Predicted vs Observed Fire Spread Rates in Ponderosa Pine Fuel Beds: A Test of American and Canadian Systems

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Abstract

The Canadian Forest Fire Behavior Prediction (FBP) System and the American BEHAVE fire behavior prediction system differ in many respects. These dissimilarities stem from a basic difference in the two approaches of the fire behavior prediction problem; the Canadians used an empirical approach in system design, while the Americans developed an adaptable theoretical model. In the spring of 1988 a series of 17 experimental fires in ponderosa pine (Pinus ponderosa Laws.) needle litter were conducted in the wind tunnel combustion facilities of the Intermountain Fire Sciences Laboratory in Missoula, Montana. The fires were part of investigations into crown fire initiation, and fire acceleration from a point source. However, the data collected allowed the observed equilibrium head fire rate of spread (ROS) to be compared to estimates computed by both the American and Canadian fire behavior prediction systems. The American BEHAVE system tended to underpredict observed ROS by 15-60 %, possibly due to wind speed profiles differing from the original developmental study or inaccurate estimation of moisture of extinction. The Canadian FBP System tended to overpredict observed ROS, due in part to problems in computing a 10-m open wind speed equivalent to the wind tunnel (midflame) wind speed.

Résumé

La Méthode canadienne de prévision du comportement des incendies de forêt et le système américain de prévision du comportement du feu BEHAVE sont différents à plusieurs égards. Ces dissimilitudes sont attribuables à une différence fondamentale des deux approches au problème de prévision du comportement du feu; les canadiens ont utilisés une approche empirique dans l'élaboration du système tandis que les américains ont élaborés un modèle théorique adaptable. Au printemps 1988, une série de 17 feux expérimentaux de litière d'aiguilles de pin ponderosa (Pinus ponderosa Laws.) a été menée aux installations de combustion avec soufflerie de l'Intermountain Fire Sciences Laboratory de Missoula au Montana. Ces essais étaient menés dans le cadre de deux projets de recherche, l'un sur la naissance de feux de cime et l'autre sur l'accélération du feu à partir d'une source ponctuelle. Les données ont toutefois permis que la vitesse observée de propagation (VDP) d'équilibre du feu soit comparée aux estimations calculées par les systèmes canadiens et américains de prévision du comportement du feu. Le système américain BEHAVE avait tendance à sous-prédire la VDP observée par 15-60%, possiblement à cause du profil de la vitesse des vents qui était différent de l'étude originale élasorée ou l'estimation inexacte de l'extinction de l'humidité. La Méthode canadienne de prévision du comportemant des incendies de forêt avait tendance à sur-prédire la VDP observée, en pantie à cause de problémes encourus lors du calcul de l'équivalent de lavitesse en plein vent de 10m à la vitesse du vent (mi-flamme) dans la soufflerie.

Introduction

During the spring of 1988, as part of a study on the acceleration of point source fires, a total of 29 experimental fires (17 of which were in ponderosa pine (Pinus ponderosa Laws.) needle litter fuel beds) were conducted in the wind tunnel burning facilities of the Intermountain Fire Sciences Laboratory in Missoula, Montana. Following completion of the burning it was thought that the observed equilibrium spread rates might be compared to a predicted rate of spread from the U.S. BEHAVE fire behavior prediction system. Additionally, although the Canadian Forest Fire Behavior Prediction (FBP) System is based on field research data, it was thought that it might be interesting to attempt a prediction, given the laboratory conditions.

All fire behavior prediction systems attempt to predict wildland fire behavior based on certain key elements of the fuel and concurrent weather conditions. These key elements vary from system to system but always include a fuel type characterization (or classification), fuel moisture content (FMC), wind speed, and topographic slope. The "proof of the pudding" of any behavior prediction system is not in the ease of use, versatility, or basis for derivation; it is how well the fire behavior prediction matches observed wildland fire behavior. While the burning of fuel beds in a

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wind tunnel cannot be considered the equivalent of a wildland fire, the results proved to be interesting.

Each fire behavior prediction system has its strengths and weaknesses. The original philosophy and derivation of each system influence how well it will work under a variety of fuel and weather conditions. The U.S. system is based on physical heat transfer theory and a series of laboratory fires. The Canadian system is based largely on field experimental fires (with wildfire data used when available) tempered with physical theory. The advantages of both research approaches are discussed elsewhere (Van Wagner 1971, Catchpole and de Mestre 1986). The differing approach to research in the two countries is likely a product of the personnel responsible for the research; the U.S. researchers are largely engineers, physisists, and mathematicians, while in Canada foresters are the primary researchers. A general description of each system should elucidate the differences.

U.S. BEHAVE

BEHAVE is an interactive computer-based fire behavior prediction and fuel modelling system developed by United States Department of Agriculture personnel at the Intermountain Fire Sciences Laboratory in Missoula, Montana. BEHAVE has been an approved U.S. national fire behavior prediction system since 1984 and is currently used in a variety of fire management applications.

BEHAVE is divided into two subsystems: FUEL (Burgan and Rothermel 1984) for fuel modelling and BURN (Andrews 1986) for operational fire behavior prediction. The objective of fuel modelling is to describe vegetation in terms that can be used in the mathematical prediction model (Rothermel 1972). Each subsystem consists of two parts: knowledge base and control (Andrews and Latham 1984). The knowledge base, which is the key component of the system, consists of mathematical models, heuristics, and fuel models. The control structure mainly facilitates the interaction between the user and the knowledge base and controls the flow of the program.

Rothermel's (1972) mathematical fire spread prediction model is the core of the fire behavior prediction capability of the BURN subsystem. The mathematical fire spread model uses wind speed, slope, fuel moisture and a fuel model to predict the rate of spread (ROS) and intensity of a fire. A fuel model is defined as a simulated fuel complex for which all the fuel descriptors required for the solution of the mathematical fire spread model have been specified. Other models in the BURN subsystem predict flame length, fire area and perimeter, spotting distance, suppression force capabilities, moisture content of fine dead fuels, wind speed adjustment factor, and curing of live fuel (Andrews 1986). Rate of spread estimation which is the focus of this study, is mainly based on the mathematical fire spread model, so the comparisons made here mainly apply to this model.

Rothermel's (1972) mathematical fire spread model was designed on the conservation of energy principle. Equilibrium ROS is the ratio between the heat flux received from the advancing flames (heat source) and the heat required for ignition by the potential fuel (heat sink). By breaking up the problem in this way Rothermel was able to quantify separately the factors affecting the heat source and the heat sink, examining each term either experimentally or analytically. The resulting model is completely different from older systems, which were mainly based on empirical relationships between burning conditions and broad fuel types. This model not only predicts ROS based on burning conditions but allows the user to describe the fuel in detail based on a number of standard fuel measurements. As a result, site-specific fuel models can be created. Thirteen stylized fuel models representative of common fuel complexes in the U.S. are in use with this system (Anderson 1982). The user can choose to use these discrete models, modify them, or create site specific fuel models if additional fuel data are available. The FUEL subsystem in BEHAVE also provides weighting procedures for inclusion of more than one fuel stratum in the description of a fuel complex.

The Rothermel fire spread model (and hence BEHAVE) is intended to describe a flame front advancing steadily in surface fuels within 2 metres of, and contiguous to, the ground; severe fire behavior (crowning, spotting, etc.) is not predicted by the model (Rothermel 1983).

The inputs required by the mathematical model for head fire ROS prediction are (Rothermel 1972):

1. ovendry fuel loading (kg/m^2),
2. fuel depth (m),
3. fuel particle surface area to volume ratio (cm^2/cm^3),
4. fuel particle low heat content (kJ/kg),
5. ovendry particle density (g/m^3),
6. fuel particle moisture content (fraction of ovendry weight),
7. fuel particle total mineral content (fraction of ovendry weight),
8. fuel particle effective mineral content ((grams silica - grams free minerals)/grams ovendry fuel),
9. wind velocity at midflame height (km/h),
10. site slope (vertical rise/horizontal run),
11. moisture content of extinction (fraction of ovendry weight).

Variables 5, 7, and 8 are held constant in the implementation of the model in BEHAVE because "they either have a small effect over their naturally occurring range or would be very difficult for the user to determine" (Burgan and Rothermel 1984). The value for moisture content of extinction in the model is difficult to obtain and requires experimental determination. Since moisture content of extinction is an influential variable, BEHAVE provides an estimation procedure (Burgan and Rothermel 1984).

THE CANADIAN FOREST FIRE BEHAVIOR PREDICTION (FBP) SYSTEM

The FBP System is a subsystem of the larger Canadian Forest Fire Danger Rating System (CFFDRS). The CFFDRS is an integrated modular forest fire danger rating system and, when complete, will consist of four modules or subsystems:

1) The Canadian Forest Fire Weather Index (FWI) System is composed of three fuel moisture codes and three relative fire behavior indexes (Canadian Forestry Service 1984). The codes and indexes are computed daily from noon temperature, relative humidity, wind speed, and 24-hr total rainfall measurements (Van Wagner 1987).

2) The Canadian Forest Fire Behavior Prediction (FBP) System is composed of four primary fire behavior outputs (head fire Rate of Spread (ROS), fuel consumption, frontal fire intensity, and type of fire) and three secondary fire growth measurements (forward spread distance, area burned, and perimeter length) (Alexander et al. 1984, Lawson et al. 1985) based on an elliptical fire growth model (Van Wagner 1969, Alexander 1985).

3) A proposed Fire Occurrence Prediction (FOP) System is envisioned as a single national framework consisting of both lightning and man-caused fire components (Stocks et al. 1988).

4) The incomplete Accessory Fuel Moisture System is a supplement to, or support of, special functions and requirements of the other three major systems. This system will include fuel specific moisture codes, corrections/adjustments for late starting fire weather stations, landform characteristics, latitude, season, time of day, and others (e.g., Van Wagner 1977).

Three factors played a prominent role in the maturation of the CFFDRS: 1) the development process was an evolution, where features were modified and retained from system to system during the 60+ years of development; 2) there is no direct fuel moisture content (FMC) evaluation (rather fire danger is calculated from direct fire weather observations); and 3) the underlying philosophy was to base the fire danger ratings on field experiments analyzed by empirical methods. This philosophy reflects the long established Canadian approach to fire behavior research: field documentation of readily measured variables on experimental fires (e.g., Alexander et al. 1984, Stocks et al. 1988) followed by analysis of the data using simple mathematical models and correlation techniques (Van Wagner 1971). Well-documented operational prescribed fires and wildfires have been used as well for system development, the latter being particularly useful to quantify the extreme end of the fire behavior scale. Laboratory-based fire research in moisture physics and heat transfer theory provides the models and framework by which field data are analyzed and explained. Because of the empirical nature of the data, phenomena not readily quantified by current physical models are automatically accounted for (e.g., the transition between surface and crown fire).

LABORATORY EXPERIMENTAL FIRES

The series of 17 experimental fires were conducted in the wind tunnel burning facilities of the Intermountain Fire Sciences Laboratory (ISFL), in Missoula, Montana. The experimental burning facilities are environmentally controlled and include two wind tunnels and a large combustion table (see Rothermel and Anderson 1966, Rothermel 1967).

During this experiment, temperature and relative humidity were held at a constant 26.7°C and 20 % throughout the burns. The moisture content of the fuel was not specifically controlled; rather, the fuel was allowed to come into equilibrium with the lab environment before burning, producing a fairly consistent fuel moisture content (FMC) for all burns (mean 8.6 %). Thus the fuel moisture functions of the two systems are not being tested. Four wind speeds were tested (0.0, 1.6, 4.8, and 8.0 km/h) covering the range of the wind tunnel's capability.

Fuel beds measured 0.915 m by 6.15 m and were composed of recently cast, cleaned ponderosa pine needles packed to a depth of 7.6 cm. Fuel beds were loaded to bulk densities of either 26.3 kg/m^3 or 13.12 kg/m^3 and packed according to procedures outlined in Schuette (1965). Fuel beds loaded to 26.3 kg/m^3 were burned at all wind speeds with a minimum of three replications (at the wind speed of 4.8 km/h five replications were done). The fuel beds loaded to 13.12 kg/m^3 were burned at one wind speed (4.8 km/h), with three replications.

For burning, the fuel beds were placed on the floor of the wind tunnel and ignited 1.2 m downwind of the front of the bed with a point ignition device. Head fire ROS was determined by regression analysis of the spread distance/elapsed time measurements, using only the measurements taken after the head fire had spread 2.0 m to allow for the period of acceleration to an equilibrium spread rate. Table 1 lists the fires conducted, environmental conditions, measured fuel moisture, and observed equilibrium ROS for each fire.

For more-complete information on the experimental design, documentation equipment, burning procedures, and results consult McAlpine (1988).

Table 1. Summary of all burns.

Burn no.	Bulk Density (kg/m³)	Wind speed (km/h)	Temp. (°C)	R.H. (%)	Fuel moist. (%)	Head fire* equil. ROS (m/min)
1	26.3	1.6	27.6	20.9	8.2	0.46
2	26.3	8.0	27.1	19.8	7.9	4.50
3	26.3	4.8	27.3	20.9	8.4	1.45
4	26.3	1.6	27.1	20.9	8.1	0.48
5	26.3	1.6	26.9	20.5	8.2	0.60
6	26.3	4.8	27.3	20.0	7.7	1.73
7	26.3	4.8	26.9	19.9	8.8	1.48
8	26.3	8.0	27.0	21.3	8.4	2.16
9	26.3	8.0	27.8	19.7	8.3	3.03
21	13.1	4.8	27.1	19.7	8.9	2.09
22	13.1	4.8	27.2	20.6	8.9	2.19
23	13.1	4.8	27.6	21.2	8.7	2.52
24	26.3	0.0	27.4	20.4	9.9	0.38
25	26.3	0.0	27.1	20.9	9.4	0.37
27	26.3	0.0	27.0	21.4	8.7	0.37
28	26.3	4.8	27.5	20.8	9.2	1.25
29	26.3	4.8	27.0	20.0	8.8	1.30

*Regression results using spread data from 2.0 to 4.95 m downwind of the ignition point.

Table 2. Rate of spread prediction results for the U.S. and Canadian fire behavior prediction systems.

Burn no.	Wind Speed (km/h)	FFMC[a]	ISI[b]	Canadian Predicted[1] ROS (m/min)	U.S. Predicted[1] ROS (m/min)	Observed head fire equil. ROS (m/min)
24	0.0	90.9	44.8	0.46 (+21)	0.21 (-45)	0.38
25	0.0	91.4	5.2	0.55 (+49)	0.22 (-41)	0.37
27	0.0	92.1	5.7	0.67 (+81)	0.22 (-41)	0.37
1	1.6	92.6	7.8	1.31 (+185)	0.39 (-15)	0.46
4	1.6	92.7	7.9	1.35 (+181)	0.39 (-19)	0.48
5	1.6	92.6	7.8	1.31 (+118)	0.39 (-35)	0.60
3	4.8	92.4	12.3	3.51 (+142)	0.96 (-34)	1.45
6	4.8	93.1	13.6	4.33 (+150)	1.01 (-42)	1.73
7	4.8	92.0	11.7	.13 (+111)	0.94 (-36)	1.48
28	4.8	91.6	11.1	2.78 (+122)	0.92 (-26)	1.25
29	4.8	92.0	11.7	3.13 (+141)	0.94 (-28)	1.30
21[2]	4.8	91.9	11.5	3.03 (+45)	1.30 (-38)	2.09
22[2]	4.8	91.9	11.5	3.03 (+38)	1.30 (-41)	2.19
23[2]	4.8	92.1	11.8	3.22 (+28)	1.31 (-48)	2.52
2	8.0	92.9	21.5	11.06 (+146)	1.81 (-60)	4.50
8	8.0	92.4	20.0	9.84 (+356)	1.75 (-19)	2.16
9	8.0	92.5	0.3	10.08 (+233)	1.76 (-42)	3.03

[1] Numbers in brackets indicate the percent deviation from the observed value [(predicted - observed)/observed].
[2] These three burns were conducted at the lower fuel bulk density of 13.1 kg/m³.
[a] FFMC - Fine Fuel Moisture Code
[b] ISI - Initial Spread Index

Fitting the Fuel and "Weather" to a Model

U.S. BEHAVE

The basic characteristics of BEHAVE made the prediction of rate of spread for this particular single layer fuel type very easy. Required fuel and environmental inputs were all simply measured or found in the literature.

Ovendry fuel loading, fuel bed depth, and fuel moisture content were measured. Ponderosa pine needle surface area to volume ratio was obtained from Brown (1970) (57.6 cm²/cm³). Heat content was assigned a value of 16,628 kJ/kg, the same value used for all 13 stylized fuel models. Wind velocity was one of the controlled variables in the wind tunnel. Slope was equal to zero for all burns. Finally, the moisture content of extinction was estimated at 34.0% through BEHAVE. BEHAVE predictions for head fire ROS appear in Table 2.

CANADIAN FBP SYSTEM

The application of the Canadian FBP System to the fuel/weather conditions of this experiment is more difficult than application of BEHAVE simply because the Canadian FBP System was designed for field conditions, integrating multilayered fuel types automatically in specific, discrete fuel types. Five distinct steps were required for a ROS prediction with the Canadian FBP System: 1) choose one of the 14 discrete fuel types to represent the artificial ponderosa pine needle litter fuel beds used; 2) calculate the equivalent Fine Fuel Moisture Code (FFMC, a moisture code from the FWI System) value from the measured FMC; 3) determine the equivalent 10-m open wind speed from literature relationships of in-stand wind speed vs. 10-m open wind speed; 4) compute the Initial Spread Index (ISI, a relative fire behavior index from the FWI System) value from the calculated FFMC and estimated equivalent 10-m open wind speed; and 5) calculate the predicted head fire ROS from the fuel type and ISI.

Selection of one of the discrete fuel models from the FBP System required some consideration. The first thought was use the C-7 (ponderosa pine--Douglas-fir) fuel type, since the fuel was ponderosa pine needle litter. Closer inspection of the C-7 fuel type description given by Alexander et al. (1984) ("except within Douglas-fir thickets the forest floor is dominated by perennial grasses, herbs and scattered shrubs") established that it does not describe closely the exclusive needle litter fuel used. The description for fuel type C-6 (red pine plantation) from Alexander et al. (1984) while not the correct species of needle litter provided a closer estimation of the fuel in question:

> "This fuel type is characterized by pure plantations of red pine, fully stocked so that crowns are

closed and no understorey or shrub layer is present. The forest floor is covered by needle litter with an underlying duff layer of up to 10 cm in depth. The raté of spread relationships accommodate three ranges in mean stand height: 1) from 4 to 9.9 m, 2) from 10 to 20 m, and 3) more than 20 m."

Fuel type C-6 requires an estimate of stand height for equation selection, however, because trees in our case had no effect on the spread rate in our artificial fuel bed (i.e., there was no chance of crowning) the maximum height (more than 20 m) was selected.

The FFMC is easily determined from the FMC by equations provided by Van Wagner (1987):

$$F = 59.5(250 - m)/(147.2 + m)$$

$$m = 147.2(101 - F)/(59.5 + F)$$

Where F = FFMC
m = FMC

The FMC varied from a low of 7.7 % to a high of 9.97 %, producing an FFMC range of 93.1 to 90.9 respectively. A list of computed FFMC values for each fire appears in Table 2.

A 10-m open wind speed equivalent to the wind speeds measured in the wind tunnel is the most difficult estimation required for this study, since it greatly influences the final predicted ROS. Models to predict "midflame" wind speed from measured wind speeds at 6.1 m (20 ft) include those by Albini and Baughman (1979), Baughman and Albini (1980), Bergen (1971), Cooper (1965), Fons (1940), and Van Wagner (1987). Correction factors to estimate the 10-m open wind speed cited in these publications range from a high of 8.33 to a low of 1.78. With this extreme variation cited in the available literature, a similarly wide range in 10-m open wind speed estimates is possible. To alleviate this problem, the original study of fire behavior in the C-6 fuel type was consulted to establish the actual measured relationship between the stand wind and 10-m open wind speed. During the original study of fire behavior in the C-6 fuel type, the 10-m open wind speed was about three times the concurrent stand wind speed.[1] This factor of three is lower than most models would predict and is undoubtably the weakest link in the prediction; nevertheless, it provides a starting point from which we can move forward and will be accounted for in the final analysis.

Once the FFMC and 10-m open wind speed equivalent have been computed, ISI calculation is a trivial matter using the standard equations for ISI given by Van Wagner (1987) (computed ISI values for each fire are listed in Table 2):

$$f(W) = e^{0.05039(W)}$$

$$f(F) = (91.9e^{-0.1386(m)})[1 + m^{5.31}/(4.93 \times 10^7)]$$

$$R = 0.208 \times f(W) \times f(F)$$

Where W = 10-m open wind speed (km/h)
f(W) = Wind effect function
m = Fine fuel moisture content (%)
f(F) = Fine fuel moisture function
R = Initial Spread Index (ISI)

Predicted head fire ROS (shown for each fire in Table 2) is then established using the equations provided by Alexander et al. (1984):

$$ROS = 0.01544 \times ISI^{2.16} \qquad \text{(for ISI} \leq 18)$$

$$ROS = 30\ [1 - e^{-0.0440 \times (ISI-11)}] \qquad \text{(for ISI} > 18)$$

Where ROS = Head fire rate of spread (m/min)
ISI = Initial Spread Index

Discussion

The information in Table 2 shows that generally the U.S. BEHAVE system underpredicts the observed laboratory ROS, while the Canadian FBP System overpredicts. This is better displayed in Figures 1 and 2, showing the trends of the prediction systems over the range of spread rates observed. The reasons for the prediction errors for each behavior prediction system are intrinsic to the design and nature of the system.

U.S. BEHAVE:

The BEHAVE system underpredicted ROS significantly, although its predictions followed the observed trend of ROS changes with varying wind velocity. Underpredictions ranged from 15 to 60 %, which can be considered a reasonable magnitude of deviation. The scientists responsible for BEHAVE have quite often cautioned users that deviations of this magnitude may occasionally happen. Specifically, they have said that "although fires are represented by single points on the chart, it must be remembered that this is only an estimate of fire behavior and a circle would be a better representation of the uncertainty of the calculation" (Rothermel 1983). Large deviations should be mostly expected when the fuel model used (stylized or site specific) does not correctly represent the fuel complex. Adjustment methods for fuel inputs have been suggested and discussed in detail (Burgan and Rothermel 1984). On the other hand, most input variables in this case were measured with an accuracy that is much higher than is possible in the field. Since homogeneity of the fuel bed is not in question in this case and since the study took place in the same wind tunnel where most of the original data for the mathematical fire spread model were obtained, one has to be very careful in trying to explain the observed deviations.

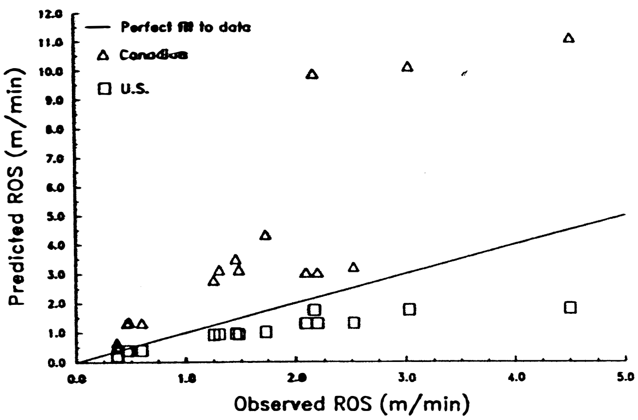

FIG 1. Comparison of observed and predicted head fire rate of spread values for both the Canadian FBP System and the U.S. BEHAVE System.

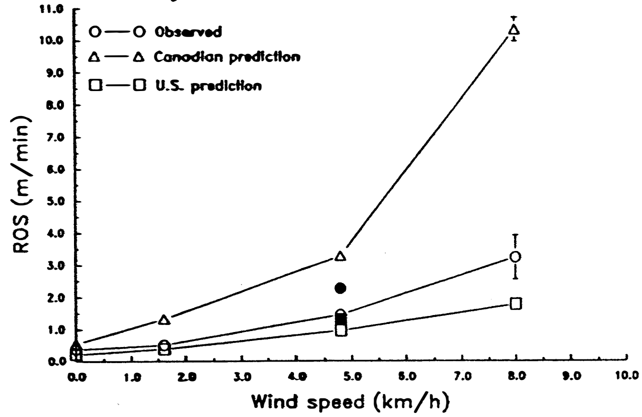

FIG 2. Observed and predicted head fire rate of spread measurments over the range of wind speeds tested. Filled symbols indicate lower fuel loading results. Average values for each set of conditions is shown, as well as standard error bars if discernible at the resolution displayed.

Two possible causes for the observed underpredictions have been identified. The first is the difference between the original wind tunnel study wind field and the one for the present study. Such differences in wind speed profiles can result in different boundary layer wind conditions. Rothermel and Anderson (1966) reported fire spread four to seven times faster in the first half of their initial test bed. When the laminar air flow of the wind tunnel was suddenly interrupted by the presence of the fuel bed, a tight rolling wind vortex was formed over the first 0.6 m of the bed. This phenomenon tipped the flames considerably further in that part of the fuel bed, resulting in more-efficient fuel preheating and consequently faster spread rates. The problem was solved by placing a 4-cm high trip fence (or spoiler) across the tunnel 0.30 m ahead of the fuel bed. This trip fence created a uniform turbulent boundary layer over the entire length of the fuel bed (Rothermel 1967). In the present study the trip fence was also utilized, but the wind profile over the fuel bed was not examined in detail. Differences in experimental design between the current study and the older study include fuel bed length (the current study fuel beds measured 6.15 m, while the original measured 3.66 m), fuel bed frames (different construction), fuel type (the current study used ponderosa pine needle litter, while the original study used excelsior and double tripod stick fuels), the addition of a wire mesh on the floor of the wind tunnel in advance of the fuel bed (to aid in the establishment of boundary layer wind conditions), and ignition technique (the current study used a point ignition device, while the older study employed a line source ignition). Ignition technique may have particular importance; the original line source ignition fires tended to spread extremely rapidly over the first portion of the bed and slowed to equilibrium,[2] while the point source ignition fires tended to accelerate to equilibrium ROS. Whether the fires stabalized at the same equilibrium ROS is open to speculation. As a result of the above factors, significant differences in the wind boundary layer could exist, causing differences in the head fire ROS values observed in the two studies and a proportionate inaccuracy in the BEHAVE predictions.

The second possible reason for the observed underpredictions is error in the estimation of moisture content of extinction (estimated at 34.0%). Rothermel's (1972) model does not provide for moisture of extinction calculation. The method used in BEHAVE is based on a simple regression line fitted to the extinction moisture values assigned to 8 of the 13 stylized fuel models. Further work has been done on this subject (Wilson 1985) but has not yet been incorporated into BEHAVE. Higher dead fuel moisture of extinction produces a "hotter" fuel model at all moisture levels and increases the moisture at which the fire is predicted to stop spreading (Burgan and Rothermel 1984). Careful examination of the data in Table 2 reveals that significant underprediction exists even in the no wind burns (burns 24, 25, 27), in which case the wind profile problem discussed previously is irrelevant. It appears that the fuel model should be "hotter", which can be achieved by increasing its moisture of extinction. The model can also be made "hotter" by changing the heat content of the fuel model to 22,183 kJ/kg, which is the mean heat content for ponderosa pine foliage reported by Kelsey et al. (1979). Both of the above modifications to the fuel model were tried simultaneously for the no wind case, but even then the underprediction only decreased to approximately half the initial value.

CANADIAN FBP SYSTEM:

As shown in Figures 1 and 2 and in Table 2, the Canadian FBP System consistently overpredicted the observed head fire ROS by 20 to 350%. Several possible explanations could be contemplated; however, there are two primary reasons: the experimental design and the wind speed estimation.

The experimental design contravenes the basis for the design of the Canadian FBP System. The FBP System was designed on the basis of small-scale experimental fires conducted under natural conditions. The laboratory fires conducted may or may not be representative of wildland fires conducted under the same environmental conditions. Factors possibly contributing include the absence of a forest stand, short-range spotting (<5m) that is accounted for automatically by the FBP System and is totally absent, fuels present in a natural setting that contribute to fire behavior in a minor way are lacking, and possible convection column effects on the fire behavior.

The conversion of the wind tunnel wind speed to an equivalent 10-m open wind speed is weak, to say the least. The range of factors documented in the literature as stated previously is large. Since the FBP System, like any other system for fire behavior prediction, is highly sensitive to changes in wind speed, small errors in this arena can cause massive prediction errors. The conversion factor chosen was somewhere in the middle of the potential range, thus a larger factor would amplify the prediction error and a smaller factor would reduce the prediction error. The argument presented for the wind profile in the U.S. BEHAVE system also likely has merit in the Canadian FBP System, i.e., it is unlikely that the wind profile simulated in the laboratory wind tunnel is precisely equivalent to that found in field conditions. Indeed the pattern of error observed in Figure 2 indicates increasing deviation from the observed ROS with increasing wind speed. Since the Canadian ROS prediction is based on empirical field research data, the pattern portrayed is likely more representative of wildland relationships (at least in this fuel type). This observation may indicate that wind tunnel wind speeds not only are not equal to field wind speeds (when they relate to forest fire ROS) but are also not linearly related.

As shown in Table 2, the ROS for the series of fires conducted with the lower fuel bulk density (13.1 kg/m^3) were fairly accurately predicted by the FBP System. This might lead us to believe that fuel bulk density is a factor in the prediction error problem; however, the original field study to document the C-6 fuel type had a fuel bulk density of 21.0 kg/m^3 (Van Wagner 1968), very close to the higher fuel loading value 26.0 kg/m^3, thus nullifying this argument.

Finally, the last possible explanation has to do with the original data upon which the C-6 fuel type is based. The data was collected from a single location, introducing a possible fixed bias in the application of the fuel type range.

Summary

The goal of this study was to compare the results of two methods of predicting head fire ROS with the observed head fire ROS. As with any model, it would have been possible to tinker with the input variable values until a good correlation was obtained, but that was not the point. The simple results from this limited laboratory study indicate that the BEHAVE fire behavior prediction system consistently underpredicted observed laboratory head fire ROS, while the Canadian FBP System overpredicted head fire ROS. Explanations can be postulated for the prediction errors observed in both systems; however, since BEHAVE was based on laboratory test fire results, a better fit to the data than was observed would be expected.

A number of reasons for the prediction errors were presented, but the most influential factor is the wind speed and the associated wind profile above the fuel. Observed head fire ROS is very sensitive to changes in wind speed, thus any predictive model must also be sensitive to changes in wind speed. How well any system for fire behavior prediction will work depends on the accuracy of the local (fire site) wind information. Small-scale perturbations in the ambient wind field will affect the head fire ROS for a short period of time; however, over the long run these minor variations should cancel out.

Endnotes

[1]Van Wagner, C.E. 1988. Personal Communication, October 20.

[2]Rothermel, R.C. 1989. Personal Communication, February 23.

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