

Short communication

Are the applications of wildland fire behaviour models getting ahead of their evaluation again?

Martin E. Alexander^a, Miguel G. Cruz^{b,*}

^a Department of Renewable Resources, Alberta School of Forest Science and Management, University of Alberta, Edmonton AB T6G 2H1, Canada

^b CSIRO Ecosystem Sciences and Climate Adaptation Flagship, GPO Box 1700, Canberra, ACT 2601, Australia

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ABSTRACT

Evaluation is a crucial component for model credibility and acceptance by researchers and resource managers. The nature and characteristics of free-burning wildland fires pose challenges to acquiring the kind of quality data necessary for adequate fire behaviour model evaluation. As a result, in some circles it has led to a research culture that tends to avoid evaluating model performance. Operational fire modelling systems commonly used in western North America have been shown to exhibit an under-prediction bias when employed to determine the threshold conditions necessary for the onset of crowning and the associated spread rate of active crown fires in conifer forest stands. This pronouncement was made a few years ago after at least a decade of model misapplication in fire and fuel management simulation modelling stemming from a lack of model evaluation. There are signs that the same situation may be repeated with developing physics-based models that simulate potential wildland fire behaviour; these models have as yet undergone limited testing against observations garnered from planned and/or accidental wildland fires. We propose a broad co-operative project encompassing modellers and experimentalists is needed to define and acquire the benchmark fire behaviour data required for model calibration and evaluation.

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1. Introduction

Wildland fire behaviour is principally concerned with the ignition or inception of a free-burning fire, its spread rate, energy released and associated flame front dimensions, perimeter and area growth, and related phenomena such as torching, crowning, spotting and firewhirl activity (Fig. 1). In recent years, models, modelling systems, and simulation modelling have come to gradually dominate scientific curiosity and practical application in predicting wildland fire behaviour. This has been a process greatly aided more by advances in computer technology (Andrews and Queen, 2003) than by breakthroughs in our understanding of fire dynamics.

Wildland fire behaviour models are typically distinguished into (1) empirical or semi-empirical and (2) physical models (Sullivan, 2009a,b). Empirical or semi-empirical-based models aim to support an operational decision-making process whereas physics-based models are primarily developed with theoretical purposes in mind, aiming to better understand the physical and chemical processes controlling fire propagation.

The use of models has played an integral role in natural resource management decision-making. But model adoption and application should be preceded by an evaluation protocol as well as verification that demonstrates model outcomes represent the processes they aim to describe within acceptable error bounds (Johnson et al., 1985; Randall et al., 2007). The evaluation process is a component of judicious development of environmental models, particularly those aimed at supporting a decision-making process (Jakeman et al., 2006; Robson et al., 2008).

Model evaluation is of critical importance in the research associated with natural hazards phenomena where the use of models or the interpretation of their outcomes has direct implications for the safety of the general public as well as fire and emergency services staff. The court process and conviction of seven experts who provided public advice ahead of the 2009 L'Aquila earthquake in central Italy (Cartledge, 2012) highlights the issues scientists and model users can be confronted with in the era of modern accountability (Eburn and Dovers, 2012).

We contend that the focus of operationally oriented models used in simulating surface and crown fire behaviour during the past 10–15 years has been misguided (Cruz and Alexander, 2010). Further, we suggest that there is the potential for the application of physics-based fire behaviour models to proceed ahead of the

* Corresponding author.

E-mail address: miguel.cruz@csiro.au (M.G. Cruz).



Fig. 1. Sequence of photos taken during the afternoon of August 22, 2005 near Coimbra, Portugal, showing some of the complexities involved in free-burning wildland fire behaviour: (a) an advancing wildfire in a maritime pine (*Pinus pinaster* A.) forest spotting into an opening (local time: 16:39:57), followed by (b and c) spot fires coalescence (respectively 16:41:14 and 16:41:28), and (d) merging with the main flame front (16:41:38), resulting in a greatly increased flame height. The elapsed time between photos (a) and (d) was 105 s (photos by M.G. Cruz).

needed model evaluation. In this paper we outline the basis for our déjà vu – like revelation. We also recommend ways to improve the situation. However, it is not our purpose here to provide a detailed evaluation protocol per Jakeman et al. (2006) and Blocken and Gualtieri (2012) for wildland fire behaviour models.

2. Operational fire behaviour models

Beginning in the late 1990s, several fire modelling systems incorporated the coupling of Rothermel's (1972) surface fire model with his crown fire rate of spread model (Rothermel, 1991) and criteria for crown fire initiation and propagation in conifer forests as described by Van Wagner (1977, 1993). These systems were in turn used extensively for assessing the effectiveness of fuel treatments on crown fire potential for more than a decade. However, as Cruz and Alexander (2010) pointed out, the operational fire modelling systems currently used to simulate the onset of crowning and active crown fire rate of spread in conifer forests of the western US exhibit a significant underprediction bias.

The principal sources of this underprediction bias were shown to include (Cruz and Alexander, 2010): (1) incompatible model linkages, (2) use of surface and crown fire rate of spread models that have inherent underprediction biases themselves (Fig. 2), and (3) a reduction in crown fire rate of spread based on the use of unsubstantiated crown fraction burned functions. The use of

uncalibrated custom fuel models to represent surface fuelbeds was considered as a fourth potential source of bias.

The results of simulation studies using operational fire modelling systems like NEXUS (Scott and Reinhardt, 2001) for example gave the illusion that most conifer forests were “crown fire-proof” given the exceptionally strong winds (e.g. $>100 \text{ km h}^{-1}$) that were considered needed to induce crowning (Scott, 2006). Schoennagel et al. (2009) identified that 44,613 fuel manipulation treatments had been implemented over an area totalling around three million hectares in 11 western US states between 2004 and 2008. Some 565,000 ha were thinning treatments, of which 15% were within the “community protection zone”. To what degree fire modelling systems like NEXUS have been applied to derive the operational prescriptions for thinning treatments aimed at mitigating crown fire potential is unknown. However, the potential for misguided management with detrimental consequences is a real possibility, as would be with other applications of these systems in fire and fuel management (e.g. Platt et al., 2011).

In spite of an increased awareness and recognition of shortcomings in these operational fire modelling systems, they continue to be applied much in the same manner as in the past (e.g. Johnson et al., 2011; Van de Water and North, 2011; Honig and Fulé, 2012). There does however appear to be a shift in emphasis from fuel management issues as in the past to broader ecological and environmental matters such as gauging the effects of forest insect infestations, forest restoration and climate change scenarios on

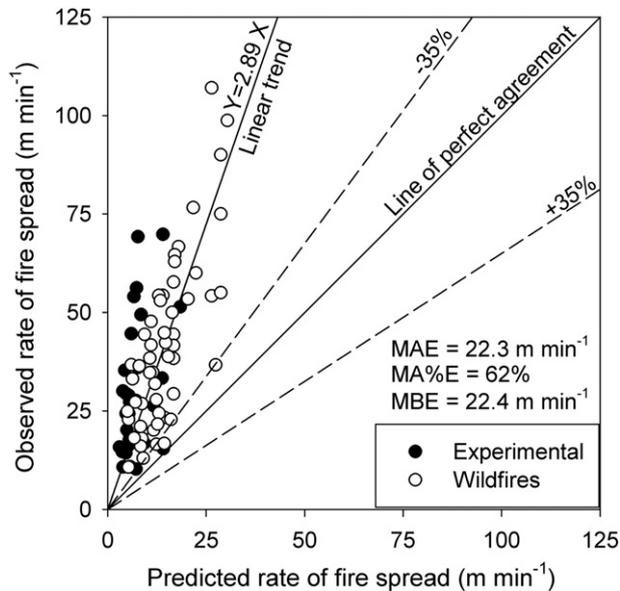


Fig. 2. Observed rates of spread of experimental active crown fires ($n = 34$) and wildfires that exhibited extensive active crowning ($n = 54$) versus predictions based on the Rothermel (1991) crown fire rate of spread model (adapted from Cruz and Alexander, 2010). The dashed lines around the line of perfect agreement indicate the $\pm 35\%$ error interval. MAE is the mean absolute error, MA%E is the mean absolute percent error, and MBE is the mean bias error (Willmott, 1982).

crown fire potential (e.g. Ager et al., 2010; Simard et al., 2011; Honig and Fulé, 2012; Schoennagel et al., 2012; Stephens et al., 2012).

Had an evaluation of the model coupling that underpins these operational fire modelling systems taken place at the outset, adjustments could have been made and more than a decade of misapplication and erroneous results reported in the literature would have been avoided. Some fire modelling system developers have resisted evaluating their product, despite concerns about severe underpredictions raised by some researchers (e.g. Fulé et al., 2001; Agee and Lolley, 2006). Scott and Reinhardt (2001) stated that there was a “lack of high-quality validation data” available to do so, and acknowledged that the “gathering high quality data from prescribed and wildfires for building and testing models of fire behavior should be made a high priority”.

Research users like Stephens et al. (2009) considered that fire behaviour “models have not all been field validated because of the difficulty of doing so” but offered no further explanation. Honig and Fulé (2012) stated that crown fire behaviour models “cannot be reasonably validated by real-world data owing to the difficulty of controlling crown fire activity”. While the possibility of an “escape” is always possible with an intentional use of fire, conducting high-intensity experimental fires has been shown to be feasible (Van Wagner, 1977; Stocks et al., 2004), even in problematic fuel types where propagation is accompanied by extensive spotting (McCaw et al., 2012).

3. Physics-based fire behaviour models

Physics-based or processes oriented fire behaviour models are formulated on the basis of the chemistry and physics of combustion and heat transfer mechanisms involved in a wildland fire (Sullivan, 2009a; Morvan, 2011). The complexity and computational requirements of some of physics-based fire behaviour models limit their testing to idealized, laboratory scale experimental fires (Morvan and Dupuy, 2001; Zhou et al., 2005). FIRETEC (Linn et al., 2002) and the Wildland–urban interface Fire Dynamics Simulator

(WFDS) (Mell et al., 2007) constitute two models recently used to quantify wildland fire dynamics.

3.1. FIRETEC development and evaluation

FIRETEC has been under development by the Earth and Environmental Sciences Division at the Los Alamos National Laboratory since 1994 for the specific purpose of modelling fire behaviour in wildland fuels. This model has continuously evolved to accommodate computational refinements such as improved treatment of sub-grid combustion and pyrolysis processes (Colman and Linn, 2007; Clark et al., 2010). Since 2005, the Institut National de la Recherche Agronomique in Avignon, France, has participated in the continuing development of FIRETEC (J.-L. Dupuy, personal communication, 2012).

FIRETEC simulations of fire behaviour in a variety of wildland fuel complexes have been undertaken over the years with the focus being on the analysis of simulated fire dynamics (Linn and Cunningham, 2005; Linn et al., 2012b) including model response to changes in topography (Pimont et al., 2012), fuel complex arrangement (Linn et al., 2010), and interacting flame fronts (Dupuy et al., 2011). This work was undertaken to qualitatively validate the capacity of FIRETEC to describe fire behaviour, rather than the accuracy of model predictions per se. Evaluations of FIRETEC simulations have until recently been limited to comparisons against outputs of empirically based rate of fire spread models like that of Cheney et al. (1998) for grasslands and those of Vega et al. (1998) and Fernandes (2001) for shrublands. FIRETEC replicated well the trends exhibited by the grassland model (Linn and Cunningham, 2005). The comparison against the shrubland models resulted in marked discrepancies possibly due to the assumptions made regarding fuel complex structure (Marino et al., 2012).

Dupuy et al. (2011) have however indicated that “reasonable agreement” was found between model predictions and spread rates observed in four small-scale free-burning experimental fires carried out in shrublands in southern France and Spain. They also thought the model provided acceptable predictions of the behaviour of interacting flame fronts in this fuel complex. Linn et al. (2012a) compared FIRETEC rate of fire spread predictions with observed values for two of the 10 experimental crown fires carried out in a jack pine (*Pinus banksiana*) – black spruce (*Picea mariana*) forest as part of the International Crown Fire Modelling Experiment (ICFME) project in Canada’s Northwest Territories (Stocks et al., 2004). The FIRETEC rate of spread predictions were in close agreement with the observed rates given the error expectations found for operational fire behaviour models (Alexander and Cruz, 2006). Although these preliminary comparisons are encouraging, the sample size is small.

3.2. WFDS development and evaluation

WFDS represents an extension of the Fire Dynamics Simulator (FDS), a well-established modelling system developed for simulating structural fires (McGrattan et al., 2007) as developed by the Fire Research Division of the National Institute of Standards and Technology (<http://fire.nist.gov/fds/>). Work began on the development of WFDS in 2003. The WFDS software is freely available for downloading (<http://www.fs.fed.us/pnw/fera/research/wfds/index.shtml>). WFDS was initially intended for modelling wildfire spread through wildland–urban interface areas (Mell et al., 2010) but it would now appear to be viewed as applicable to wildland fuels in general and other fire situations (e.g. Morvan et al., 2011).

FDS has undergone a continuous, well-documented model verification and validation process of fire dynamics in structural

and industrial settings (McDermott et al., 2010; McGrattan et al., 2010). This process has ultimately increased model credibility and allowed its developers to identify model shortcomings that have led to model reformulation and its ongoing improvement.

To date, evaluations of WFDS have been limited to (i) comparisons against an existing empirical-based fire behaviour model and data associated with two outdoor experimental grassland fires and (ii) laboratory experiments of individual burning Douglas-fir trees involving a stationary heat source and trees of different heights and moistures. Mell et al. (2007) found that WFDS simulations of head fire rate of spread “compared favourably” to the rate of fire spread model developed by Cheney et al. (1993) for continuous, cured grassland fuels (the very simplest of wildland fuelbeds made up of homogeneous, thermally thin fuels without marked gradients in fuel moisture) as well as the fire perimeter growth dynamics of two experimental fires (Fig. 3). The Cheney et al. (1993) empirical-based model was found to underpredict the spread rate potential of wind-driven wildfires in grassland fuels. Cheney et al. (1998) subsequently revised the model to more accurately reflect free-burning fire propagation in grassland fuels. This suggests that the WFDS numerical and thermophysical parameterization used by Mell et al. (2007) is likely to underpredict the spread rate of Australian grassland fires.

Mell et al. (2009) also reported favourable comparisons between predictions and measurements made involving the burning of individual 2- and 5-m tall Douglas-fir (*Pseudotsuga menziesii*) trees in a laboratory setting (Fig. 4a). While these outcomes are encouraging from a general fire behaviour standpoint, the situation is considerably different from what would be experienced within a forest involving a free-burning surface fire with a distinct horizontal flame zone depth (Fig. 4b) as opposed to a stationary “ring of fire” (Fig. 4a). Nevertheless, some authors have regarded this laboratory experiment as proof that WFDS is suitable for predicting crown fire initiation (e.g. Contreras et al., 2012).

3.3. FIRETEC and WFDS applications

Initially portrayed as research models (Linn et al., 2012a), physics-based fire behaviour models such as FIRETEC and WFDS are increasingly being utilized to address a number of specific fire and fuel management applications, without evaluation for the fuel complexes that the simulations are being carried out in, namely conifer forests or shrublands. This is a situation analogous to what began to occur some 15 years ago with the operational systems

mentioned previously. Furthermore, simpler models are being derived from trends exhibited by the physics-based models to support a field application (Contreras et al., 2012).

Cassagne et al. (2011) for example used FIRETEC to evaluate the effectiveness of prescribed burning to reduce fire hazard and the temporal extent of this effect, yet to date FIRETEC has not been shown to be able to reliably predict rate of spread, let alone fireline intensity or flame height in shrubland fuel complexes. Nonetheless, on the basis of the simulated results, Cassagne et al. (2011) have suggested prescribed burning return intervals that will ensure safe fire-fighting operations. Similarly, Pimont et al. (2011) have made inferences relative to the effect of distinct silvicultural treatments on fire behaviour in pine forests.

Like FIRETEC, WFDS has recently been applied to specific fire and fuel management applications. Hoffman et al. (2012) for example used WFDS to quantify the effects of tree mortality on potential crown fire hazard associated with mountain pine beetle (*Dendroctonus ponderosae*) attacks in lodgepole pine forests (*Pinus contorta*). They justified their use of WFDS over other models based on its ability to account for the spatial variability in fuels and fuel-fire-atmospheric interactions that current operational fire behaviour modelling systems are incapable of addressing. However, WFDS has not been subjected to an evaluation related to these factors, nor did Hoffman et al. (2012) offer empirical evidence or other information to substantiate the idea that their simulations of fire behaviour in lodgepole pine stands attacked by mountain pine beetle were representative of real-world situations.

A fair question is just how realistic are the simulations from WFDS in lodgepole pine stands attacked by the mountain pine beetle attacked or even unaffected stands? The application of WFDS to conifer forests (Parsons et al., 2011; Contreras et al., 2012), shouldn't imply that it is necessarily capable of producing realistic predictions of fire behaviour in these fuel complex structures.

There is a current trend towards management-oriented outcomes being derived from the results of physics-based fire behaviour models. This arises, in part, from the pressure stakeholders and funding agencies often put on researchers to produce immediate, tangible results (J.-L. Dupuy, personal communication, 2012), leading to models producing management outputs in scenarios they have not been evaluated against. The obvious question then is: what are the associated safety and environmental hazards if the parameterization in these modelling exercises proves to be wrong?

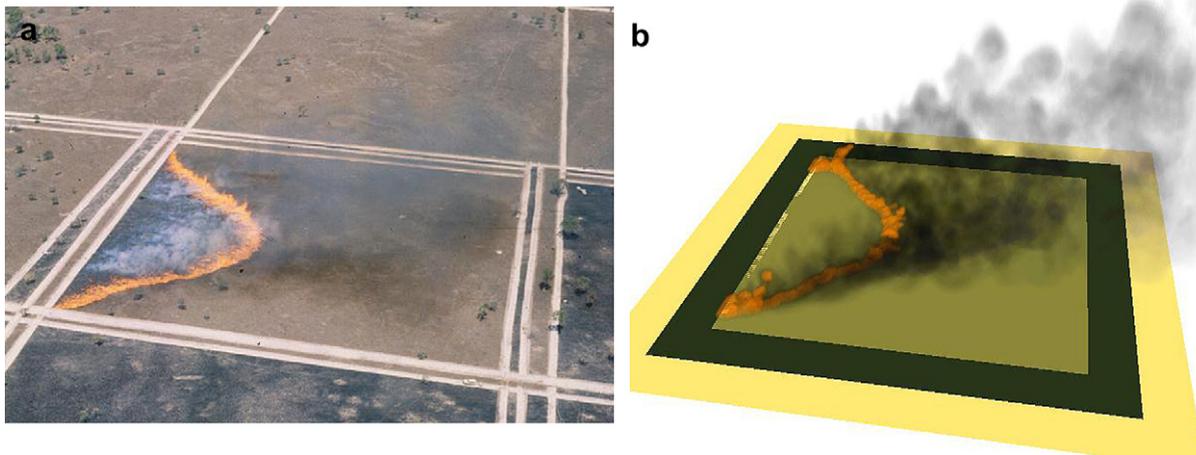


Fig. 3. Comparison of observed versus simulated fire behaviour (from Mell et al., 2007): (a) oblique aerial photograph of an experimental grass fire in the Northern Territory of Australia (200 by 200 m plot size) and (b) a WFDS visual simulation of the experimental grass fire at the same elapsed time since ignition. For a comparable view of an experimental crown fire from the International Crown Fire Modelling Experiment (Stocks et al., 2004) and the corresponding FIRETEC visual simulation, see Pimont et al. (2009).



Fig. 4. Photos of two contrasting fire behaviour situations involving conifer trees: (a) burning a 2-m tall Douglas-fir tree in the Large Fire Laboratory at the National Institute of Standards and Technology campus in Gaithersburg, MD (photo from Mell et al., 2009) and (b) surface heading fire associated with prescribed underburning in a maritime pine (*Pinus pinaster*) plantation in central Portugal (photo by P.M. Fernandes, Universidade de Trás-os-Montes e Alto Douro, Vila Real, Portugal).

4. Implications for wildland fire research

Extensive model evaluation needs to be viewed as an integral and crucial part of the model development process as demonstrated, for example by Cruz et al. (in press), especially when the ultimate aim of the model is to support a decision-making process (Jakeman et al., 2006; Alexandrov et al., 2011). The evaluation of models such as FIRETEC and WFDS is a complex process given the range of phenomena and multiple scales represented. Some of the elements of these models, such as pyrolysis, combustion and heat transfer processes, and the fire-induced flow fields, are extremely difficult to measure in a field setting. Nonetheless, the attempt to transpose model outputs from the simulation realm into specific fire and fuel management applications needs to be preceded by an evaluation of the accuracy of the models in describing such basic fire behaviour characteristics as the spread rate, intensity and flame height of free-burning fires.

Consider the case of the crown fire rate of spread model of Albini (1996). The initial model developed showed good performance when compared against a dataset of nine experimental crown fires in an immature jack pine forest, one of which was used for calibration purposes (Albini and Stocks, 1986). However, the lack of additional data for evaluation purposes and the high computational requirements ultimately precluded further application. Evaluation of the model against data collected as part of the ICFME project (Stocks et al., 2004) showed inconsistencies in model behaviour and performance (Butler et al., 2004). The need to better understand crown fire dynamics and further test the performance of the Albini (1996) model was the principal justification for the ICFME undertaking. Had this evaluation not been carried out, the model might have been implemented in various decision support systems, leading to misguided and potentially hazardous management policies and directives.

Physics-based fire behaviour models hold great promise in advancing our theoretical understanding of wildland fire dynamics, including direct linkages to biophysical processes. But are the results they produce realistic? Are the rate of spread outputs accurate across the several orders of magnitude this quantity spans in a wildfire? Given that there is so little testing against empirical field observations, there is a great deal of uncertainty associated with their validity and in turn a potential lack of creditability in these models. For example, neither FIRETEC nor WFDS has been evaluated for their ability to predict crown fire initiation such as

undertaken for the Cruz et al. (2006) crown fuel ignition model based on experimental surface and crown fires. One of the potential limitations of existing fire behaviour datasets that could be used to evaluate physics-based models is that there could be input variables that were not documented, thereby necessitating the need to make assumptions such as Mell et al. (2007) and Linn et al. (2012a) have had to undertake.

An active program of experimental burning coupled with the monitoring of prescribed fires and wildfires (Stocks et al., 2004; Alexander and Taylor, 2010) is sorely needed to evaluate both current operational and physics-based fire behaviour models before any further applications are undertaken (Cruz et al., 2003). It is recognized that the type of data necessary to evaluate physics-based models is not traditionally measured (e.g. detailed 3-D description of the fuel complex and wind field, as well as measurement of convective and radiative heat fluxes). A concerted effort on the part of both fire behaviour modellers and experimentalists will be required to produce the type of benchmark data on fire propagation covering a broad range of fuel types needed for model evaluation purposes. Such an undertaking will also need the full support of land management agencies and fire operations personnel. We can cite several examples of where this has happen in the past with other wildland fire behaviour research projects (Stocks et al., 2004; Cruz et al., in press; McCaw et al., 2012).

The general reluctance to undertake evaluations seen earlier with operational counterparts should be avoided with physics-based fire behaviour models. Research and operational users of these models should insist on it and refrain from focusing on specific fire and fuel management applications until such time as an evaluation has been accomplished to a reasonable endpoint. Research funding agencies should also recognize the pressing need to support studies to quantitatively evaluate physics-based models. Noteworthy, although our paper focus on fire behaviour modelling, the need for system evaluation extends to other fire modelling subjects such as fire danger rating (Sharples et al., 2009) and wildfire risk assessment (Fiorucci et al., 2008).

For maximum efficiency and in the spirit of a “common good”, a cooperative project at a global level (Weber, 1995) in all these undertakings should be undertaken with a view to first publishing a peer-reviewed research problem analysis in order to systematically guide the process (Stoltenberg et al., 1970). Such details are beyond the scope of the present paper but model evaluation would undoubtedly include examination of the wealth of existing,

independent datasets (e.g. Cheney et al., 1993, 1998; Stocks et al., 2004; Alexander and Cruz, 2006; Cruz et al., 2006, in press; McCaw et al., 2012).

5. Summary

Operational fire modelling systems were previously shown to possess a number of weaknesses that limited their use in assessing the flammability of natural forests and the effectiveness of fuel treatments in reducing crown fire potential. Had evaluations been undertaken as part of system development prior to implementation, more than a decade of misapplication could have been averted.

The potential for a similar situation to arise exists with respect to the use of the present generation of physics-based models of wildland fire behaviour. Considering the implications to public and wildland firefighter safety, community wildfire protection, environmental quality, and ecological integrity, this is not considered acceptable. Model evaluation based on field observations and measurements of free-burning fires across a range of fuel types and fireline intensities is needed.

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