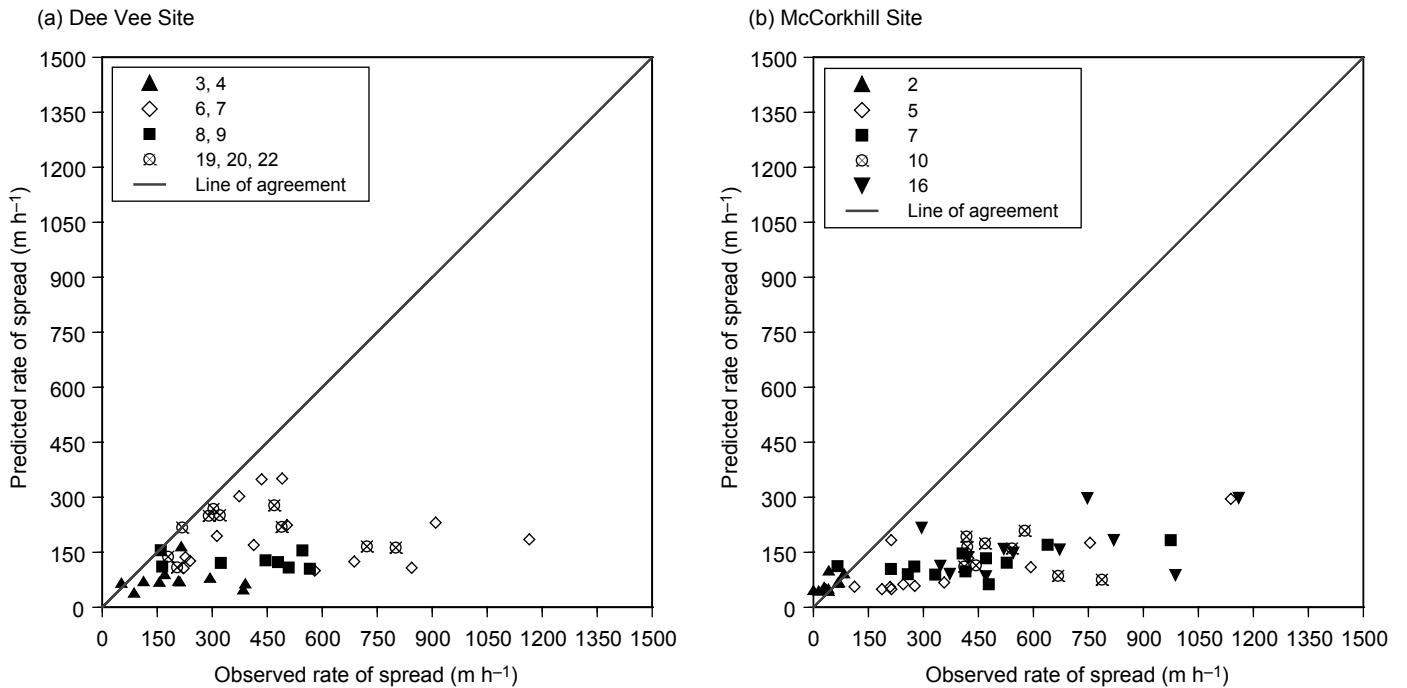


Figure 2. Observed rates of spread compared with predictions from the McArthur FFDM based on measured surface fine fuel load (FFDM_{sf}). Symbols identify different fuel ages and the line of agreement is shown.

Two experimental fires at Dee Vee behaved contrary to the general trend of under-prediction by the FFBT. Experimental fire Plot 6C burnt on 27 February 1998 in 6-y-old fuel had R_{observed} of 226 m h⁻¹ and slope-corrected predicted spread rates of 623 m h⁻¹ and 467 m h⁻¹ for FFBT_{load} and FFBT_{age} respectively. Predicted rates of spread for this plot were high because measured in-forest

winds (21 km h⁻¹) were considerably stronger than observed at other plots burnt on the same day (mean value 13.8 km h⁻¹). Plot 6C was located on a slope and the wind measurements were made about 40 m downhill of the ignition line where the slope was up to 7°. It is possible that the wind affecting the fire was less than the measured wind speed due to the influence of local terrain.

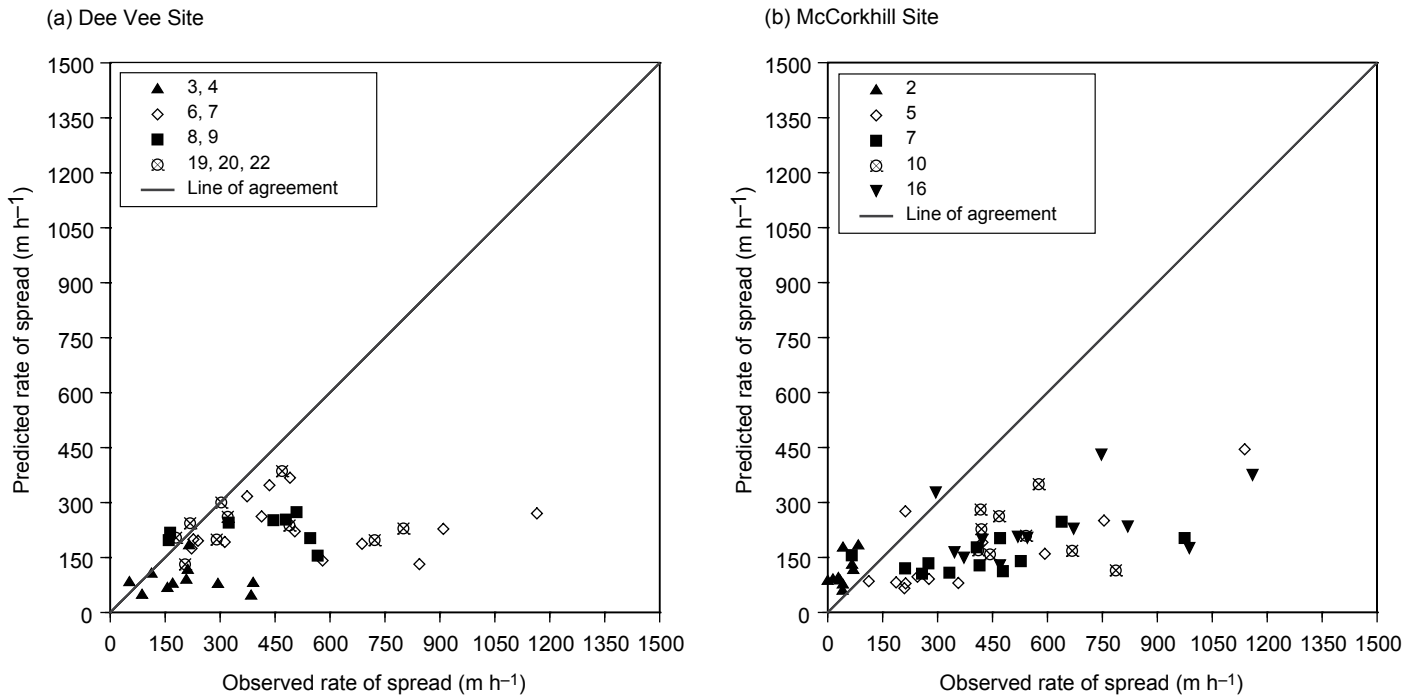


Figure 3. Observed rates of spread compared with predictions from the McArthur FFDM based on measured surface and near-surface fuel fine fuel load (FFDM_{sf+nsf}). Symbols identify different fuel ages and the line of agreement is shown.

Table 7. Statistics for linear regression equations of the form $R_{\text{predicted}} = a + b.R_{\text{observed}}$ where $R_{\text{predicted}}$ is the rate of spread predicted by existing fire spread models for dry eucalypt forest, R_{observed} is the slope-corrected rate of spread, and a and b are constants for intercept and slope respectively. Units are m h^{-1} .

Site	Model ^a	Intercept (s.e.)	Slope (s.e.)	r^2
Dee Vee <i>n</i> = 43	FFDM _{sf}	116.9 (23.0)	0.09 (0.05)	0.08
	FFDM _{sf+nsf}	146.8 (23.8)	0.12 (0.05)	0.12
	FFBT _{load}	8.0 (44.1)	0.58 (0.10)	0.47
	FFBT _{age}	-18.7 (57.4)	0.61 (0.12)	0.37
	Burrows	17.9 (27.9)	0.34 (0.06)	0.44
McCorkhill <i>n</i> = 55	FFDM _{sf}	57.0 (11.4)	0.15 (0.22)	0.47
	FFDM _{sf+nsf}	93.5 (16.7)	0.20 (0.33)	0.41
	FFBT _{load}	37.8 (17.8)	0.28 (0.03)	0.55
	FFBT _{age}	2.6 (17.7)	0.31 (0.35)	0.60
	Burrows	37.6 (9.9)	0.12 (0.20)	0.41

^aFFBT = Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985); FFDM = Forest Fire Danger Meter Mark V (McArthur 1973); Burrows = Burrows (1999); sf = surface fuel load; nsf = near-surface fuel load; load = loading of surface and near-surface fuel adjusted using the fuel quantity correction factor

The second example was Fire 22F burnt on 14 February 2001 in 22-y-old fuel which had R_{observed} of 800 m h^{-1} and slope-corrected predicted spread rates of 832 m h^{-1} and 1386 m h^{-1} for FFBT_{load} and FFBT_{age} respectively. In this case the correction factor based on age appears to over-estimate the effect of fuel quantity on rate of spread.

Observed rates of spread compared with Burrows’ model predictions

Rates of spread predicted by Burrows’ model ranged from 47 to 709 m h^{-1} at Dee Vee, and from 21 to 276 m h^{-1} at McCorkhill. Observed rates of spread were substantially greater than predicted by Burrows’ model, particularly at McCorkhill where the mean predicted rate of spread (87 m h^{-1}) was about one-fifth the mean observed value of 405 m h^{-1} (Fig. 7). The model also under-predicted at Dee Vee, where the mean predicted rate of spread (163 m h^{-1}) was about two-fifths of the observed value of 392 m h^{-1} . Agreement between predicted and observed rates of spread was better at Dee Vee than at McCorkhill (Table 6), as was the case for the FFBT and FFDM. Predictions were not well correlated with observed spread rates at either site and were generally poorer than predictions from the FFBT models that included an effect of fuel age or loading on rate of spread (Table 7).

Predictions in relation to wind speed

Both the FFDM and FFBT predicted reasonably well at low wind speeds ($<12.5 \text{ km h}^{-1}$) with agreement index values (*d*) of 0.99 and 0.91 respectively in the low shrub fuels at Dee Vee, and 0.91 and 0.85 respectively for the tall shrub fuels at McCorkhill (Fig. 8). Both models consistently under-predicted rate of spread at wind speeds $>12.5 \text{ km h}^{-1}$ and agreement between predicted and observed rates of spread was poor, with agreement indices of 0.34 and 0.40 in the tall shrub fuels and 0.63 and 0.85 in the low shrub fuels for the FFDM and FFBT respectively.

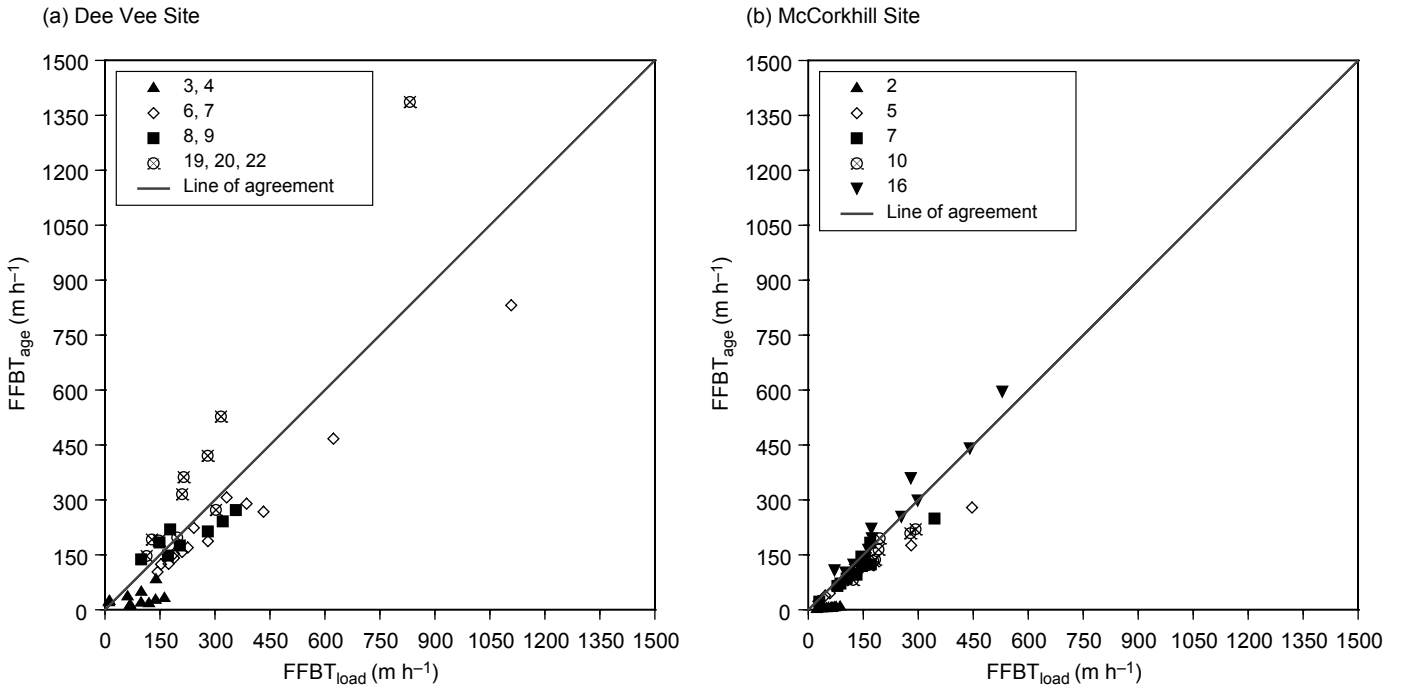


Figure 4. Comparison of predicted rates of spread from the FFBT based on measured fuel loading and fuel age.

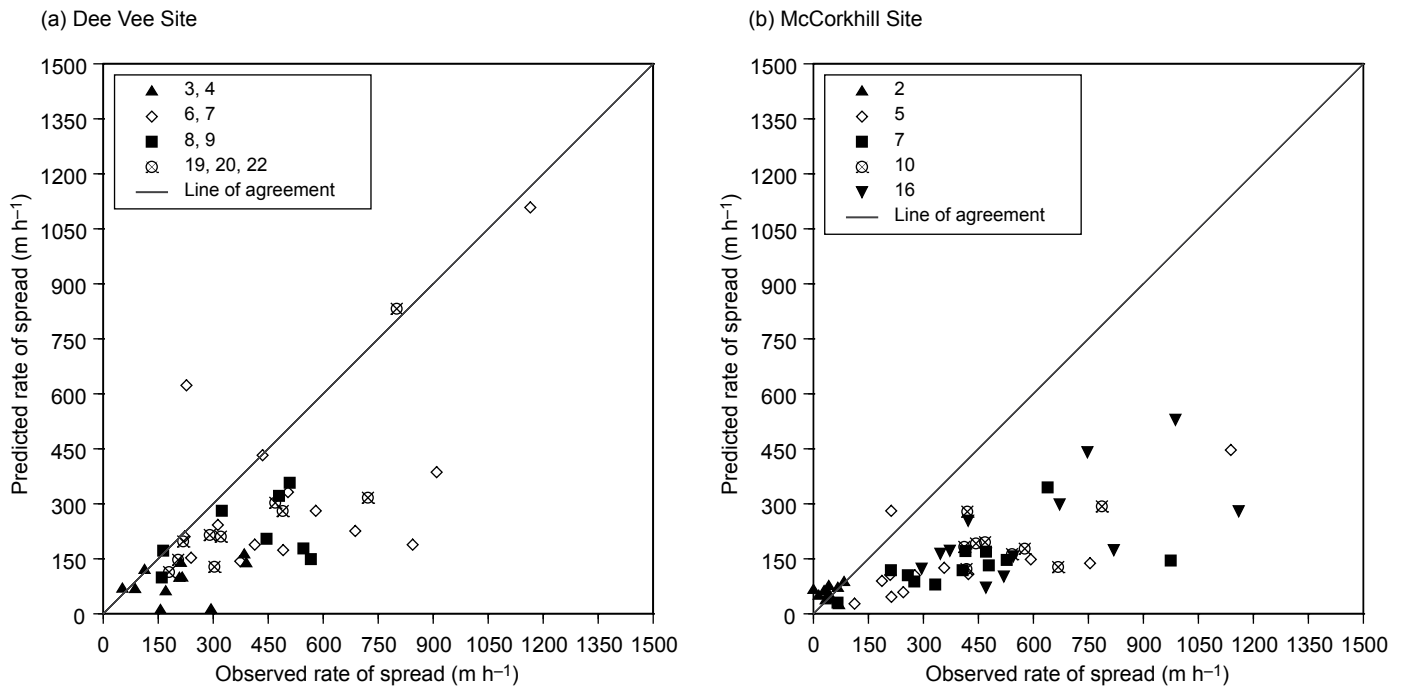


Figure 5. Observed rates of spread compared with predictions from the Forest Fire Behaviour Tables ($FFBT_{load}$) based on measured surface and near-surface fuel load. Symbols identify different fuel ages and the line of agreement is shown.

Discussion

Experimental fires conducted under a wide range of summer burning conditions consistently spread faster, by a factor of two to five times, than predicted by three existing fire spread models developed for dry eucalypt forest. Models under-predicted to a greater extent for stands with the tall shrub understorey at

McCorkhill than for those with the low shrub understorey at Dee Vee, despite adjustments made to predictions to account for the effects of different fuel loading (FFDM and FFBT) and the expected flammability characteristics of the understorey shrub layer (FFBT). The findings of this study support preliminary warnings, based largely on anecdotal evidence, that existing fire spread models tend to under-predict the rate of spread of

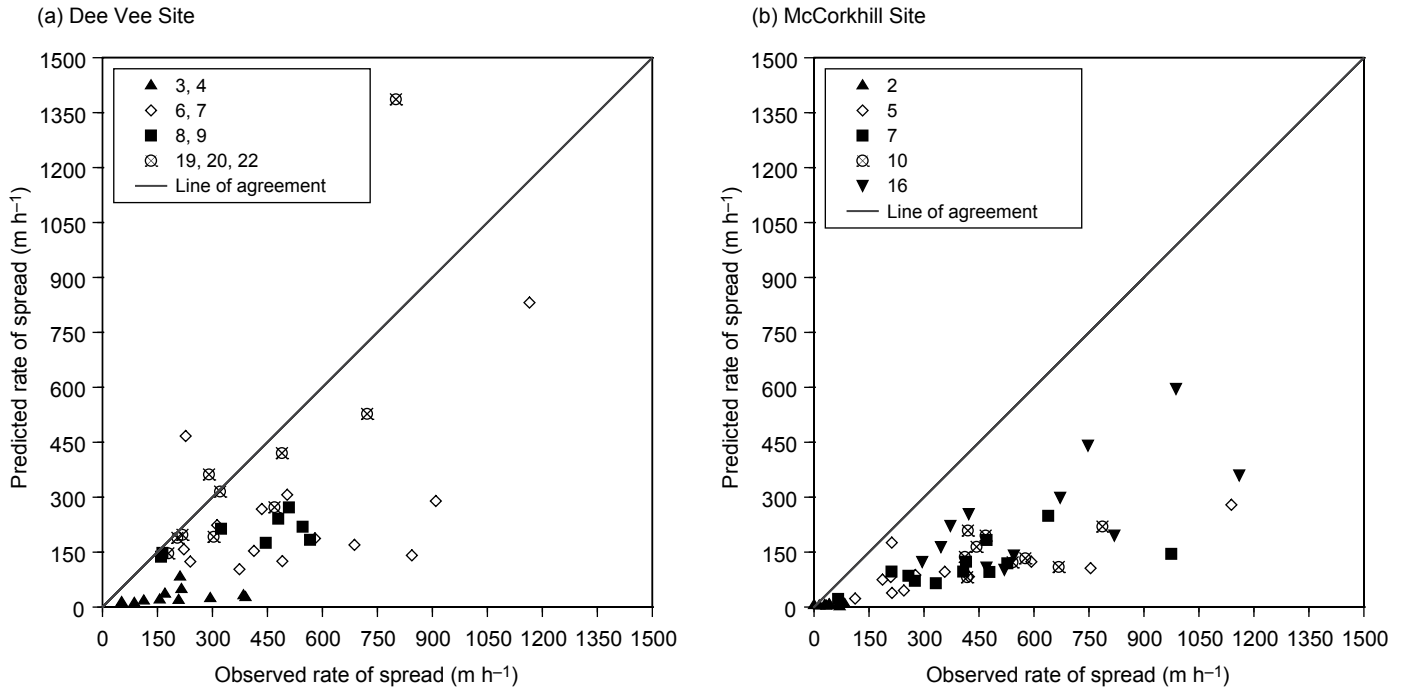


Figure 6. Observed rates of spread compared with predictions from the Forest Fire Behaviour Tables (FFBT_{age}) based on fuel age. Symbols identify fuels of different ages and the line of agreement is shown.

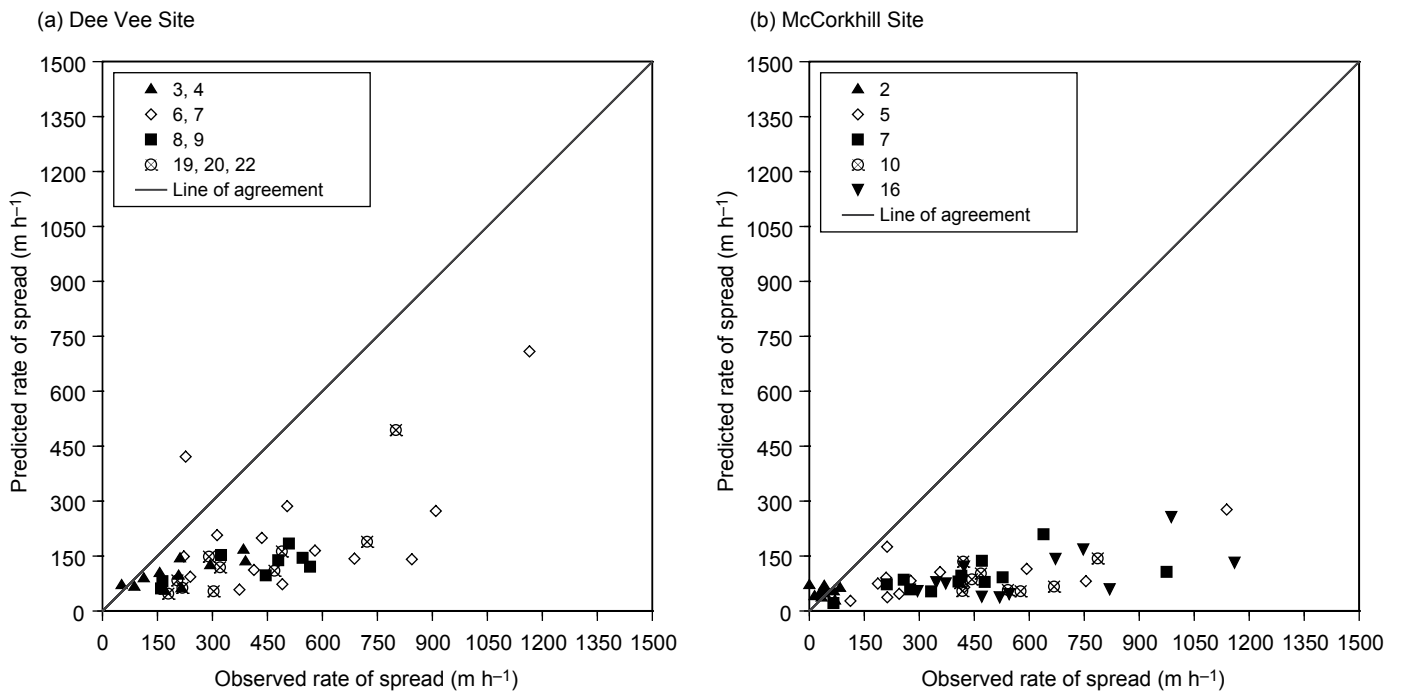


Figure 7. Observed rates of spread compared with predictions from Burrows' (1999) fire behaviour model. Symbols identify fuels of different ages and the line of agreement is shown.

larger and more intense fires (Cheney *et al.* 1998; CSIRO 1999). Under-predicting the rate of spread can lead to under-estimation of other fire behaviour characteristics including fire intensity, flame dimensions and spotting potential. It can also result in ineffective fire suppression planning that can, in the worst case, endanger the lives of fire-fighters and members of the broader community.

Cheney and Gould (1997) proposed that the rate of spread of a fire is influenced by the width of the headfire and the wind speed, and that potential rates of spread in eucalypt forests may not be achieved until headfires are 150–200 m wide. Headfire width has been demonstrated to affect the rate of spread of fires in open grasslands (Cheney and Gould 1995). We consider that the faster

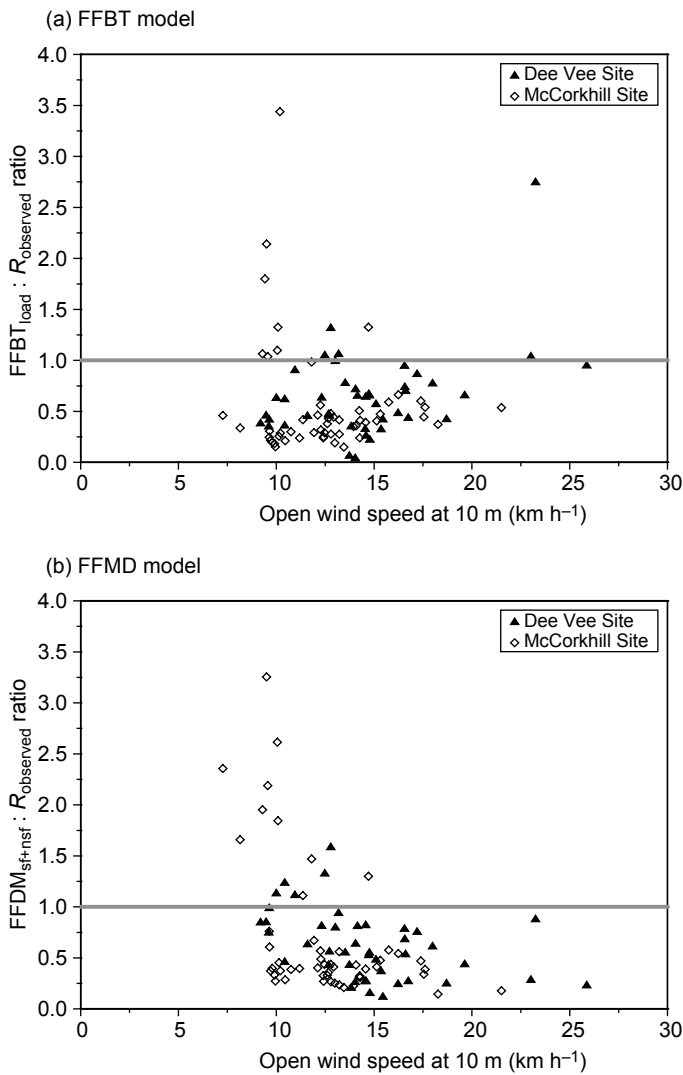


Figure 8. Scatterplot showing the ratio of predicted/observed rate of spread for (a) $FFBT_{load}$ and (b) $FFMD_{sf+nsf}$ in relation to wind speed at 10 m in the open.

rates of spread observed during Project Vesta experiments are directly attributable to the use of ignition lines longer (120 m) than those used in previous experimental studies in eucalypt forests. The greater the length of the ignition line, the greater will be the chance of a fire establishing a head wide enough to achieve the potential quasi-steady rate of spread for the prevailing conditions within the experimental plot. Conversely, the shorter the ignition line the more likely it will be that a fire will establish a narrow head and settle on a quasi-steady rate of spread below the potential for the prevailing conditions. Experimental evidence from Project Vesta indicates that the ignition technique used allowed the fires to approach their potential rate of spread for the conditions within 2 minutes of ignition being completed (Cheney *et al.* 2001; Gould *et al.* 2003). Rates of spread might possibly have been greater had longer ignition lines been used, although comparison with wildfires burning under comparable weather conditions suggests that fires were spreading at rates within 20% of their potential maximum (Gould *et al.* 2007). The FFBT and Burrows' models are primarily derived from experimental fires with ignition lines about 50 m long, and Burrows (1999) noted the possibility that his fire spread equation could under-predict,

although not to the same extent as earlier models. Project Vesta experiments were conducted under dry summer conditions with a range of air temperature, relative humidity, drought index and fine fuel moisture content similar to that of Burrows' (1999) experiments, supporting our hypothesis that factors other than the severity of burning conditions are responsible for differences in observed rates of spread. McArthur's fire experiments were mostly conducted under conditions of moderate to high fire danger, although these conditions are not documented in any of his publications (Cheney, *pers. comm.*).

Inclusion of information about the quantity and age of fuel in the surface and near-surface layers reduced the tendency of the models to under-predict the rate of spread and reduced the errors associated with predictions. The FFDM performed better when predictions were based on the combined loading of surface and near-surface fuel, while predictions from the FFBT that included measured fuel loading or a correction based on fuel age were superior to those from Burrows' model which does not take fuel load into account. The FFBT incorporate a linear relationship between fine fuel load and rate of spread which shows an increasing effect of fuel loading in drier fuels (Sneeuwjagt and Peet 1985). However, Peet's original data provided only limited experimental evidence of this effect, and were not subject to rigorous statistical analysis. Burrows (1999) was unable to find a significant effect of fine fuel load on rate of spread despite an extensive dataset of 67 experimental fires and 206 spread observations, and he acknowledged the possibility that the effect of fuel loading identified by McArthur (1967) and Peet (1972) might have been due to fuel structural differences associated with age rather than fuel quantity per se. Most of his experiments were conducted in 7-y-old fuels with a median surface litter loading of 8 t ha⁻¹ (range 3.2–19.5 t ha⁻¹) but the extent of variation in other fuel characteristics (e.g. litter depth, proportion of dead understorey foliage) was not reported. Clearly, the accuracy of fire spread predictions depends on a sound understanding of the relationship between fuel characteristics and fire behaviour, and an understanding of how fuel characteristics change with time since the last fire.

Conclusion

Rates of spread predicted by the FFDM and FFBT were closest to observed values when winds were light (<12 km h⁻¹) and shrub fuels were sparse. Outside of these conditions, predictions tend to be less accurate and may prove inconsistent from one situation to the next. For this reason, the FFDM and FFBT may not provide a reliable basis for predicting the behaviour of high-intensity wildfires and may contribute to poor operational decisions, particularly under conditions where there is a sudden change in wind direction and wind strength.

We strongly make the point, however, that the FFDM and FFBT remain valid for predicting spread during the early stages of fire growth when fires are developing from a point ignition and the headfire remains narrow. This situation typically exists during prescribed burning, when many small fires are ignited under mild conditions but do not reach their potential rate of spread before coalescing — often during the early evening, as air temperature declines and relative humidity and fuel moisture content increase.

This study has demonstrated that fire spread prediction is improved by the inclusion of fuel load, as shown by the superior performance of the FFBT over the Burrows model. We believe, however, that other descriptors may better quantify the potential contribution of complex vegetation fuels to the behaviour of moderate and high-intensity fires.

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