Evaluation of a Dynamic Load Transfer Function Using Grassland Curing Data

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***Abstract**—Understanding and calculating fire behaviour in various fuel types is essential for effective fire management, including wildfire suppression and fuels management. Fire spread in grassland fuel is affected by the curing level, the amount of dead fuel expressed as a percentage of the total (live and dead fuel combined). The influence of live fuel is included in various fire models in different ways. U.S. fire behavior prediction systems are based on Rothermel's fire spread model, which uses the load of live and dead fuel and the moisture content of each. Dynamic fuel models include a transfer of fuel load from the live to dead class as a function of live fuel moisture. Australian and New Zealand grassland fire behavior models rely heavily on the curing level as a major determinant of the ability for a fire to develop and spread, and place greater direct emphasis on both the proportion and moisture content of the dead fine fuels. A joint Australian and New Zealand study under the Australian Bushfire Cooperative Research Centre (CRC) is addressing various methods of assessing curing levels in grasslands. Data from that study are used to evaluate the dynamic fuel load transfer function used in fuel models developed for the Rothermel spread model. Results showed that live fuel moisture is not an indicator of level of curing. A significant difference is demonstrated in calculated rate of spread using the load transfer model versus direct entry of live fuel moisture and level of curing.*

Introduction

Fuels management planning often involves modeling potential fire behavior to identify areas of risk, assess hazard, and evaluate the effectiveness of various fuel treatment options. Fire behavior for a given fuel type can be modeled under a range of weather conditions and seasonal changes. Fire behavior modeling supports other aspects of fire management including suppression, prevention, and prescribed fire.

Fire behavior is influenced primarily by the fuel type (grass, shrub, etc.), fuel condition (moisture content, percentage of dead fuel), wind speed, and slope. The moisture content of fine dead fuel varies diurnally in response to changes in temperature, humidity, solar radiation, and rainfall. Live fuel moisture changes seasonally due to the physiology of the plant and its response to seasonal weather conditions. Seasonal curing of live herbaceous plants leads to a change in the ratio of dead to live material in the fuel complex, commonly referred to as level of curing. Live fuel plays an important role in determining the behavior of grassland fire (Cheney and Sullivan 1997, Cheney and others 1998). The level of curing has a major effect on grass fire behavior, in particular fire spread (Alexander 1993, Anderson and Pearce 2003).

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The influence of live fuel is incorporated into fire behavior models in several ways. The fire models used in New Zealand and Australia place the emphasis on level of curing, whereas U.S. models utilize live fuel moisture. New Zealand uses the Canadian grassland fire behavior models from the Canadian Fire Behavior Prediction System based on data collected in Australia (Forestry Canada Fire Danger Group 1992). There are models for cut or matted grass and for natural standing grass.

In Australia a fire model has been developed for grassland (three defined pasture types) by Cheney and others (1998) to replace existing models based on the McArthur Mark 3 and Mark 5 Fire Danger Meters (McArthur 1966, McArthur 1977) and provided in equation form by Noble and others (1980). Although the fire models used in New Zealand and Australia are quite different, they both predict fire spread in grasslands from fine dead fuel moisture, wind speed, and degree of curing.

Fire behavior prediction systems in the U.S. are based on Rothermel's (1972) surface fire spread model. Calculations are based on a description of the fuel, fuel moisture content of each size class of dead and live fuel, wind speed, and slope. The fire model itself does not include the influence of curing. Dynamic fuel models are used as a means of modeling changes in fire behavior that occur as herbaceous fuels cure and die.

In this paper we evaluate the dynamic load transfer function that is part of fuel models developed for use with Rothermel's surface fire spread model (Scott and Burgan 2005). We compare the load transfer model predictions with field sampled grassland curing data and we examine the influence of the load transfer function on rate of spread calculations.

Grassland Curing Study

Grassland curing data are being collected as part of an ongoing study under the Australian Bushfire Cooperative Research Centre (CRC): "Improved Methods for the Assessment and Prediction of Grassland Curing" (www.bushfirecrc.com). Grass curing describes the annual or seasonal cycle of grasses dying and drying out following flowering. Degree of curing refers to the proportion of cured (dead) material in grasslands, expressed as a percentage of the total grassland fuel complex (live and dead material). It is a critical input to grassland fire behavior and fire danger models used in Australia and New Zealand. Current curing inputs are often inaccurate, leading to incorrect determination of grassland fire danger levels and potential fire behavior. Many important fire management decisions and strategies are based upon this grassland fire behavior information, and fire managers need access to accurate and reliable information to protect life and property.

The degree of curing is currently assessed visually or by satellite remote sensing using an index based on the reflective properties of grasses at different wavelengths. Visual assessment is often inaccurate, sometimes differing vastly from the actual curing value obtained from destructive sampling. Problems include difficulties obtaining and extrapolating estimates over large areas, experience of observers, calibration of visual assessments, and timing and frequency of observations (Anderson 2005, Anderson and Pearce 2003, Millie and Adams 1999).

Remote sensing is used to assess curing levels in grasslands over parts of Australia (Paltridge and Barber 1988, Barber 1990, Allan and others 2003). However, the algorithms developed have had little validation outside of southern Australia, and there are issues with the accuracy of the technique due to atmospheric conditions and lack of uniformity of grasslands within pixels.

The Bushfire CRC project is examining improved remote sensing approaches, and will also include evaluation and modification of agricultural pasture growth models for curing determination. These models account for environmental and physiological factors regulating grass growth. An Australasian-wide field sampling program is providing data for development and validation of techniques. We used preliminary field data for this analysis.

Destructive sampling of grasses is the most accurate method of collecting curing data, but is not practical to implement on a large scale. It is labor-intensive to collect and process destructive samples, and there are further issues with obtaining spatially-representative samples of curing across the landscape.

Curing data in the CRC study were obtained by destructive field sampling. Sampling quadrats were located along two transects at right angles to each other and a total number of approximately five samples were collected. For each sample, all the vegetation from within a 0.25m² frame was clipped with shears to the ground level and removed and placed in a bag. In the laboratory, the samples were then separated into live and dead material, oven dried at 100°C for 24 hours and then weighed. The degree of curing was then determined by calculating the percentage of dead material expressed as a percentage of the total (live and dead) material.

Samples of live, dead, and combined fuel moisture were also collected in the field, to investigate the feasibility of using grass fuel moisture data to calculate curing percentage, assuming that the moisture status of the grasses represents a live or dead state. Live and dead fuel moisture samples were collected randomly from within the curing sampling area, sealed in tins, weighed, oven-dried for 24 hours at 100°C and reweighed. The moisture content of the combined (live and dead) fuel was calculated using the material collected as part of the destructive sample from the 0.25m² sampling frame. Collecting representative fuel moisture data in the field can be difficult. Live moisture varies by the part of the plant and the stage of growth as well as by grass species. For example on the same date and location Australian native grass may have a moisture content of 125% while improved pasture has a moisture content of 250%.

Table 1 shows the data from the grassland curing study used in this analysis. There are ten sites, three in New Zealand and seven in Australia. The type of grass and level of grazing is noted for each. The grass is characterized by loading and height. The date of each of the fourteen sample data points is given with the live fuel moisture and level of curing.

Dynamic Load Transfer Function

The dynamic load transfer function is part the of dynamic fuel models developed for use with Rothermel's (1972) surface fire spread model. Dynamic fuel models are used as a means of modeling changes in fire behavior that occur as herbaceous fuels cure and die. The fire model itself does not include the influence of curing. Calculations in Rothermel's fire model are based on fuel model, fuel moisture content of each size class of dead and live fuel, wind speed, and slope. A fuel model is a set of intrinsic fuel parameters that are required by the fire model.

Table 1—Data from the Australian Bushfire Cooperative Research Centre (CRC) study: "Improved Methods for the Assessment and Prediction of Grassland Curing."

	Site description				Sample data		
Location*	Grass type**	Grazing***	Total fuel load	Grass height	Date	Live fuel moisture content	Level of curing
			(ton/acre)	(ft)		---------(%)	----------
Monaro	IP	UG	3.8	1.1	8/8/2005	211	93
Monaro	IP	UG	3.6	1.1	9/6/2005	270	91
Fisher	IP	LG	1.4	1.5	8/18/2005	315	87
Majura	IP	UG	1.5	2.3	1/16/2006	92	79
Majura	IP	UG	1.2	2.3	2/22/2006	113	71
Umbigong	NG	LG	2.2	0.8	8/30/2005	124	92
Tidbinbilla	IP	HG	0.6	0.7	1/24/2006	152	99
Braidwood	IP	LG	1.0	0.7	1/5/2006	142	80
Braidwood	IP	LG	0.7	0.7	2/14/2006	192	84
Milton	IP	UG	7.0		9/12/2005	331	72
Darfield	IP	LG	1.1	0.5	9/16/2005	292	58
Darfield	IP	LG	0.7	0.5	2/20/2006	320	86
Godley Head	IP/NG	UG	4.1	1.0	9/17/2005	234	80
Lake Lyndon	IP/NG	UG	2.3	0.8	2/14/2006	165	70

*Darfield, Godley Head, and Lake Lyndon are in New Zealand; the rest are in Australia.
**IP = Improved Pasture; NG = Native Grass.
***UG = Ungrazed; LG = Lightly Grazed; HG = Heavily Grazed.

The standard set of 13 fire behavior fuel models, which has been widely used since 1976, are static; fuel model parameters do not change (Albini 1976, Anderson 1982). Dynamic fuel models, on the other hand, include the dynamic load transfer function which changes the fuel description by moving some of the load from the live category to dead. Although rarely used, the option of developing dynamic custom fuel models was available in the BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984). Seventeen of the recently developed set of 40 standard fuel models are dynamic (Scott and Burgan 2005). These 40 fuel models were designed to represent a wider range of fuel types than the set of 13, and have been implemented in the BehavePlus fire modeling system (Andrews and others 2004), the FARSITE fire area simulator (Finney 1998), and other fire behavior prediction systems in the U.S.

The dynamic fuel load transfer function is shown in figure 1. Load is transferred from the live herbaceous class to dead as a function of live fuel moisture. The same relationship is used for all dynamic fuel models.

- For live herbaceous fuel moisture content of 120 percent or higher, most of the herbaceous fuels are assumed to be green, and the initial live herbaceous load for the fuel model stays in the live category.
- For live fuel moisture of 30 percent or lower, the herbaceous fuels are considered fully cured, and all live herbaceous load is transferred to the dead category.
- For live fuel moisture between 30 and 120 percent, part of the live herbaceous load is transferred to dead. For example, if live fuel moisture is 75 percent (halfway between 30 and 120 percent), half of the initial live herbaceous load is transferred to dead herbaceous, the remainder stays in the live herbaceous class.

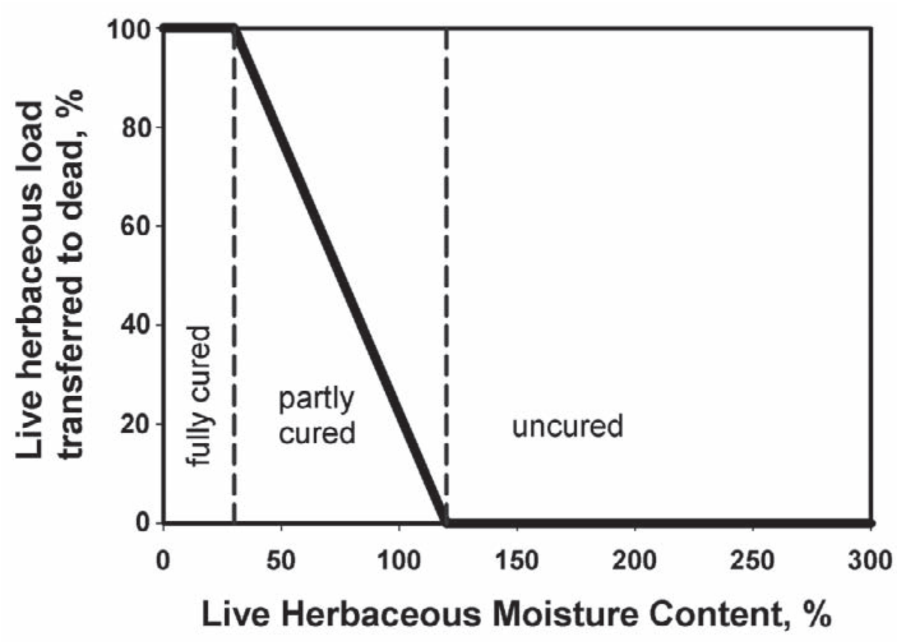

Figure 1—Percent of the live herbaceous fuel load that is transferred to the dead category (Burgan 1979). There is dead fuel in the fuel model when the percent is zero, for the section of the graph labeled "uncured."

Table 2 gives the parameters for the standard fire behavior fuel models applicable to grasses. Fuel models 1, 2, and 3 are from the original set of 13 and are static. Fuel models GR1 through GR9 are dynamic fuel models from the set of 40. The listed fuel loadings for the dynamic fuel models are the values before the fuel load transfer function is applied. The percentage of the total load that is dead fuel prior to load transfer is also given on the table. Scott and Burgan (2005) refer to the percent load transferred as *curing percent*, and say that the parameters on the table are for *uncured* fuel. There is, however, dead fuel in the fuel models even before any load is transferred from live to dead. As an illustration of the difference between percent load transferred and percent dead, table 2 gives the percent dead at 50 percent load transferred. Fuel model GR2 is 63 percent dead (63 percent cured) when 50 percent of the load is transferred from live to dead. In Australasian and Canadian fire behaviour models, degree of curing in grasslands is defined as percent dead. For this paper, we use the terminology "percent load transferred" where Scott and Burgan used the term "percent cured".

As an illustration of the effect of live fuel moisture for static and dynamic fuel models, the BehavePlus fire modeling system was used to compare calculated rate of spread using Rothermel's fire spread model for seven fuel models under the same wind and fuel moisture conditions (5 percent dead fuel moisture, 5 mi/h wind, no slope) (figure 2). Fuel models 1 and 3 have no live fuel, so rate of spread is not affected by a change in live fuel moisture. Fuel model 2 is a static model with a live fuel component. The effect of live fuel moisture is therefore limited to the relationships in the original formulation of the Rothermel (1972) fire model. Fuel models GR1, GR2, GR4, and GR7 are dynamic. Live fuel moisture is not only used in the rate of spread

Table 2—Load and depth for grass fire behavior fuel models. Percent dead for no load transfer and for 50% load transfer from live herbaceous to dead are given to illustrate the difference between percent load transferred and percent dead.

Fuel model		Fuel model parameters						
		Fuel load (ton/ac)				Depth	Percent dead fuel	Percent dead at
		1-h	10-h	100-h	live herb	(ft)	prior to load transfer	50% load transfer
1	Short Grass	0.74				1.0	N/A	N/A
2	Grass and timber understory	2.0	1.0	0.5	0.5	1.0	N/A	N/A
3	Tall Grass	3.0				2.5	N/A	N/A
GR1	Short, Sparse, Dry climate	0.1			0.3	0.4	25.0	63
GR2	Low Load, Dry Climate	0.1			1.0	1.0	9.1	55
GR3	Low Load, Very Coarse, Humid Climate	0.1	0.4		1.5	2.0	6.3	63
GR4	Moderate Load, Dry Climate	0.25			1.9	2.0	11.6	56
GR5	Low Load, Humid Climate	0.4			2.5	1.5	13.8	57
GR6	Moderate Load, Humid Climate	0.1			3.4	1.5	2.9	51
GR7	High Load, Dry Climate	1.0			5.4	3.0	15.6	58
GR8	High Load, Very Coarse, Humid Climate	0.5	1.0		7.3	4.0	6.4	59
GR9	Very High Load, Humid Climate	1.0	1.0		9.0	5.0	10.0	59

calculations according to the fire spread model, but also to change the fuel model according to the fuel load transfer function. For fuel model GR7 under the specified dead moisture and wind conditions, there is a four-fold increase in calculated rate of spread as live fuel moisture decreases from 100 to 75 percent; and rate of spread increases by a factor of 2.4 for the very small change in live fuel moisture from 100 to 95 percent. In his paper "Sensitivity of a fire behavior model to changes in live fuel moisture" Jolly (2005) found that the grass fuel models within the set of 40 new fuels showed the highest sensitivity to live fuel moisture changes. They were most sensitive to changes in live fuel moisture from 90 to 100%.

The fuel load transfer function was developed as part of a live fuel moisture model developed by Burgan (1979) for use in the U.S. National Fire Danger Rating System (Deeming and others 1977). The load transfer function is a conceptual model; development was not based on live fuel moisture and

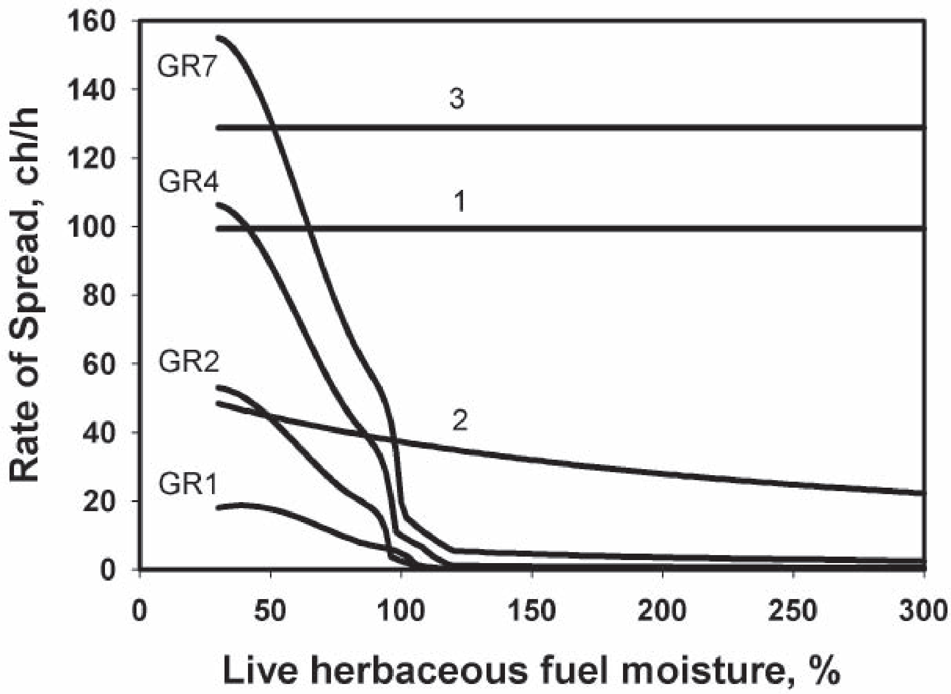

Figure 2—Comparison of calculated rate of spread for seven fuel models to illustrate sensitivity to live fuel moisture for static (1, 2, 3) and dynamic (GR1, GR2, GR4, GR7) fuel models. Dynamic fuel models include the use of the load transfer function.

curing data. The live fuel moisture range of 30 to 120 percent was defined as the transition stage because 120 percent "roughly defines the moisture content at which new growth is complete and the foliage is mature." Thirty percent was defined as the minimum moisture for transition because "that is the approximate fiber saturation point, below which plants are assumed to be dead." The fuel load transfer function has not previously been evaluated using field data.

Results

Table 3 gives the sample data for live fuel moisture and level of curing, and the model values for percent load transferred and percent dead calculated from the sampled live fuel moisture. We compare the sampled and modeled level of curing (percent dead). A fuel model was assigned to each sample site based primarily on the fuel loadings of the sample data in table 1. The Milton site in coastal Australia was the only one designated as humid. Only three of the fourteen sample points had live fuel moisture content below 120 percent. According to the dynamic fuel load transfer function, moisture above 120 percent indicates no load is transferred from live to dead. The modeled percent dead for the fuel models is calculated from the percent dead for the fuel model before the load transfer (see table 2) and the percent transferred from live to dead according to the dynamic load transfer function.

Table 3—Fuel models were assigned to each site primarily based on fuel loading. Field data includes live fuel moisture and level of curing (percent dead). The fuel load transfer function is used to calculate percent load transferred for the associated live fuel moisture value. Percent dead is affected by the fuel model (see table 2).

		Sample data		Model values	
Location	**Fuel model**	**Live fuel moisture content**	**Level of curing**	**Percent load transferred live to dead**	**Percent dead**
		- - - - - - - - - (%) - - - - - - - - -			
Monaro	GR7	211	93	0	15.6
Monaro	GR7	270	91	0	15.6
Fisher	GR4	315	87	0	11.6
Majura	GR4	92	79	34.5	42.1
Majura	GR4	113	71	12.1	22.3
Umbigong	GR4	124	92	0.5	12.0
Tidbinbilla	GR1	152	99	0	25.0
Braidwood	GR1	142	80	0	25.0
Braidwood	GR1	192	84	0	25.0
Milton	GR8	331	72	0	6.4
Darfield	GR2	292	58	0	9.1
Darfield	GR2	320	86	0	9.1
Godley Head	GR7	234	80	0	15.6
Lake Lyndon	GR4	165	70	0	11.6

Figure 3 is a plot of the sample data, level of curing (percent dead) vs. live fuel moisture, with an indication of the assigned fuel model. The dynamic fuel load transfer function is used to plot percent dead for each fuel model. Figure 4 is a plot of predicted and observed level of curing (percent dead). The lowest observed curing level was 58 percent while the highest predicted value was 42 percent. A simple look at the plots precludes the need for a statistical analysis.

The load transfer function is based on the assumption that fuel is "uncured" when live fuel moisture is over 120 percent. Note that a significant amount of the grass fuel load is dead at high live fuel moisture values. For example, the live fuel moisture content was 315 percent for the Fisher site, corresponding to a measured 87 percent curing level. The load transfer function gives no load transfer and 11.6 percent dead fuel for fuel model GR4 and live fuel moisture 315 percent.

It is apparent that there is no useful relationship between live fuel moisture and curing level for this data. We conclude that for this data set, live fuel moisture is not an indicator of level of curing.

Influence on Rate of Spread Calculations

The dynamic load transfer model is an intrinsic part of dynamic fuel models. Given that we have shown that live fuel moisture may not be an indicator of curing, we examine the option of independent specification of live fuel moisture and curing level.

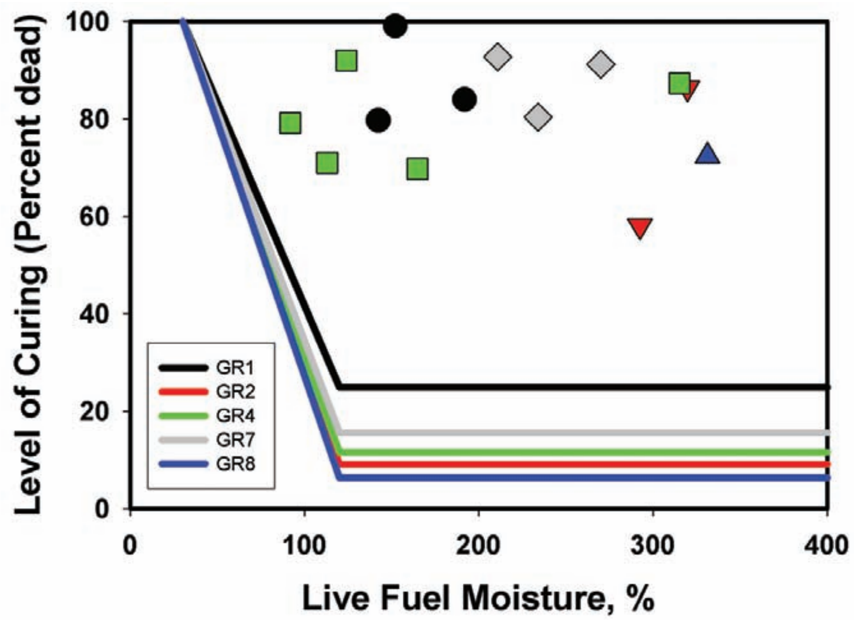

Figure 3—Australian and New Zealand live fuel moisture and curing data compared to the dynamic load transfer function. There is a different curve for each fuel model because of the dead fuel in the fuel models when there is zero load transferred from live to dead. The sample data points are from table 3.

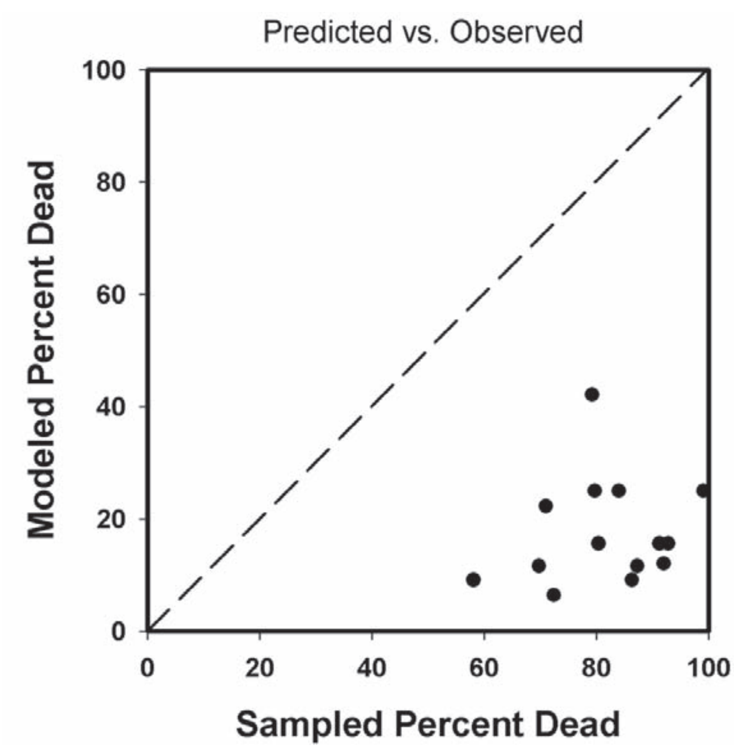

Figure 4—Predicted vs. observed level of curing (percent dead). Data are from table 3.

As a means of dealing with the required relationship between curing and live fuel moisture, Scott and Burgan (2005) give the following guidance in use of the dynamic fuel models: "It will often be preferable to estimate live herbaceous moisture content by working backward from observed or estimated degree of herbaceous curing. For example, if the fuelbed is observed to be 50 percent cured, use a value of 75 percent for live herbaceous moisture content." A user who knows both live fuel moisture and curing level must choose which to use. It is not possible, for example, under the current formulation, to calculate rate of spread for live fuel moisture of 200 percent and 50 percent cured. (Recall that Scott and Burgan use the term percent cured for the percent load transferred from live to dead rather than the percent dead.)

Table 4 shows the live fuel moisture values that correspond to 100, 75, 50, 25, and 0 percent load transferred according to the function. The calculated rate of spread for fuel model GR4 (5 percent dead fuel moisture, 5 mi/h wind, and no slope) is given for each and indicated on the curve in figure 5. For example, live fuel moisture of 75 percent and a 50 percent load transfer gives rate of spread of 53 ch/h. These calculations are as implemented in the BehavePlus fire modeling system using the dynamic fuel models as described by Scott and Burgan.

Consider the effect of not using the dynamic load transfer function, but rather directly supplying values for live fuel moisture and load transfer percent. Table 5 shows calculated rate of spread for a range of live fuel moisture values and load transfer levels. The highlighted values in table 5 correspond to those in table 4 and are indicated on figures 6 and 7. Figure 6 is rate of spread for five levels of load transfer for a range of live fuel moisture. The curves in figure 6 correspond to the columns in table 5. For a fixed load transfer of 50 percent, live fuel moisture from 30 to 300 percent results in rate of spread from 11 to 90 ch/h. Similarly, figure 7 is rate of spread for seven levels of live fuel moisture for a range of load transfer values. The curves in figure 7 correspond to the rows in table 5. For a fixed live fuel moisture of 75 percent, load transfer from 0 to 100 percent results in rate of spread from 2 to 110 ch/h. There is a significant difference between the results using the dynamic load transfer function and specifying live fuel moisture and curing independently.

Table 4—Live fuel moisture and percent load transferred from live to dead according to the dynamic load transfer function. Associated calculated rate of spread for fuel model GR4, 5 percent dead fuel moisture, 5 mi/h midflame wind, and no slope. The five highlighted rate of spread values are shown in figure 5.

Live fuel moisture	Load transferred live to dead*	Rate of spread
- - - - - - - - -	*(%)* - - - - - - - - -	*(ch/h)*
30	100	**110**
53	75	**87**
75	50	**53**
98	25	**11**
120	0	**1**
200	0	1
300	0	1

*Referred to as percent cured by Scott and Burgan (2005).

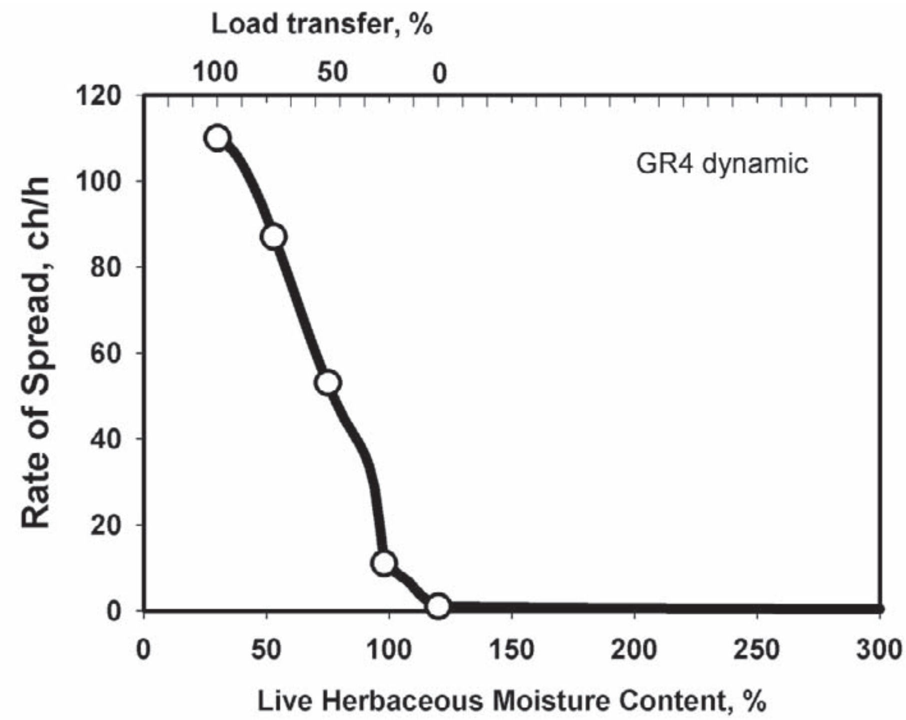

Figure 5—Calculated rate of spread for dynamic fuel model GR4, which incorporates the fuel load transfer function. Load is transferred from the live to the dead class as a function of live fuel moisture. The data points on the curve are given in table 4.

Table 5—Calculated rate of spread for a range of live fuel moisture and load transfer values. The highlighted values correspond to those in table 4 and are plotted on the curves in figures 6 and 7. The curves in figure 6 correspond to the columns of this table. The curves in figure 7 correspond to the rows.

	Rate of spread (ch/h)				
Live herbaceous moisture (%)	**Load transferred from live to dead*, %**				
	100	75	50	25	0
30	**110**	103	90	69	3
53	110	**87**	66	49	2
75	110	76	**53**	33	2
98	110	66	44	**11**	1
120	110	59	38	10	**1**
200	110	43	24	6	1
300	110	32	11	5	1

*Referred to as percent cured by Scott and Burgan (2005)

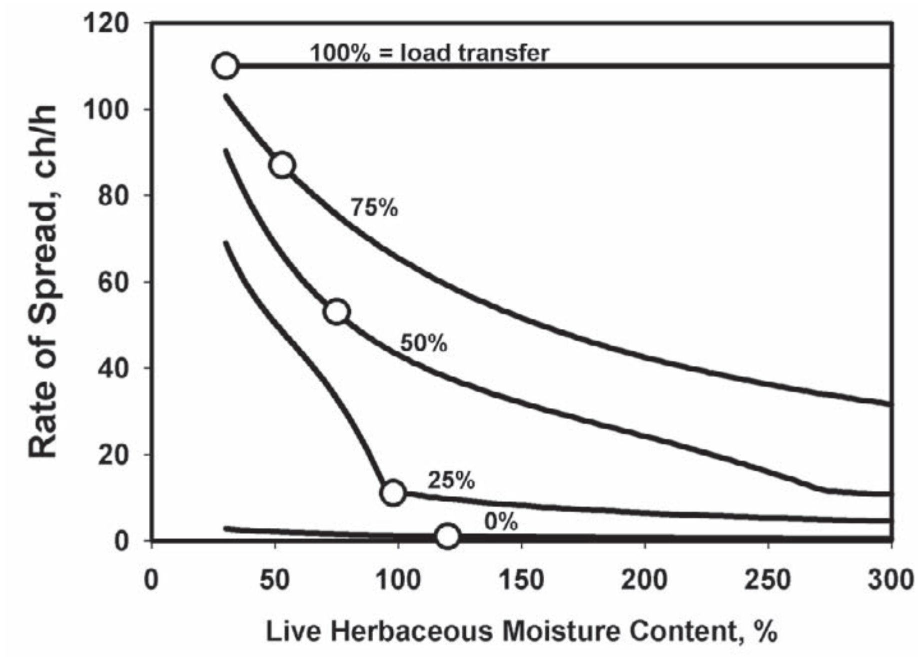

Figure 6—Rate of spread is calculated for several levels of load transfer for a range of live fuel moisture. Use of the load transfer function results in only the single indicated point on each curve. The curves correspond to the columns in table 5.

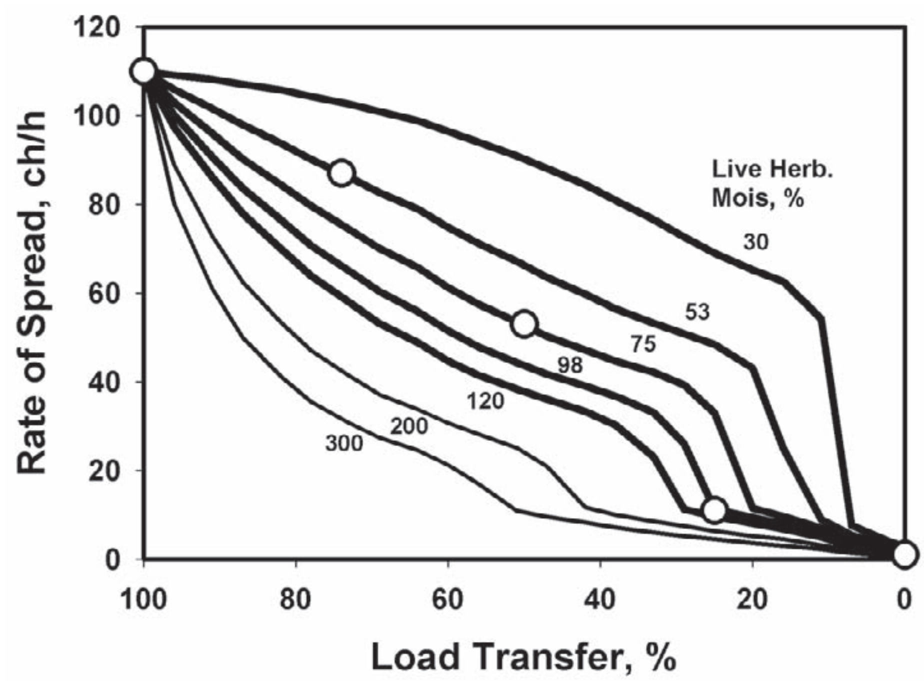

Figure 7—Rate of spread is calculated for several values of live herbaceous moisture for a range of load transfer percentage. Use of the load transfer function results in only the single indicated point on each curve. The curves correspond to the rows in table 5.

Discussion

It is recognized that curing level is an important factor in determining fire behavior in grass fuel types. Because the Rothermel (1972) fire spread model does not include the influence of curing, fuel models that incorporate a dynamic load transfer function have been developed by Scott and Burgan (2005) to reflect seasonal curing. Live fuel moisture is used to estimate the load that is transferred from the live to dead class in the fuel model. Evaluation of the dynamic load transfer function using field sampled data from Australia and New Zealand showed that the assumption that level of curing is related to live fuel moisture needs to be questioned.

An examination of the use of the dynamic load transfer function compared to the option of independent specification of live fuel moisture and curing level showed a significant difference in rate of spread calculations using Rothermel's model. Although both live fuel moisture and degree of curing are currently difficult to determine, we suggest that the required use of the dynamic load transfer function be reconsidered in anticipation of improved models and methods of assessment.

There is a need for longer term research on the curing process, a description of the seasonal changes in the grasslands for fire modeling, and on the combustion processes involved in the burning of a mixture of live and dead fuel. It is imperative that fire researchers and fire managers continue to question, validate, and refine fire behavior models and their underlying assumptions for effective fire and fuel management.

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References

Albini, F. A. 1976. Estimating wildfire behavior and effects. GTR-INT-30, USDA Forest Service, Ogden, UT.

Alexander, M. E. 1994. Proposed revision of fire danger class criteria for forest and rural fire areas in New Zealand. Wellington, New Zealand.

Allan, G., A. Johnson, S. Cridland, and N. Fitzgerald. 2003. Application of NDVI for predicting fuel curing at landscape scales in northern Australia: can remotely sensed data help schedule fire management operations? International Journal of Wildland Fire 12:299-308.

Anderson, H. E. 1982. Aids to determining fuel models for estimating fire behavior. GTR-INT-122, USDA Forest Service, Ogden, UT.

Anderson, S. 2005. Assessing and predicting the curing of grasslands. *in* Australasian Fire Authorities Council/Bushfire CRC Conference, Auckland, New Zealand.

Anderson, S., W. Anderson, F. Hines, and A. Fountain. N.D. Project Report: Determination of field sampling methods for the assessment of curing levels in grasslands. Ensis Forest Biosecurity and Protection.

Anderson, S. A. J., and H. G. Pearce. 2003. Improved methods for the assessment of grassland curing. *in* 3rd International Wildland conference, Sydney, Australia.

Andrews, P. L., C. D. Bevins, and R. C. Seli. 2004. BehavePlus fire modeling system, version 3.0: User's Guide. RMRS-GTR-106WWW, USDA Forest Service.

Barber, J. R. 1990. Monitoring the curing of grassland fire fuels in Victoria, Australia with sensors in satellites and aircraft. A Country Fire Authority Study in Remote Sensing, Country Fire Authority, Victoria.

Burgan, R. E. 1979. Estimating live fuel moisture for the 1978 national fire danger rating system. GTR-INT-226, USDA Forest Service, Ogden, UT.

Burgan, R. E., and R. C. Rothermel. 1984. BEHAVE: fire behavior prediction and fuel modeling system--FUEL subsystem. GTR-INT-167, USDA Forest Service, Ogden, UT.

Cheney, N. P., J. S. Gould, and W. R. Catchpole. 1998. Prediction of fire spread in grasslands. International Journal of Wildland Fire 8:1-13.

Cheney, P., and A. Sullivan. 1997. Grassfires: fuel, weather, and fire behaviour. CSIRO Publishing, Collingwood, Australia.

Deeming, J. E., R. E. Burgan, and J. D. Cohen. 1977. The National Fire-Danger Rating System--1978. GTR-INT-39, USDA Forest Service, Ogden, UT.

Finney, M. A. 1998. FARSITE: fire area simulator--model development and evaluation. RP-RMRS-4, USDA Forest Service.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. ST-X-3, Forestry Canada, Ottawa, Canada.

Jolly, W. M. 2005. Sensitivity of a fire behavior model to changes in live fuel moisture. *in* Sixth Symposium on Fire and Forest Meteorology, Canmore, AB, Canada.

McArthur, A. G. 1966. Weather and grassland fire behaviour. No. 100, Commonwealth of Australia, Canberra, Australia.

McArthur, A. G. 1977. Grassland fire danger meter Mk V. CSIRO Division of Forest Research Annual Report 1976-1977. Canberra, Australia.

Millie, S., and R. Adams. 1999. Measures of grassland curing: a comparison of destructive sampling with visual and satellite estimates. Pages pp 257-263 *in* Australian Bushfire 99 Conference, Albury, NSW.

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

Paltridge, G. W., and J. Barber. 1988. Monitoring Grassland Dryness and Fire Potential in Australia with NOAA / AVHRR Data. Remote Sensing of Environment 25:381-394.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. RP-INT-115, USDA Forest Service, Ogden, UT.

Scott, J. H., and R. E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. RMRS-GTR-153, USDA Forest Service, Rocky Mountain Research Station.