

Sensitivity of a surface fire spread model and associated fire behaviour fuel models to changes in live fuel moisture

W. Matt Jolly

USDA Forest Service, RMRS, Fire Sciences Laboratory, Missoula, MT, USA. Email: mjolly@fs.fed.us

Abstract. Fire behaviour models are used to assess the potential characteristics of wildland fires such as rates of spread, fireline intensity and flame length. These calculations help support fire management strategies while keeping fireline personnel safe. Live fuel moisture is an important component of fire behaviour models but the sensitivity of existing models to live fuel moisture has not been thoroughly evaluated. The Rothermel surface fire spread model was used to estimate key surface fire behaviour values over a range of live fuel moistures for all 53 standard fuel models. Fire behaviour characteristics are shown to be highly sensitive to live fuel moisture but the response is fuel model dependent. In many cases, small changes in live fuel moisture elicit drastic changes in predicted fire behaviour. These large changes are a result of a combination of the model-calculated live fuel moisture of extinction, the effective wind speed limit and the dynamic load transfer function of some of the fuel models tested. Surface fire spread model sensitivity to live fuel moisture changes is discussed in the context of predicted fire fighter safety zone area because the area of a predicted safety zone may increase by an order of magnitude for a 10% decrease in live fuel moisture depending on the fuel model chosen.

Additional keywords: fire behaviour models, live fuel moisture, live fuel moisture of extinction, safety zones.

Introduction

Fire behaviour modelling concepts

Many factors influence fire behaviour but they can be loosely divided into three main components: fuels, weather and topography (Countryman 1972). Fuels are comprised of the amount, arrangement, moisture content and physical characteristics of both live and dead plant material. Weather factors such as wind speed and wind direction, relative humidity, solar radiation and air temperature can influence fire behaviour directly by influencing fire spread rate and direction and indirectly by changing the fuel moisture content. Topographic factors such as slope steepness directly influence fire spread rate by decreasing the distance between the flaming front of a fire and the fuel ahead of the fire, which improves preheating of those fuels and increases fire spread rate. Other topographic factors such as aspect determine the amount of solar radiation that a particular area receives and thus indirectly influence fire behaviour by changing the fuel moisture content. Fire models attempt to integrate this triad of controlling factors into metrics that can be used to assess the potential characteristics of a fire such as its spread rate, flame lengths and intensity. These fire behaviour estimates can then be used to develop management strategies that maximise effectiveness while keeping fire fighters safe.

Models are simplified ways of looking at systems that are often complex and highly variable. When using models, such as fire behaviour models, it is important to fully understand their sensitivity to a given set of inputs. Mathematical models are often developed with only one choice of parameters even though those values vary across the landscape and over time. The variability of a given parameter is rarely considered. For example, field-measured live fuel moisture values have standard deviations as

high as 47% for observations taken on the same site, species and day (Agee *et al.* 2002), but users are required to enter only one live fuel moisture value to estimate fire behaviour using the Rothermel surface fire spread model (Rothermel 1972). Therefore, the choice of a single value for live fuel moisture is problematic. Sensitivity analyses are useful because they identify model parameters that must be chosen with care because of their large impact on model predictions and other parameters, which may have only a small impact on model predictions.

Rothermel surface fire spread model and fire behaviour fuel models

The Rothermel surface fire spread model (1972) integrates many of the aforementioned components of fuels, weather and topography to predict fire behaviour characteristics. The parameters for this model can be categorised into two main groups: environmental parameters and fuel parameters (Andrews and Queen 2001). Environmental parameters include surface wind speeds and slope steepness, while fuel parameters include fuel moistures and fuel loadings of different fuel categories. The current implementation of the Rothermel surface fire spread model uses fuel models to simplify the representation of the fuel complex for the fire spread model. Fuel models describe the amount and physical characteristics of each live and dead fuel category. These fuel models include the original 13 fuel models described by Albini (1976) and Anderson (1982) and 40 additional fuel models described by Scott and Burgan (2005).

Dead fuel size classes are defined in terms of how rapidly a given fuel particle size responds to changes in environmental conditions (i.e. 1 hour, 10 hours, etc.) and are generally characterised by their diameter. Live fuel classes are defined by their

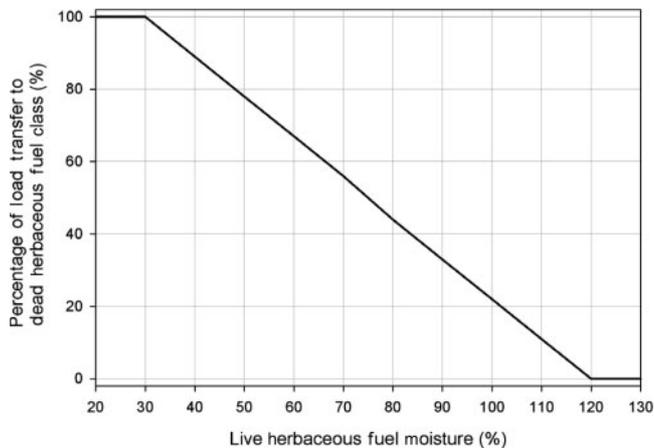


Fig. 1. Load transfer function for dynamic fuel models. As live fuel moisture decreases below 120%, load is transferred from the live herbaceous fuel class to the dead herbaceous fuel class. Below 30% live herbaceous fuel moisture, all the live herbaceous loading is transferred to the dead herbaceous loading fuel class.

growth form and are characterised as either woody or herbaceous. The moisture dynamics of live fuels differ from dead fuels because their moisture content is driven predominately by phenological processes or development stages of a plant, and they are likely the most poorly understood component of fire behaviour (Burgan 1979). The surface fire spread model only considers live fuels that are six-feet (1.83-m) tall or less. Woody fuels include small stature evergreen or deciduous shrubs and juvenile trees, and herbaceous fuels cover the spectrum of forbs, annual grasses and perennial grasses. In all static fuel models, live fuel loadings do not vary seasonally. However, seventeen of the 40 Scott and Burgan fuel models are dynamic. This means that live herbaceous fuel loadings are shifted into the dead herbaceous fuel loading as a function of the live herbaceous moisture content. As the live herbaceous fuel moisture drops below 120%, fuel loading is transferred from the live herbaceous fuel loading to a dead herbaceous fuel class whose fuel moisture is the same as that set for the one-hour fuel class. When live herbaceous fuel moisture reaches 30%, the entire available fuel loading has been transferred into the dead herbaceous fuel class. This is shown graphically in Fig. 1. This load transfer can significantly affect fire behaviour predictions because dead fuels have lower moisture contents than live fuels and thus serve as a larger heat source for combustion. This is meant to represent the accumulation of dead fuel as herbs cure throughout the season. Curing is not currently a direct input into the Rothermel surface fire spread model and can only be indirectly inferred by back-calculating curing as a function of the live herbaceous fuel moisture (Scott and Burgan 2005). Other models developed for use in Canada, New Zealand and Australia use degree of curing as a direct input (McArthur 1966, 1977; Noble *et al.* 1980; Forestry Canada Fire Danger Group 1992; Cheney *et al.* 1998).

In this study, it is shown that the sensitivity of the fire model to changes in live fuel moisture is directly related to the proportion of live fuel in a particular fuel model. It is also shown that in some cases, very small changes in the live fuel moisture content elicit large changes in predicted fire behaviour. Finally, results

are expressed in terms of their impact on estimated firefighter safety zone size, which emphasises that extreme care should be used when choosing live fuel moisture values for fuel models that are heavily weighted towards live fuels.

Methods

BehavePlus fire modelling system

The Rothermel (1972) surface fire spread model, as implemented in the BehavePlus fire behaviour modelling system (Andrews and Bevins 2003), was used for this study. BehavePlus provides an interface to the surface fire spread model that predicts fire behaviour using information about fuels, weather and topography. This program is used extensively throughout the United States to estimate fire behaviour in support of prescribed fire, wildland fire use and fire suppression activities. BehavePlus is not a fire model but rather it is a fire modelling system. It is a collection of many fire behaviour and fire effects models that are integrated into a single interface. The surface fire spread model in BehavePlus is linked to several other models such as those used to estimate the potential for and spread rate of crown fires (Van Wagner 1977; Rothermel 1991) and firefighter minimum safety zone size (Butler and Cohen 1998). This surface fire spread model is also the foundation for other tools used to assess fire behaviour and fire growth such as FLAMMAP (Finney 2006) and the Fire Area Simulator (FARSITE) (Finney 2004). Weather and topography, fuel loading, dead fuel moisture and other fuel parameters were held constant while varying live fuel moisture across a range of values. This allows one to assess the sensitivity of the model in predicting fire behaviour across a range of live fuel moistures.

Dead fuel moistures were set to 5%, midflame wind speed was set to 5 miles per hour and slope was set to zero. Live fuel moistures for both herbaceous and woody vegetation were varied from 30 to 300% in steps of 10%. This covers the range of observed values for live fuel moisture (Ceccato *et al.* 2003). An example seasonal time series of field-measured live fuel moisture values are shown for reference in Fig. 2. The range of live fuel moistures were supplied to the surface fire spread model to estimate the rate of spread, fireline intensity and flame length for all 53 fire behaviour fuel models.

Sensitivity analyses

Local gradients have been suggested as a suitable means to estimate the sensitivity of a given model (McRae *et al.* 1982; Isukapalli 1999). The rate of change of spread rate, fireline intensity and flame length was calculated with respect to a unit change in live fuel moistures. Also calculated was the maximum change over the entire range of live fuel moistures, hereafter referred to as the maximum local gradient (MLG). The MLG measures the rate of change of a response function over a range of values and determines the maximum change in a predicted output for a unit change in the input. It is equivalent to maximising the first derivative of the response function. An example of the MLG estimated over a range of model-predicted surface fire spread rates is shown in Fig. 3. In this example, the maximum local gradient is observed at 100% live fuel moisture where rate of spread increases from 2.5 to 17 chains per hour. The MLG expresses

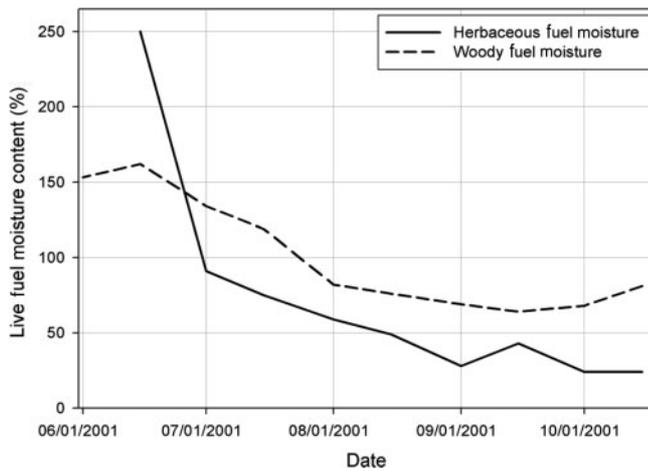


Fig. 2. Field-measured live fuel moisture for a Sagebrush fuel type in the Grand Tetons National Park. The solid black lines shows the live herbaceous fuel moisture and the dashed black line shows the woody fuel moisture throughout the season.

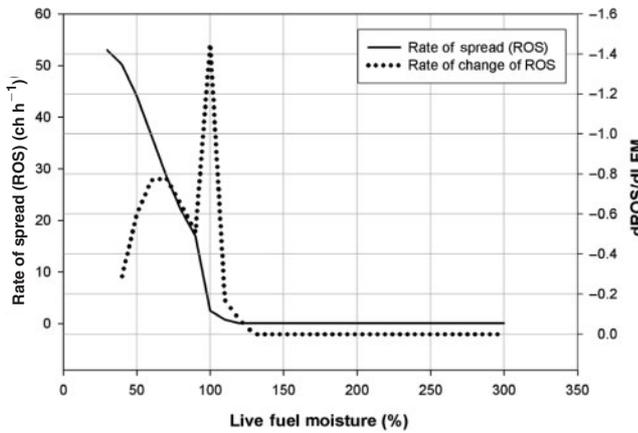


Fig. 3. Illustration of the predicted rate of spread in fuel model gr2 over a range of live fuel moistures and the corresponding rate of change in rate of spread (dROS/dLFM). Large values show areas where model predictions are highly sensitive to changes in live fuel moisture.

the largest change in rate of spread, fireline intensity and flame length for a one percent change in live fuel moisture. In addition to the MLG, the live fuel moisture content at which each fuel model is most sensitive was also calculated.

Results

Fig. 4 shows examples of three types of sensitivity to live fuel moisture changes. For example, fuel model 2 is moderately sensitive, fuel model gr2 is highly sensitive and fuel model 6 is insensitive because it contains no live fuels. The fuel models generally fell within one of these three categories. Thirty two of the 53 fuel models tested contained live fuels. Fuel models 1, 3, 6, 8–9, 11–13, t11–t19 and sb1–sb4 include no live fuels and are thus not discussed further. In general, a fuel model whose predicted fire behaviour was sensitive to live fuel moisture changes

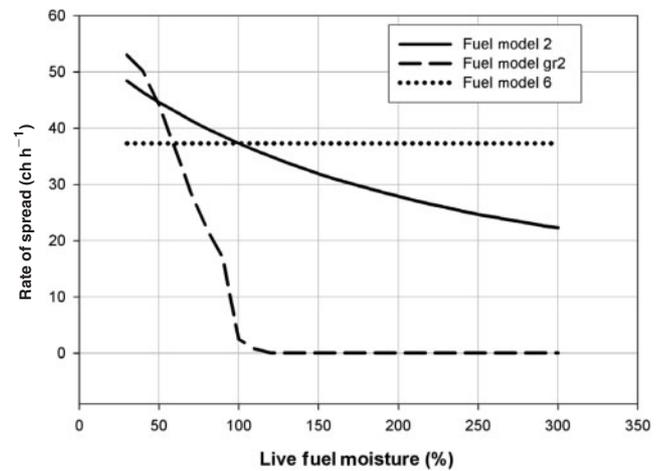


Fig. 4. Predicted rate of spread for three fuel models showing three different sensitivity patterns to changes in live fuel moisture. The solid black curve shows a fuel model that is sensitive to live fuel moisture (LFM) changes, the dashed line shows a fuel model that is very sensitive and the dotted line shows a model that is insensitive to LFM changes because it contains no live fuel. In general, all fuel models fell into one of these three categories.

showed similar sensitivity for spread rate, fireline intensity and flame length. All fuel models showed some sensitivity to live fuel moisture changes and several models were highly sensitive. The results of the MLG analysis of the Rothermel surface fire spread model for each fire behaviour fuel model that contains live fuels are presented in Table 1 and are shown graphically in Fig. 5. The grass fuel models within the set of 40 new fuels showed the highest sensitivity to live fuel moisture changes. The most sensitive of these models were the dynamic fuel models where fuel loadings are shifted between the live herbaceous and the dead herbaceous fuel class. When herbaceous fuels were included in the fuel model, their loading was a strong determinant of the sensitivity of that fuel model to change in live fuel moisture.

The fuel moisture value where the model was most sensitive varied by fuel model and model group. All of the original 13 fuel models, the timber litter models (t11–t19) and the slash–blowdown models (sb1–sb4) showed a maximum sensitivity at 30% live fuel moisture, but many of the new 40 fuel models showed sensitivities at much higher fuel moisture levels. Grass models gr1–gr9 were most sensitive to a live fuel moisture of 90–100%, grass–shrub (gs1–gs4) models were most sensitive between 70 and 90%, shrub models were most sensitive between 30 and 110% and the timber understory models (tu1–tu5) were most sensitive between 30 and 100% (Table 1 and column labels in Fig. 5).

Discussion

The sensitivity of the Rothermel surface fire spread model to changes in live fuel moisture is dependent on the fuel model because fuel models determine the proportion of fuel loadings in each of the live and dead fuel classes. This distribution of fuel loadings determines two important components to the surface fire spread model: the live fuel moisture of extinction and the effective wind speed limit.

Table 1. Results from maximum local gradient (MLG) analysis of the Rothermel surface fire spread model for each fire behaviour fuel model that contains live fuel

Fuel model code	Model type	Fireline intensity			Flame length			Rate of spread					
		Max. rate of change (BTU ft ⁻¹ s ⁻¹ % ⁻¹) ^A	Moisture of max. sens. (%)	Max. diff. for 10% change (BTU ft ⁻¹ s ⁻¹)	Max. diff. for 10% change (%)	Max. rate of change (ft % ⁻¹)	Moisture of max. sens. (%)	Max. diff. for 10% change (ft)	Max. rate of change (ch h ⁻¹ % ⁻¹) ^B	Moisture of max. sens. (%)	Max. diff. for 10% change (ch h ⁻¹)	Max. diff. for 10% change (%)	
2	Static	-2.10	30	21	104.9	-0.02	30	0.20	102.7	-0.20	30	2.00	104.3
4	Static	-157.20	30	1572	119.2	-0.24	30	2.40	108.5	-2.17	30	21.70	115.1
5	Static	-18.90	30	189	127.2	-0.13	130	1.30	154.2	-1.02	30	10.20	120.4
7	Static	-3.20	30	32	107.3	-0.03	50	0.30	104.3	-0.29	30	2.90	106.8
10	Static	-5.40	30	54	113.6	-0.05	30	0.50	107.1	-0.17	30	1.70	111.5
gr1	Dynamic	-0.60	60	6	133.3	-0.08	100	0.80	500.0	-0.44	100	4.40	1200.0
gr2	Dynamic	-6.20	90	62	2166.7	-0.23	90	2.30	387.5	-1.45	90	14.50	680.0
gr3	Dynamic	-9.90	60	99	132.0	-0.30	100	3.00	600.0	-1.47	100	14.70	1080.0
gr4	Dynamic	-24.60	90	246	1084.0	-0.39	90	3.90	295.0	-2.58	90	25.80	360.6
gr5	Dynamic	-26.10	60	261	131.4	-0.40	100	4.00	310.5	-1.51	100	15.10	369.6
gr6	Dynamic	-52.20	90	522	1286.4	-0.57	90	5.70	319.2	-2.43	90	24.30	392.8
gr7	Dynamic	-126.70	90	1267	660.6	-0.76	90	7.60	240.7	-3.54	90	35.40	280.6
gr8	Dynamic	-142.70	60	1427	133.3	-0.69	100	6.90	337.9	-2.38	50	23.80	121.7
gr9	Dynamic	-282.10	60	2821	132.9	-1.14	100	11.40	337.5	-4.26	100	42.60	413.2
gs1	Dynamic	-6.50	70	65	370.8	-0.17	70	1.70	189.5	-0.90	70	9.00	205.9
gs2	Dynamic	-11.30	30	113	126.8	-0.21	90	2.10	191.3	-0.98	90	9.80	215.3
gs3	Dynamic	-30.10	30	301	125.9	-0.27	90	2.70	250.0	-1.34	30	13.40	120.7
gs4	Dynamic	-157.00	30	1570	133.7	-0.82	80	8.20	270.8	-1.74	80	17.40	309.6
sh1	Dynamic	-7.70	40	77	218.5	-0.23	50	2.30	387.5	-1.03	50	10.30	529.2
sh2	Static	-9.80	30	98	127.1	-0.14	100	1.40	182.4	-0.29	30	2.90	121.0
sh3	Static	-89.40	40	894	857.6	-0.69	40	6.90	272.5	-1.90	40	19.00	313.5
sh4	Static	-26.40	30	264	128.3	-0.19	110	1.90	165.5	-1.30	30	13.00	121.7
sh5	Static	-84.60	30	846	123.2	-0.19	30	1.90	109.7	-2.07	30	20.70	118.9
sh6	Static	-22.10	30	221	116.2	-0.09	30	0.90	107.3	-0.60	30	6.00	114.5
sh7	Static	-78.80	30	788	123.7	-0.19	30	1.90	110.1	-1.41	30	14.10	119.3
sh8	Static	-61.70	30	617	130.1	-0.20	30	2.00	113.3	-1.05	30	10.50	123.4
sh9	Dynamic	-160.80	30	1608	126.5	-0.29	30	2.90	111.7	-1.72	30	17.20	121.3
tu1	Dynamic	-1.50	30	15	130.0	-0.08	100	0.80	233.3	-0.14	30	1.40	123.7
tu2	Static	-0.60	30	6	104.7	-0.01	40	0.10	102.4	-0.08	30	0.80	104.9
tu3	Dynamic	-14.60	30	146	117.4	-0.08	30	0.80	108.1	-0.68	30	6.80	114.7
tu4	Static	-5.30	30	53	112.4	-0.04	30	0.40	105.5	-0.20	30	2.00	110.4
tu5	Static	-8.30	30	83	111.1	-0.05	30	0.50	105.3	-0.13	30	1.30	109.2

^ABTU, British thermal unit = 1055.056 J.

^Bch, chain = 20.1168 m.

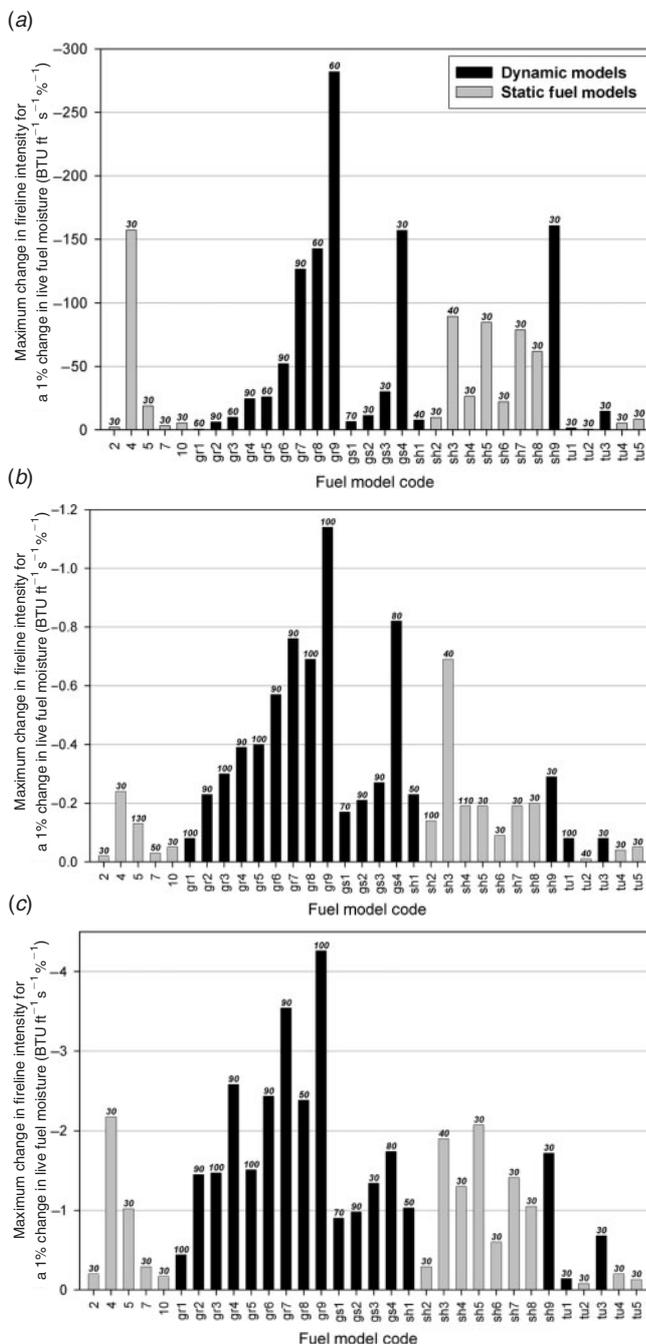


Fig. 5. Maximum local gradient for predicted fire behaviour over a range of live fuel moistures. Fuel models with no live fuels are excluded for clarity. Graphs are shown for each of the three fire behaviour characteristics tested: fireline intensity (a), flame length (b) and rate of spread (c). The numbers above the bars for each fuel model denote the live fuel moisture content where each fuel model is most sensitive.

Live fuel moisture of extinction

The live fuel moisture of extinction is defined as the moisture content above which live fuels will no longer burn. It is calculated from the dead fuel moisture of extinction (which is a parameter in the fuel model), the dead fuel moisture content and

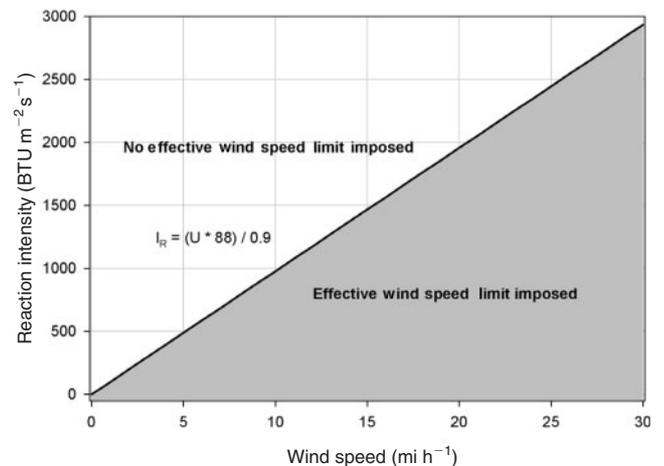


Fig. 6. The relationship between the wind speed and reaction intensity is used to determine the maximum wind multiplier for the Rothermel surface fire spread model.

the proportion of live fuel loading to total fuel loading (Fosberg and Schroeder 1971). This moisture of extinction determines whether or not live fuels are available to burn and generally we observe an abrupt change in predicted fire behaviour around this extinction moisture value.

It has long been recognised that the moisture of extinction is an ill-defined concept and that many environmental and fuel parameters are important in determining whether or not a fire will burn in a particular fuel type (Wilson 1982, 1985, 1990; Catchpole and Catchpole 1991). Newer approaches that examine fire spread as a probability rather than a discrete event show greater promise for reducing model prediction errors in live fuels (Weise *et al.* 2005). However, it is important to understand the current surface fire spread model because of its widespread use in fire management applications throughout the United States.

Effective wind speed limit

The Rothermel surface fire spread model limits the wind multiplication factor in low intensity fires. This modification mimics the observations of decreasing surface fire spread rates as the wind speed increases (McArthur 1969). The model assumes that the ratio of the wind speed to the reaction intensity must be greater than 0.9 (Rothermel 1972). This is shown graphically in Fig. 6. The reaction intensity is the amount of heat released by the fire per unit area over some amount of time. When wind speeds are high and reaction intensities are low, the effective wind speed is forced to equal $0.9 \times$ reaction intensity (IR) (this is shown as the black line in Fig. 6). In our test, the reaction intensity must exceed $488 \text{ BTU m}^{-2} \text{ s}^{-1}$ (BTU = British thermal unit) to avoid this imposed wind speed restriction. When live fuel moistures are high and thus not available for combustion, the only fuels that contribute to combustion are the dead fuels. When dead fuel loadings in a particular fuel model are low, the reaction intensity for those fuel models is low and the wind speed limit is imposed. As live fuel moisture decreases below the live fuel moisture of extinction, the live fuels also contribute to combustion and help to raise the reaction intensity above the threshold value for the

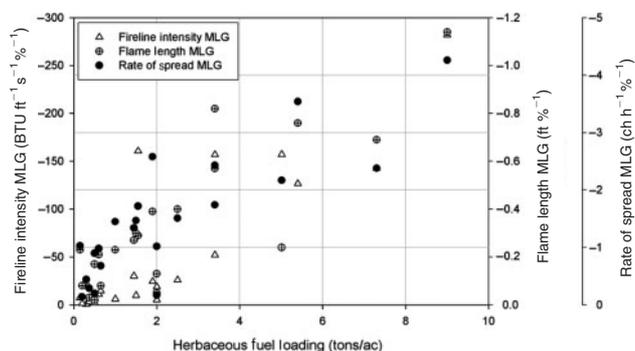


Fig. 7. Relationship between the maximum local gradient (MLG) of three predicted fire behaviour characteristics over a range of live fuel moistures and the herbaceous fuel loadings of a given fuel model. Fuel models without live herbaceous loading are omitted for clarity. In general, model sensitivity increased with increasing herbaceous fuel loadings for all three variables.

wind limit restriction. This causes an abrupt change in the predicted fire behaviour because both the live fuels are adding to the combustion process and the effective wind speeds are much higher.

Differences between static and dynamic fuel models

As mentioned previously, the live fuel moisture of extinction is calculated as a function of three variables: the dead fuel moisture, the dead fuel moisture of extinction and the ratio of live fuel to total fuel. The dead fuel moisture of extinction is a fuel model parameter and thus does not vary. For our test, the dead fuel moisture was also fixed. In the original 13 fuel models, the ratio of live fuel loading to total fuel loadings was always constant. However, in the dynamic models of Scott and Burgan, live fuel is transferred into a dead fuel category as a function of the live fuel moisture. This changes the ratio of live fuel to total fuel and subsequently changes the live fuel moisture of extinction. Therefore, in the dynamic fuel models, the live fuel moisture of extinction varies indirectly as a function of the live fuel moisture.

In addition, many of the new 40 dynamic fuel models have very little initial fuel loading in the dead fuel categories. Instead they attribute most of their spread and intensity to fuels that are transferred from the live herbaceous loading to dead herbaceous loading once the live herbaceous fuel moistures drop below 120%. This makes these models susceptible to the imposed effective wind speed limit at high live fuel moistures when no load has been transferred to the dead fuel classes and the live fuels are not contributing to the reaction intensity. In fact, the only fuel models that met the imposed wind speed limit criteria were dynamic fuel models (gr1–gr6, gr8, gs1–gs3, sh1 and tu1). Once a sufficient amount of load has been transferred, the reactions intensities exceed the wind speed limit criteria and the spread rates increase rapidly. The importance of this load transfer function is further illustrated in Fig. 7 where it is shown that the MLG is related to the amount of herbaceous fuel loadings in a particular fuel model.

Although loadings of live fuels in nature vary seasonally, static fire behaviour fuel models do not account for these different loadings. Instead, they assume that their moisture content is directly related to their seasonal availability to contribute to fire

spread and intensity. As such, by varying the live fuel moisture we are assessing the seasonal changes in predicted fire behaviour for static fuel models. Dynamic fuel models are more complicated because one not only varies the live fuel moisture, one also varies the ratio of live fuel loading to dead fuel loading. This complicates the comparison of dynamic and static fuel models.

Implications for firefighter safety

Predicted fire behaviour can be used to provide guidelines for firefighter safety zone size. Butler and Cohen (1998) suggested that at a minimum, a safety zone should separate firefighters from the flaming front by no less than four times the flame height. In models where the moisture of highest sensitivity is near common summertime values, extreme caution should be exercised when choosing moisture values to parameterise the model to predict flame height. For example, the grass fuel models were most sensitive within the range of 90–100% live fuel moisture, and summertime live herbaceous fuel moistures are common within this range (Mutch 1967). For fuel model gr9, a decrease in the fuel moisture from 110 to 100% increases predicted flame length from 4.8 to 16.2 ft (1.46 to 4.94 m). This is a 230% increase in predicted flame length for a very small decrease in moisture content. Assuming the potential for fire on all sides (i.e. a circular safety zone) and that flame length equals flame height (Andrews and Bevins 2003), the estimated safety zone size area would need to be increased 10.4 times the area estimated at 110% live fuel moisture. It is, therefore, necessary to exercise extreme caution when choosing parameters for the surface fire spread model to estimate fire behaviour to ensure firefighter safety. A good rule of thumb is to always exercise the ‘worst case’ scenario to avoid underpredicting potential fire behaviour characteristics and ensure firefighter safety.

Implications for fire behaviour predictions

In addition to the human safety aspects of understanding model sensitivity to live fuel moisture changes there are also some general aspects of fire behaviour prediction to consider. The original 13 fuel models all showed sensitivity well below the range of live fuel moistures that would commonly be used to initialise the surface fire spread models. In contrast, many of the recently added 40 fuel models were sensitive within the range of values that are commonly observed during periods of high fire potential, in particular the dynamic grass models. If users select a live fuel moisture value that is too high, they could severely underpredict fire behaviour, which potentially leads to incorrect or dangerous decisions depending on the intended purpose of the fire behaviour predictions. It is, therefore, important to fully understand the sensitivity of each fuel model to live fuel moisture changes when predicting fire behaviour with the Rothermel surface fire spread model and any of the standard set of 53 fuel models that contain live fuels.

Acknowledgements

I would like to thank Pat Andrews and the three anonymous reviewers for their constructive comments on earlier drafts of this manuscript. This research was supported in part by funds provided by the Joint Fire Science Program and the Rocky Mountain Research Station, Forest Service, USA Department of Agriculture. We would like to thank Chip Collins and members of the

National Park Service live fuel moisture sampling team in the Grand Tetons National Park for sharing the live fuel moisture data presented here.

References

- Agee JK, Wright CS, Williamson N, Huff MH (2002) Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. *Forest Ecology and Management* **167**, 57–66. doi:10.1016/S0378-1127(01)00690-9
- Albini FA (1976) Estimating wildfire behavior and effects. INT-30, USDA, Forest Service, Ogden, UT.
- Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. GTR-INT-122, USDA Forest Service. (Ogden, UT)
- Andrews PL, Bevins CD (2003) BehavePlus fire modeling system, version 2: Overview. In '2nd International Wildland Fire Ecology and Fire Management Congress'. (Orlando, FL)
- Andrews PL, Queen LP (2001) Fire modeling and information system technology. *International Journal of Wildland Fire* **10**, 343–352. doi:10.1071/WF01033
- Burgan RE (1979) Estimating live fuel moisture for the 1978 national fire danger rating system. GTR-INT-226, USDA Forest Service. (Ogden, UT)
- Butler B, Cohen JD (1998) Firefighter Safety Zones: A theoretical model based on radiative heating. *International Journal of Wildland Fire* **8**, 73–77. doi:10.1071/WF9980073
- Catchpole EA, Catchpole WR (1991) Modelling moisture damping for fire spread in a mixture of live and dead fuels. *International Journal of Wildland Fire* **1**, 101–106. doi:10.1071/WF9910101
- Ceccato P, Leblon B, Chuvieco E, Flasse S, Carlson JD (2003) Estimation of live fuel moisture content. In 'Wildland fire danger estimation and mapping, the role of remote sensing data'. (Ed. E Chuvieco) (World Scientific Publishing Co. Pte. Ltd.: Singapore)
- Cheney NP, Gould JS, Catchpole WR (1998) Prediction of fire spread in grasslands. *International Journal of Wildland Fire* **8**, 1–13. doi:10.1071/WF9980001
- Countryman CM (1972) The fire environment concept. (USDA Forest Service: Berkeley, CA)
- Finney MA (2004) FARSITE: Fire Area Simulator – Model development and evaluation. RMRS-RP-4 Revised, USDA, Forest Service, Rocky Mountain Research Station. (Fort Collins, CO)
- Finney MA (2006) An overview of FlamMap modeling capabilities. In 'Fuels Management – How to measure success'. (Eds PL Andrews, B Butler) p. 809. (USDA Forest Service, Rocky Mountain Research Station: Portland, OR)
- Forestry Canada Fire Danger Group (1992) Development and structure of the Canadian Forest Fire Behavior Prediction System. (Ottawa, ON)
- Fosberg MA, Schroeder MJ (1971) Fine herbaceous fuels in fire-danger rating. RM-185, USDA, Forest Service. (Fort Collins, CO)
- Isukapalli SS (1999) Uncertainty analysis of transport-transformation models. (Rutgers University, Newark: NJ)
- McArthur AG (1966) Forest fire danger meter. (Commonwealth of Australia: Canberra, Australia)
- McArthur AG (1969) The Tasmanian bushfires of 7th February, 1967 and associated fire behaviour characteristics. A7. (Forest Research Institute, Canberra: Australia)
- McArthur AG (1977) Grassland fire danger meter Mk V. (Canberra, Australia)
- McRae GJ, Tilden JW, Seinfeld JH (1982) Global sensitivity analysis – a computational implementation of the Fourier Amplitude Sensitivity Test (FAST). *Computers & Chemical Engineering* **6**, 15–25. doi:10.1016/0098-1354(82)80003-3
- Mutch RW (1967) Cheatgrass coloration – a key to flammability? *Journal of Range Management* **20**, 259.
- Noble IR, Gill AM, Bary GAV (1980) McArthur's fire-danger meters expressed as equations. *Austral Ecology* **5**, 201–203. doi:10.1111/J.1442-9993.1980.TB01243.X
- Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. INT-115, USDA, Forest Service. (Ogden, UT)
- Rothermel RC (1991) Predicting behavior and size of crown fires in the Northern Rocky Mountains. INT-438, USDA, U.S. Forest Service. (Ogden, UT)
- Scott JH, Burgan RE (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. (Fort Collins, CO)
- Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7**, 23–34.
- Weise DR, Zhou X, Sun L, Mahalingam S (2005) Fire spread in chaparral – 'go or no-go?'. *International Journal of Wildland Fire* **14**, 99–106. doi:10.1071/WF04049
- Wilson RA, Jr (1982) A reexamination of fire spread in free-burning porous fuel beds. INT-289, USDA, Forest Service. (Ogden, UT)
- Wilson RA, Jr (1985) Observations of extinction and marginal burning states in free burning porous fuel beds. *Combustion Science and Technology* **44**, 179–193.
- Wilson RA, Jr (1990) Reexamination of Rothermel's fire spread equations in no-wind and no-slope conditions. INT-434, USDA, Forest Service. (Ogden, UT)

Manuscript received 16 May 2006, accepted 2 February 2007