Fire Management

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Drought Factor (fine fuel consumption) prediction from field measurement of Fine Fuel Moisture Content

Greg McCarthy
Forest Ecology/Fire Research
Orbost
Forest Science Centre

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State Government Victoria
Department of Sustainability and Environment

FOREST SCIENCE CENTRE

INTRODUCTION

Drought Factor (McArthur 1975) was developed to predict the amount of fine fuel which would be available to be consumed in the flaming front of a fire. The predictive model used by McArthur was based on a combination of the Keetch Byram Drought Index, and the amount, and time since fall, of recent rain. McArthur postulated that, since the major influences on fine fuel moisture content were seasonal dryness and short term drying, a predictive model using a combination of drought index, and time since recent rain, should be an acceptable way of calculating the amount of fine fuel which should be burnt by a fire. Further, that the amount of fine fuel left unburnt should be due to fuel moisture content, resulting from the influences of both soil and atmospheric moisture. This model is built in to the McArthur Mark V Forest Fire Danger Meter, with the numbers from 1 to 10, which appear in the windows of the innermost disc, being the prediction of the Drought Factor. A Drought Factor of 5 is intended to indicate that about 50% of the fine fuel should be available to burn, and a Drought Factor of 10 is intended to indicate that 100% of the fine fuel should be available to burn.

Although this model was thought to give acceptable results in terms of predicting availability of fine fuels, there had been no intensive testing of it's accuracy since it had been developed in the 1960s.

A major change in the technology for measurement of fine fuel moisture content occurred in the early 1990s, when Tolhurst and Hood (Chatto and Tolhurst 1997) developed the prototype of the Wiltronics T-H Fine Fuel Moisture Meter. This meter - which determines fine fuel moisture content (of fine fuels such as leaves or needles) by measuring the electrical resistance of a minced sample - has increased the ease of measuring fine fuel moisture content in field situations. The Wiltronics Meter is portable and can accurately measure the fine fuel moisture content of a single sample in about 3 to 5 minutes. It's accuracy is to within 1% in most situations, and it can measure moisture contents from about 3% ODW (Oven Dry Weight) to 200% ODW.

Fuel sampling carried out after wildfires in the 1990s indicated that the Drought Factor, as predicted by the McArthur Mark V Meter, may be significantly understimating the actual consumption of fine fuels. Measured fine fuel consumption levels of 90% compared unfavourably to a predicted Drought Factor of 6 for the   fire. This fire occurred during a drying cycle early in the Summer. It is possible that the McArthur Drought Factor model is unable to cope with a rapid drying event which may occur at any stage during the seasonal wetting and drying process.

Given the availability and improved operational speed of the Wiltronics Meter, it was proposed that fuel availability in relation to fuel moisture content could be investigated at real fire situations, with the intention of producing a simple model to describe the relationship between fuel availability and the fuel moisture content of specific parts of the fine fuel complex.

The aims of this study, given the above background information, were as follows

1) To assess the possibility of predicting fine fuel consumption from direct measurement of fine fuel moisture content.
2) To produce a field methodology for predicting fine fuel consumption using fine fuel moisture content (measured with the Wiltronics Fine Fuel Moisture Meter) and other site and fire behaviour factors.
3) To assess the accuracy of this technique in comparison with the current model derived from McArthur's Drought Factor.

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Particular thanks to Glenn Dooley, who cheerfully assisted with this project, and spent many hours with the author "sifting through the ashes".

METHODS

Fires sampled

It was originally intended that fuel availability in relation to fuel moisture content would be investigated by sampling at going wildfires. A lack of suitable fires during the first season of the study - 2001/02 - and the inherent logistical difficulties of getting to going wildfires in a reasonable time, meant that sampling occurred most frequently at prescribed fuel reduction burns.

The majority of the prescribed burns sampled were in Gippsland, and were located in coastal and foothill mixed species forest.

During the 2002/03 prescribed burning season, a small number of both spring and autumn fuel reduction burns were studied. These included the spring rotations of five of the Fire Effects Study Areas (Tolhurst 1992) in the Wombat Forest in Central Victoria. Four wildfires from Gippsland were also included in the study from this season.

Fuel quantity sampling

At each sample location five samples of litter fuel were taken from a standard sample area of 0.085 sq m. These samples were weighed with a spring balance which was accurate to +/- 1 gm. The material sampled was all fuel with a thickness less than 6 mm. The sites sampled had little live material present. Where some live material was present, any of less than 2 mm thickness was included in the sample.

A deliberate attempt was made to sample sites which had mostly litter and bark fuels only, as it was thought that the presence of substantial shrub fuels would only produce further unnecessary variation in both fuel moisture contents and fire behaviour outcomes.

Figure 1 Fuel quantity sampling showing litter fuel collected from 0.085 m^2 sample plot. Fuel is then weighed with spring balance.

Fuel moisture sampling

The fine fuel moisture content was sampled at the top (surface) and bottom (profile) of the litter bed. The bottom of the litter bed was expected to represent fuel moisture variations due mostly to seasonal soil moisture fluctuation. The top of the litter bed was expected to represent fuel moisture variations due to diurnal wetting and drying, and also to recent rainfall events.

The Wiltronics TH Fine Fuel Moisture Meter (Chatto and Tolhurst 1997) was used to sample fine fuel moisture contents. At each sampling area, three samples of fine fuel moisture content were taken at both the top and bottom of the litter bed.

Figure 2 Wiltronics TH Fine Fuel Moisture Meter (prototype model shown) used for fuel moisture sampling.

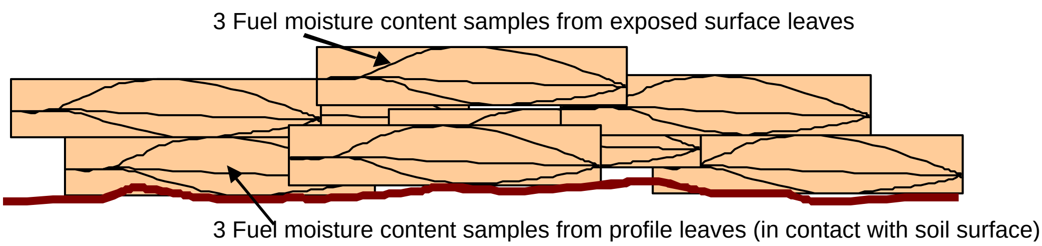


Figure 3 Fuel moisture sample locations. Three samples from exposed surface and three samples from profile (leaves in contact with soil surface).

Weather

Air temperature, relative humidity, and wind speed and direction were recorded at hourly intervals before, during, and after ignition of the sampled area. Air temperature and relative humidity were measured with a Bacharach handheld Sling Psychrometer. Wind speed was measured with a Davis Turbometer handheld electronic anemometer.

Topography

Slope and aspect were recorded for each sample site. Where these varied across the site they were apportioned to slope and aspect classes.

Drought Index and recent rainfall

Keetch Byram Drought Index (KBDI) and recent rainfall were obtained for all sample sites. In some instances this information was derived from the nearest Automatic Weather Station (AWS). Alternatively, it came from records kept at the local Fire District, or other nearby locality. KBDI trends for the previous four months were obtained also.

Drought Factor

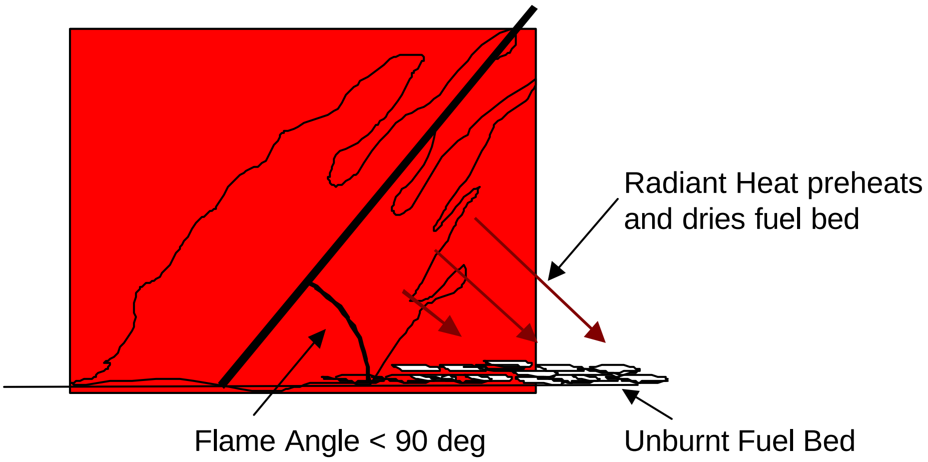
Drought Factor, as predicted by McArthur, was derived by use of the McArthur Mk. V Forest Fire Danger Meter directly. It was not calculated by using any of the three equation-based systems - i.e. Noble, Bary & Gill (1980), Griffiths (1999) or Bally (1989).

Ignition technique

To simulate wildfire conditions as closely as possible, most plots were ignited with a line headfire of at least 50 m width. This was done to produce the maximum possible fire intensity in the shortest time. The line headfire was generally ignited on the downhill side of the fuel consumption plot area, thus allowing the slope effect to carry the headfire across the area which had been sampled for fine fuel quantity and fuel moisture content.

For the backing fires measured, a single line of fire was measured as it progressed either into the prevailing wind, or down the existing slope.

Headfires had flame angles of less than 90^0 to the unburnt fuel bed, whereas backing fires had flame angles of greater than 90^0 to the unburnt fuel bed.



BACKING FIRE

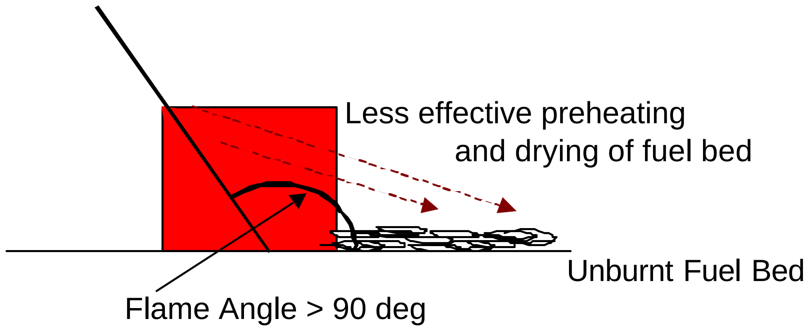


Figure 4 Flame type diagrams showing flame angles for headfire and backfire.

Fuel quantity resampling

Following the passage of the fire through the sampled area, fuel resampling was carried out on five 0.085 sq m sample areas. These were located as close as possible, but not directly on, the areas which were sampled prior to burning. The material collected included all leaf, twig and bark material less than 6 mm thickness which had not been completely consumed by the fire. This material included some ash, but was mostly charcoalled (i.e. partially burnt) fragments and any completely unburnt material. The intention was to collect any material which either had not been burnt at all, or could possibly have been burnt more completely. A deliberate attempt was made not to include any dirt, stones or pre-existing charcoal fragments when doing this resampling.

Figure 5 Fuel quantity resampling after fire has burnt through test area. All material which has not burnt to ash is gathered and weighed. Care taken not to collect dirt or stones.

RESULTS

Site conditions and fuel consumption data from test fires

Table 1 shows the ambient weather, fire danger index and drought conditions for the 20 test fires, and one wildfire, studied during the 2001/02 burning season. It shows that Keetch Byram Drought Index (KBDI) values varied from 14 up to 68, and that the predicted Drought Factor, from these KBDI values and the amount of recent rain, varied from 5 to 10.

Table 1 Weather, fire danger and drought conditions for the 21 test fires for the 2001/02 burning seaeson

Fire District	Fire/FRB name	Date	Temp av. (^{0}C)	RH Av (%)	Windspeed av.(km/hr)	Wind dirn. Av. (deg)	FDI av.	KBDI	Predicted Drought Factor
Nowa Nowa	Oak Tk	2-Apr-02	27	49	1	120	3	42	5
Nowa Nowa	Oak Tk	2-Apr-02	27	49	1	120	3	42	5
Heyfield	Roberts Rd	5-Mar-02	27	55	0	0	3	14	6
Heyfield	Roberts Rd	6-Mar-02	21	70	0	0	1	15	6
Heyfield	Roberts Rd	6-Mar-02	27	50	6	300	4	15	6
Heyfield	Roberts Rd	8-Mar-02	21	60	5	45	2	17	6
Nowa Nowa	Moonlight	3-Apr-02	29	35	6	320	7	44	6
Nowa Nowa	Spankers	24-Mar-02	27	47	2	320	6	68	9
Nowa Nowa	Spankers	24-Mar-02	27	47	2	320	6	68	9
Nowa Nowa	Spankers	24-Mar-02	27	47	2	320	6	68	9
Bairnsdale	Waterfords	12-Apr-02	26	52	0	0	4	36	7
Bairnsdale	Waterfords	12-Apr-02	26	52	0	0	4	36	7
Bairnsdale	Waterfords	12-Apr-02	26	52	0	0	4	36	7
Nowa Nowa	Ironstone	9-Apr-02	28	37	7	350	8	44	7
Nowa Nowa	Ironstone	9-Apr-02	28	37	7	350	8	44	7
Nowa Nowa	Ironstone	9-Apr-02	28	37	7	350	8	44	7
Erica	O'Keefe	9-May-02	19	40	5	320	5	59	7
Erica	O'Keefe	9-May-02	19	40	5	320	5	59	7
Erica	O'Keefe	9-May-02	19	40	5	320	5	59	7
Erica	O'Keefe	9-May-02	19	40	5	320	5	59	7
Bulga	Martindale	3-Jan-02	28	25	10	260	17	110	10

Table 2 shows the ambient weather, fire danger index and drought conditions for the 11 test fires/wildfires studied during the 2002/03 burning season. It shows that Keetch Byram Drought Index (KBDI) values varied from 35 up to 100, and that the predicted Drought Factor, from these KBDI values and the amount of recent rain, varied from 5 to 10.

Table 2 Weather, fire danger and drought conditions for the 11 test fires for the 2002/03 burning season

Fire District	Fire/FRB name	Date	Temp av. (^{0}C)	RH Av (%)	Windspeed av.(km/hr)	Wind dirn. Av. (deg)	FDI av.	KBDI	Predicted Drought Factor
Daylesford	Blakeville FESA	14-Nov-02	16	59	2	360	3	35	5
Daylesford	Barkstead FESA	13-Nov-02	19	26	4	170	5	35	5
Daylesford	Kang Ck FESA	15-Nov-02	19	34	3	230	5	35	6
Daylesford	Musk Ck FESA	15-Nov-02	15	49	5	180	3	30	6
Daylesford	Burnt Bridge FESA	15-Nov-02	13	51	6	140	3	30	6
Nowa Nowa	Frog Hop	18-Oct-02	27	32	15	320	13	70	7.5
Swifts Ck	Steenholdt	31-Oct-02	25	33	25	340	18	50	9
Orbost	Rodger	18-Feb-03	23	25	12	180	20	100	9
Orbost	Majors Ck	20-Mar-03	20	33	20	270	10	94	9
Nowa Nowa	Forestech	8-May-03	23	45	5	270	7	86	7
Orbost	Raynor	23-Nov-02	27	36	10	140	11	50	7.5

Table 3 shows the unburnt and burnt weight of the fuel consumption plot samples (0.085 m^2); the percentage of fuel unburnt; the mean exposed surface and profile fuel moisture contents; the mean flame height and forward rate of spread of the test fires lit to run through the sample plots; and the mean slope and aspect for the sample plot sites. It shows that, for the range of site, weather and fuel moisture conditons, the percentage of fuel unburnt (average) varied from 6.3 % to 50.3 % - this would correspond to a variation in Drought Factor from 9.5 (i.e. 95% of the fine fuel burnt) to 5 (i.e. 50 % of the fine fuel burnt).

Table 3 Fuel weights/consumption, fuel moisture contents, fire behaviour and topography at the 21 test fires for the 2001/02 burning season

Fire District	Fire/FRB name	Weight Unburnt Av. (gm)	Weight burnt Av. (gm)	% unburnt	FMC Exposed Surface Av (%ODW)	FMC Profile Av (%ODW)	Headfire (2) /Backfire (1)	Flame Ht av. (m)	FROS (m/hr)	Aspect (deg)	Slope (deg)
Nowa Nowa	Oak Tk	96.2	23.2	24.1	11.5	21.7	2	0.7	75	160	10
Nowa Nowa	Oak Tk	96.2	30.8	32.0	11.5	21.7	1	0.7	75	160	10
Heyfield	Roberts Rd	92.4	5.8	6.3	11.2	14.2	2	1	150	280	10
Heyfield	Roberts Rd	94	7.4	7.9	11.6	13.2	2	0.6	100	320	15
Heyfield	Roberts Rd	120.6	10.8	9.0	10.1	13.5	2	0.7	50	340	15
Heyfield	Roberts Rd	120.6	10.8	9.0	10.1	13.5	2	0.7	50	340	15
Nowa Nowa	Moonlight	81.2	11.6	14.3	10.4	11.9	2	0.5	200	320	7
Nowa Nowa	Spankers	74.6	9	12.1	10.0	13.7	2	0.6	100	290	7
Nowa Nowa	Spankers	83.6	9.4	11.2	10.0	13.7	2	0.75	150	270	12
Nowa Nowa	Spankers	76.8	12.6	16.4	10.0	13.0	2	0.5	30	180	15
Bairnsdale	Waterfords	137.6	15.8	11.5	10.8	13.6	2	0.55	150	350	10
Bairnsdale	Waterfords	93.6	15.6	16.7	10.4	13.7	2	0.45	150	340	12
Bairnsdale	Waterfords	85.2	13.4	15.7	14.6	24.2	2	0.4	75	160	23
Nowa Nowa	Ironstone	96.2	15	15.6	11.8	14.5	2	0.6	100	110	12
Nowa Nowa	Ironstone	115.4	28.2	24.4	13.5	30.0	2	0.35	50	140	20
Nowa Nowa	Ironstone	111	28.8	25.9	13.5	30.0	2	0.25	20	160	9
Erica	O'Keefe	88.6	9.6	10.8	11.2	12.4	2	0.6	100	30	25
Erica	O'Keefe	88.6	18.6	21.0	11.2	12.4	2	0.6	75	10	3
Erica	O'Keefe	88.6	44.6	50.3	11.6	15.2	1	0.2	10	180	5
Erica	O'Keefe	88.6	29.2	33.0	11.6	15.2	1	0.3	15	140	5
Bulga	Martindale	65.5	10.8	16.5	4.6	8.1	1	0.7	20	270	10

Table 4 shows the unburnt and burnt weight of the fuel consumption plot samples (0.085 m^2); the percentage of fuel unburnt; the mean exposed surface and profile fuel moisture contents; the mean flame height and forward rate of spread of the test fires lit to run through the sample plots; and the mean slope and aspect for the sample plot sites. It shows that, for the range of site, weather and fuel moisture conditons, the percentage of fuel unburnt (average) varied from 3.6 % to 46.8 % - this would correspond to a variation in Drought Factor from 9.5 (i.e. 95% of the fine fuel burnt) to 5 (i.e. 50 % of the fine fuel burnt).

Table 4 Fuel weights/consumption, fuel moisture contents, fire behaviour and topography at the 11 test fires for the 2002/03 burning season

Fire District	Fire/FRB name	Weight Unburnt Av. (gm)	Weight burnt Av. (gm)	% unburnt	FMC Exposed Surface Av (%ODW)	FMC Profile Av (%ODW)	Headfire (2) /Backfire (1)	Flame Ht av. (m)	FROS (m/hr)	Aspect (deg)	Slope (deg)
Daylesford	**Blakeville FESA**	**149**	**12.4**	8.3	11.4	18.7	2	1.5	200		
Daylesford	**Barkstead FESA**	**131**	**9.2**	7.0	10.0	14.5	2	0.8	50	230	2
Daylesford	**Kang Ck FESA**	**173**	**12.4**	7.2	5.1	12.3	2	1	90	70	5
Daylesford	**Musk Ck FESA**	**236**	**8.4**	3.6	10.4	14.4	2	1.3	400	270	12
Daylesford	**Burnt Bridge FESA**	**113**	**10**	8.8	10.1	13.1	2	0.7	100	50	10
Nowa Nowa	**Frog Hop**	**140**	**29**	20.7	10.4	13.9	2	0.4	50	270	7
Swifts Ck	**Steenholdt**	**113**	**11**	9.7	8.8	11.5	2	1.2	200	50	20
Orbost	**Rodger**	**162**	**13**	7.8	10.6	15.3	1.5	0.8	50	140	5
Orbost	**Majors Ck**	**203**	**95**	46.8	10.3	58.3	2	0.65	75	250	10
Nowa Nowa	**Forestech**	**104**	**42**	40.8	9.5	12.6	1	0.2	10	80	2
Orbost	**Raynor**	**104**	**43**	**41.3**	**8.8**	36.0	**2**	**0.7**	**30**	360	4

Table 5 shows a comparison of the predicted and actual Drought Factor (or amount of fine fuel available for burning). It shows that generally the actual amount of fine fuel available for burning was greater than that indicated by the predicted Drought Factor.

Table 5 Predicted and actual Drought Factor (% of fine fuel available for burning) for all test fires for the 2001/02 and 2002/03 burning seasons

Fire District	Fire/FRB name	Predicted Drought Factor	% unburnt	Actual Drought Factor
Nowa Nowa	Oak Tk	5	24.1	7.5
Nowa Nowa	Oak Tk	5	32.0	6
Heyfield	Roberts Rd	6	6.3	9.5
Heyfield	Roberts Rd	6	7.9	9
Heyfield	Roberts Rd	6	9.0	9
Heyfield	Roberts Rd	6	9.0	9
Nowa Nowa	Moonlight	6	14.3	8.5
Nowa Nowa	Spankers	9	12.1	9
Nowa Nowa	Spankers	9	11.2	9
Nowa Nowa	Spankers	9	16.4	8.5
Bairnsdale	Waterfords	7	11.5	9
Bairnsdale	Waterfords	7	16.7	8.5
Bairnsdale	Waterfords	7	15.7	8.5
Nowa Nowa	Ironstone	7	15.6	8.5
Nowa Nowa	Ironstone	7	24.4	7.5
Nowa Nowa	Ironstone	7	25.9	7.5
Erica	O'Keefe	7	10.8	9
Erica	O'Keefe	7	21.0	8
Erica	O'Keefe	7	50.3	5
Erica	O'Keefe	7	33.0	7
Bulga	Martindale	10		8.4
Daylesford	Blakeville FESA		8.3	9.2
Daylesford	Barkstead FESA		7.0	9.3
Daylesford	Kang Ck FESA		7.2	9.3
Daylesford	Musk Ck FESA		3.6	9.6
Daylesford	Burnt Bridge FESA		8.8	9.1
Nowa Nowa	Frog Hop	8	20.7	7.5
Swifts Ck	Steenholdt	9	9.7	9
Orbost	Rodger	10	7.8	9.2
Orbost	Majors Ck	8	46.8	5.5
Nowa Nowa	Forestech	10	42.4	5.9
Orbost	Raynor	7.5	41.3	6

Correlation of fuel consumption with fuel moisture, fire behaviour and topography factors

The variation in actual consumption of fine fuel was best explained by variations in:

the profile fuel moisture content (FMC),
the flame height,
the presence of a headfire or a backing fire,
and the slope of the site.

The exposed surface FMC and the Predicted Drought Factor did not show any significant correlation with the variation in fuel consumption.

The following equation describes the most significant three factor model for explaining variations in fuel consumption from the factors described above:

% unburnt= 0.79*FMCprof + 16.9*backfire - 14.2*flameht + 11.8 (*Equation 1*)

(Model: n = 32, r^2=0.78, p < 0.001)

(Where % unburnt = % of fine fuel remaining after test fire;
FMCprof = fuel moisture content of profile fuels,
backfire = presence of backing fire,
flameht = average flame height across the sample area;

Variable	Co-eff.	(std error)	p value
FMCprof	0.79	0.1	<0.01
backfire	16.9	3.0	<0.01
flameht	-14.2	3.8	<0.01

A second three factor model, using slope instead of the headfire/backfire variable, was able to explain 72% of the variation in the data. This model may be more useful as slope is a continuous variable.

% unburnt= 0.71*FMCprof - 21.4*flameht -0.56* slope + 24.3 (*Equation 2*)

(Model: n = 32, r^2=0.72, p < 0.001)

(Where % unburnt = % of fine fuel remaining after test fire;
FMCprof = fuel moisture content of profile fuels,
flameht = average flame height across the sample area;
slope = average slope across the sample area

Variable	Co-eff.	(std error)	p value
FMCprof	0.71	0.1	<0.01
flameht	-21.4	4.8	<0.01
slope	-0.56	0.1	<0.01

Figure 6 A typical headfire produced by prescribed burning. With drier profile FMCs, higher flame heights and reduced flame angles will increase the consumption of fine fuels.

Figure 7 A typical backing fire produced by prescribed burning. Low flames heights and flame angles > 90^0 to the unburnt fuel bed will reduce the consumption of fine fuels, even with relatively dry profile FMCs.

DISCUSSION

As this study progressed it became apparent that fire intensity was almost as significant an influence on fuel consumption as was fuel moisture content. Thus the factors which contributed to greater fire intensity - presence of headfire, steeper slope, following wind - seemed to make a significant difference to the amount of fine fuel which was consumed (for roughly the same fuel quantity and arrangement). Headfire on steeper upslopes always appeared to consume the most fine fuel, whereas backing fire with adverse slope usually appeared to consume the least fine fuel.

The effect of slope was significant. Positive slope generally contributed to greater fire intensity (i.e. greater flame height and greater forward rate of spread). The principal reason for this was flame angle. The effect of slope is particularly important in reducing flame angle, thereby allowing greater preheating fuels ahead of the flame front, thus drying them out and making them available to burn more completely.

At the Waterfords Road FRB, a headfire on a steep (20^0+) southern aspect managed to consume roughly the same amount of fine fuel as headfires on the adjacent flatter northern aspects, despite higher profile fuel moisture contents.

The effect of aspect was less important than that of slope, although fuels were mostly drier (particularly profile fuels) on northern and western aspects in comparison with southern and eastern aspects. Drier fuel meant more fine fuel consumption, for the same fire behaviour inputs, so aspect had some influence this way.

The variation of fuel consumption with slope and fire behaviour was best observed at the O'Keefe FRB in the Erica Fire District. This site was the steepest sampled for the 2001/02 burning season. Headfire on the steep northern aspect here consumed roughly 90% of the fine fuel. This consumption reduced to about 85% on the same northern aspect with headfire, but with little slope. Very low backing fire on the adjacent southern aspect (with higher profile fuel moisture contents) only consumed about 50% of the fine fuel. Slightly more intense backing fire on the same southern aspect consumed about 70% of the fine fuel. The predicted Drought Factor for this fire was 7. The observed fuel consumption clearly showed that headfire on steeper slopes could easily exceed this Drought Factor prediction of 7 (70% of the fine fuel being available to burn) by a factor of 20 % or greater.

The influence of profile fuel moisture was significant, but a model for predicting consumption of fine fuel using profile fuel moisture content only, could only explain about 35% of the variation in the data The models shown in Equations 1and 2, using fire behaviour inputs as well, were able to explain about 78% , and 72% respectively, of the variation in the data. Therefore a model for fuel consumption should include these inputs.

Surface fine fuel moisture content did not show any direct correlation with fine fuel consumption. However it is known that surface fuel moisture content has a direct influence on fire behaviour (McArthur 1973, Luke and McArthur, 1978, Tolhurst and Cheney 1999). Surface fuels must be below about 16% ODW for useful prescribed burning. The highest surface FMC for any of the fires studied was 13.5 %ODW, with the average being 10.5 % ODW. Therefore all the fires studied were at surface FMCs which allowed for free burning of the surface fuels. The difference between surface FMC and profile FMC did show significant correlation with fuel consumption. This indicates that the absolute value of surface FMC is important to whether surface fuels burn freely, and that it's value relative to profile FMC is important to fine fuel consumption.

The most significant effect of high profile fuel moisture content on fuel consumption was observed at the Majors Creek Fire near Orbost in March 2003. This fire started from a lightning strike which occurred late in the evening. Rain associated with this lightning storm dampened the fuels such that there was little progress of the fire until the following day. Wind on this following day pushed the fire along, causing headward spread of about 700 m over three hours. Although this fire spread quite effectively, very high profile fuel moistures caused there to be relatively low consumption of fine fuels.

The observation which best highlighted the effect of slope/flame angle on fine fuel consumption at low profile FMCs, occurred at the Martindale Fire in the NSW Hunter Valley in January 2002. Despite very low surface and profile FMCs, a downslope backing fire was only able to consume about 84% of the available fine fuel. A flame angle of 110^0 to 140^0 to the unburnt fuel was able to inhibit pre-heating, to the extent where a further 5-10% of the fine fuel was left unburnt than would be expected (i.e. when compared to sites burnt with a headfire).

Flame residence time had little influence on fine fuel consumption. Although backing fires gave longer flame residence times over any section of the litter bed, this did not mean that fine fuel consumption increased. This seems counter intuitive. However the results show that higher flames were always associated with higher consumptions of fine fuel. Therefore flame height, along with fuel moisture and flame angle, appear to have much more influence on fine fuel consumption than residence time.

The finding that the calculated (McArthur) Drought Factor gave an underprediction of actual fine fuel consumption, for the drier forests in Gippsland in the autumn, does not agree with the findings of Tolhurst *et al.* (1992). These authors studied fine fuel consumption associated with autumn and spring prescribed fires in the Wombat Forest in Central Victoria. They found that, for both spring and autumn prescribed fires, the calculated Drought Factor consistently over-estimated the actual consumption of fine fuels, with this over-estimation being higher in the spring fires.

The important site, weather and ignition technique differences which may explain this inconsistency are:
- these higher elevation damp forests (i.e. the Wombat) often have higher crown cover values than drier forests in Gippsland. These higher cover values give slower drying for roughly the same weather inputs. Hence the Wombat Forest profile fuels may be damper (at similar times) and may give slightly less fine fuel consumption, even at similar fire behaviour levels;
- secondly, for the Spring fires, the Wombat Forest has generally deeper litter beds than the drier forest in Gippsland. Moist soil will keep these deeper litter beds moister for longer during the Spring. Higher profile fuel moisture contents will mean less fine fuel consumption;
- thirdly, most of these autumn fires in Gippsland were lit with the deliberate intention of producing the biggest flames possible. The Wombat burns were deliberately restrained to imitate low intensity fuel reduction burns. Therefore the Gippsland burns had a much greater chance of producing fine fuel consumptions which were above the predicted Drought Factor.

The McArthur Drought Factor was developed in the dry, cool forest around Canberra. The differences in prediction found when it is shifted to the coastal forest of Gippsland, or to the plateau forest of Central Victoria, may be partly due to site and fuel differences. However it is unlikely that McArthur intended the Drought Factor model to be much more than an approximation of what might happen to fine fuel consumption for various combinations of seasonal dryness and short term rainfall, in a variety of locations.

He was undoubtedly more concerned with being able to tell when drought and recent rain (or lack of it) would combine to give high fine fuel availabilities during the summer - and hence higher levels of fire behaviour that may defeat suppression efforts.

The findings of this study indicate that actual fine fuel consumption can be better predicted by measuring profile fuel moisture content directly. This is now possible due to the development of the Wiltronics TH Fine Fuel Moisture Meter. Although it may be more convenient to calculate the Drought Factor from existing temperature and rainfall records, direct measurement and monitoring of profile FMCs will provide better answers for likely fine fuel consumption. This would in turn provide a better prediction of fire danger.

That is, instead of calculating the McArthur Drought Factor, an equivalent Drought Factor could be derived from measurement of profile fuel moisture content, and prediction of fire behaviour from fuel hazard (litter bed height for surface fine fuel - McCarthy 2003 in prep.) and site(slope/aspect). This equivalent Drought Factor would then be put back into the McArthur modelling for prediction of FDI.

As outlined in the Methods, Drought Factor was derived using the McArthur Mk V Forest Fire Danger Meter directly. However most fire control agencies across Australia rely on automated calculations of the Drought Factor using one of the three main algorithm-based systems - Noble, Bary & Gill (1980), Griffiths (1999) or Bally (1989). Calculation using these methods may produce Drought Factor values which vary from that derived by using the McArthur Meter directly. However it is likely that this variation will not be large enough to have significant impact on the subsequent calculation of the FDI. A CSIRO report for the Bureau of Meteorology (CSIRO, 2001) recommends that the method which produces the best approximation of the McArthur Meter is that of Bally (1989).

For future work on fine fuel consumption, there are clearly two aspects of this work which require further investigation:

1. Sample at wildfires at higher FDIs
As the majority of data in this study came from observations of prescribed fires, there is clearly a need to look at wildfires at higher FDIs. Additionally, it would be useful to include variations in profile FMCs as well as higher FDIs. These higher profile FDIs may result from rainfall either just before, or just after, the wildfire event. This additional data would enhance the application of the models for a greater range of fuel and weather conditions.

2. Sample bark and elevated fuel consumption
Past work (McCarthy et al. 1999, McCarthy and Tolhurst 1998) indicates that bark and elevated fuels provide more difficulties for fire suppression than surface fuels. Assessing bark and elevated fuel consumption, for a range of fuel, fire behaviour and fuel moisture conditions, would allow models to be built for predicting consumption of these vertically arranged fuel elements. This should assist fire managers charged with the responsibility of managing fuel levels across the landscape, and particularly in urban interface areas.

CONCLUSIONS

Fine fuel moisture content of profile fuels has a significant influence on fine fuel consumption, but a fuel consumption model using FMC alone (e.g. the McArthur Drought Factor model) cannot adequately predict the likely variation in fine fuel consumption.

FMC of surface fuel is less important to consumption of fine fuel, but still has strong influence on fire behaviour. This effect on fire behaviour directly affects fine fuel consumption through changes in fire intensity.

Flame height and slope, in addition to profile FMC, have significant influences on fine fuel consumption, and have been included in predictive models for fine fuel consumption.

Fine fuel consumption can be underpredicted by the current Drought Factor model in the McArthur Meter Mk. 5 for fires in drier foothill forest (e.g. East Gippsland coastal and foothill forest) in the Autumn.

Fine fuel consumption can be overpredicted by the current Drought Factor model for fires in moist foothill forest (e.g. the Wombat Forest) in the Autumn. Overprediction becomes more pronounced with Spring fires, where moist soil and high profile FMCs can significantly reduce fuel consumption.

Headfires, resulting from wind and/or slope, and with flame angles less than 90^0 to the unburnt fuel, generally increase fine fuel consumption. Backing fires, with lower flame heights and flame angles greater than 90^0, generally decrease fine fuel consumption, despite longer residence times.

Fire danger rating (McArthur FDI) could be improved by using an equivalent Drought Factor. This equivalent Drought Factor would based on: measurement of profile FMC (Wiltronics Meter); prediction of flame height (from litter bed height); and slope.

REFERENCES

Chatto, K. and Tolhurst, K.G. (1997) The Development and Testing of the *Wiltronics T-H Fine Fuel Moisture Meter*. Research Report No.46. Fire Management, Dept of Natural Resources and Environment, Vic.

CSIRO (2001) Review of the Operational Calculation of McArthur's Drought Factor. Report prepared for the Austn.Commonwealth Bureau of Meteorology. CSIRO Client Report No. 921 prepared by Andrew Sullivan.

Griffiths, D. (1999) Improved formula for the Drought Factor in McArthur's Forest Fire Danger Meter. *Australian Forestry*, **62**(2):202-206.

Luke, R.H. and McArthur, A.G., (1978) Bushfires in Australia. Australian Govt. Publishing Service. Commonwealth of Australia, Canberra. 359 pp.

McArthur, A.G. (1973) Forest Fire Danger Meter Mk. 5. Commonwealth of Aust. Forestry and Timber Bureau.

McCarthy, G.J. (2003) Fuel Hazard rating for Forest Fuels - Surface Fine Fuel Hazard. Research Report No. 44. Fire Management Branch, Dept. of Natural Resources and Environment, Vic.

McCarthy, G.J. and Tolhurst, K.G. (1998) Effectiveness of Fire-fighting First Attack Operations, DNRE Victoria 1991/92-1994/95. Research Report No. 45. Fire Management Branch. Dept of Natural Resources and Environment, Vic.

McCarthy, G.J. and Tolhurst, K.G. (2001) Effectiveness of Broad Scale Fuel Reduction Burning in Victoria. Research Report No.51. Fire Management. Dept of Natural Resources and Environment, Vic.

McCarthy, G. J., Tolhurst, K.G., and Chatto, C. (1999) Overall Fuel Hazard Guide. 3rd Edition. Research Report 47. Fire Management. Dept. of Natural Resources and Environment Vic.

McCarthy, G.J. (2003, in prep.) Fuel Hazard rating for Forest Fuels - Surface Fine Fuel Hazard. Research Report No. 44 (?). Fire Management Branch, Dept. of Natural Resources and Environment, Vic.

Noble ,I.R., Bary, G.A.V. and Gill, A.M. (1980) McArthur's fire danger meters expressed as equations. *Australian Journal of Ecology*, **5**:201-203

Tolhurst, K.G., Kellas, J.D. and Wilson, A.A.G. (1992) Low Intensity Fire Behaviour and Fuel Dynamics in Dry Sclerophyll Forest, Wombat State Forest. In: Tolhurst, K.G. and Flinn, D.W. (1992) Ecological Impacts of Fuel Reduction Burning in Dry Sclerophyll Forest. Research Report No. 349. Forest Research, Dept. of Conservation and Natural Resources, Vic. 40pp.

Tolhurst, K.G. and Cheney, N.P. (1999) Synopsis of the Knowledge Used in Prescribed Burning in Victoria. Dept. of Natural Resources and Environment. Victoria. 97 pp.