Limitations on the accuracy of model predictions of wildland fire behaviour: A state-of-the-knowledge overview

by Martin E. Alexander[1] and Miguel G. Cruz[2]

ABSTRACT

The degree of accuracy in model predictions of wildland fire behaviour characteristics are dependent on the model's applicability to a given situation, the validity of the model's relationships, and the reliability of the model input data. While much progress has been made by fire behaviour research in the past 35 years or so in addressing these three sources of model error, the accuracy in model predictions are still very much at the mercy of our present understanding of the natural phenomena exhibited by free-burning wildland fires and the inherent temporal and spatial variability in the fire environment. This paper will serve as a state-of-the-art primer on the subject of error sources in model predictions of wildland fire behaviour and includes a short historical overview of wildland fire behaviour research as it relates to model development.

Keywords: fire behaviour prediction, fire environment, fire modelling, model applicability, model input accuracy, model relationships, rate of fire spread

RÉSUMÉ

Le niveau de précision des modèles de prédiction sur les caractéristiques du comportement des incendies de forêt dépend de leur pertinence à une situation donnée, de la validité des relations comprises dans le modèle, et de la fiabilité des intrants du modèle. Bien que la recherche sur le comportement du feu ait fait beaucoup de progrès au cours des quelque 35 dernières années afin d'atténuer les sources d'erreurs du modèle, la précision des prédictions demeure tributaires de notre compréhension actuelle des phénomènes naturels qui se produisent lorsqu'un incendie de forêt brûle librement et de la variabilité temporelle et spatiale propre à l'environnement de l'incendie. Ce document se veut une amorce à la fine pointe des connaissances sur les sources d'erreur dans les modèles de prédiction sur le comportement des incendies de forêt et comprend un aperçu historique de la recherche sur le comportement des incendies forestiers concernant le développement de modèles de prédiction.

Mots-clés : comportement d'un incendie, environnement de l'incendie, modélisation des incendies, pertinence du modèle, précision des intrants du modèle, relations du modèle, taux de propagation du feu

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Introduction

Wildland fire behaviour is broadly defined as the manner in which fuel ignites, flame develops, fire spreads and exhibits other related phenomena as determined by the interactions of fire with its environment—i.e., fuels, weather and topography (Merrill and Alexander 1987). More specifically, fire behaviour includes "a set of characteristics that describe the rate of the fire's spread, the fuel strata it consumes, the overall shape of its perimeter, its rate of energy release along the perimeter, its mode of propagation, and perhaps the geometry of the flames along the perimeter" (Albini 1984). The immediate needs of fire operations personnel for fire behaviour information would most likely be met by a partial list of such descriptors (McArthur 1968, Alexander 2000a), although fire behaviour researchers would be focused on developing predictive models for all these characteristics.

Safe and effective control of wildfires and the use of fire as a management tool is dependent on the ability to predict fire behaviour as accurately as possible (Countryman 1972). Fire behaviour is determined by complex chemical and physical processes occurring over a wide range of spatial and temporal scales (Santoni *et al.* 2011). The observed spread rate in a high-intensity, free-burning wildfire, for example, can span over four orders of magnitude around its perimeter (Cruz *et al.* 2012). The ability to accurately model fire processes over these disparate scales offer significant challenges.

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How accurately can we expect to predict wildland fire behaviour? It is quite unlikely that the minute-by-minute behaviour of a fire will be achievable as the hour-to-hour variation remains a challenge. The difficulty in predicting wildland fire behaviour boils down to the fact that there are numerous, interacting variables involved (Fig. 1). Even if a perfect mathematical model for predicting fire behaviour were available, there are still uncertainties associated with inherent variation in fuels, weather and topography in both time and space (Countryman 1972).

The main sources of error in model predictions of wildland fire behaviour are lack of model applicability, internal inaccuracy, and data input errors (Albini 1976a). This paper represents in part an expansion and updating of the earlier scholarship on the subject of error sources associated with predictions of wildland fire behaviour by the late Dr. Frank Albini. Readers and "students of fire" may find the extensive bibliography, which includes many items long since forgotten, of great value in exploring the subject in greater depth.

A Brief Historical Sketch of Developments in Wildland Fire Behaviour Research

The first known field research into rate of fire spread was undertaken by Show (1919) who documented the growth of experimental point source fires in the ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) forest type of northern California during the summers of 1915 to 1917. Gisborne (1927) published the first wildfire case study. Field studies involving experimental fires began in earnest in the early 1930s in the U.S. (Curry 1936, Curry and Fons 1938, Bickford and Bruce 1939) and Canada (Wright 1932, Paul 1969, Simard 1970).

Jemison (1939) describes some of the frustration in those early years:

> "Rates of spread vary in a bewildering way. It would be easy to yield to the temptation to throw up our hands and say that it is useless to try for anything but good guesses at the rate a given fire will spread under given conditions of fuel, weather, and topography. The saner attitude is to keep digging away at the effect of this or that factor on rate of spread in the belief that in time the intricate puzzle will be solved by the creation of something that can rightfully be called the science of rate of spread."

The size of experimental fires in brush lands gradually expanded to that approaching a landscape scale in the late 1950s (Schroeder and Countryman 1960) and experimental burning eventually extended to the deliberate initiation of crown fires in conifer forests in Canada beginning in the early 1960s (Van Wagner 1968, Stocks 1987a,b, 1989, Alexander and Quintilio 1990, Stocks *et al.* 2004a,b).

Experimental fires carried out in a laboratory environment, including a wind tunnel (Fons 1940), were initiated soon afterwards to supplement the field studies of fire behaviour (Curry and Fons 1940, Fons 1946) that gradually evolved into more complex, outdoor investigations of fire behaviour involving heavy slash fuel loads (Fahnestock 1960, Fahnestock and Dieterich 1962, Anderson *et al.* 1966, Countryman 1969). Indoor experimental burning significantly escalated with the creation of the three national forest fire laboratories by the U.S. Forest Service during the period from 1959 to 1963 (Wilson and Davis 1988, USDA Forest Service 1993, Smith 2012). Still, the active monitoring and documentation of wildfires (Traylor 1961,

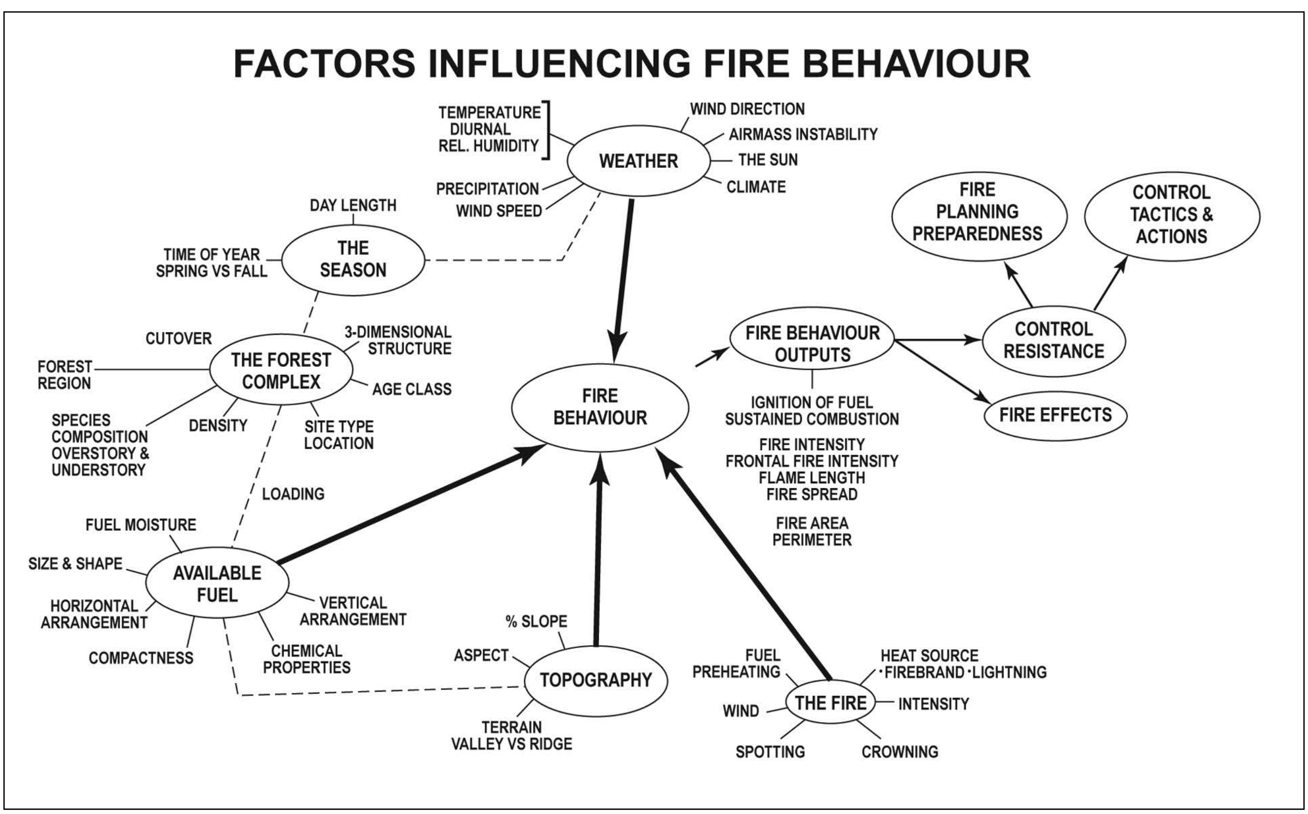

Fig. 1. Flow diagram illustrating the various factors influencing wildland fire behaviour and in turn the complexities involved in its prediction (from OMNR 1982).

Hardy and Franks 1963), begun in the mid 1920s, continued until the early 1970s.

For a time, individual fire report (Donoghue 1982) data were analyzed as source of information to produce estimates of rate of fire spread (Abell 1937, 1940, Jemison and Keetch 1942, Banks and Frayer 1966). Barrows (1951) produced the first comprehensive guide to the systematic prediction of wildland fire behaviour, which was based in part on such an approach. However, it was McArthur (1958, 1960) who, following his appointment as Australia's first full-time bushfire researcher in 1953, would produce in very short order the first operational models to the quantitative prediction of fire behaviour in the form of field guides for native forests and grasslands (Luke 1961, McArthur 1960, 1962, McArthur and Luke 1963, Cheney 1968). Refinements of these models (Fig. 2) and work on additional fuel types has continued to this day (Cruz and Gould 2009b).

Numerous mathematical models, computerized decision support systems, and guides have come to be developed for predicting wildland fire behaviour as documented in earlier reviews by Catchpole and de Mestre (1986), Weber (1991), Perry (1998), Pastor *et al.* (2003) and more recently by Sullivan (2009a,b,c). Fire behaviour models are typically distinguished into two main categories: (1) physical and (2) empirical or semi-empirical models. Physical or process-based models (e.g., Morvan and Dupuy 2001, Linn *et al.* 2005) are mostly developed with theoretical purposes in mind, aiming to better understand the physical and chemical processes controlling fire propagation. The justification for empirical or semi-empirical models (e.g., Neuenschwander 1980, Fernandes *et al.* 2009) is to support a decision-making process; the emphasis is on the purpose and perfection of the process description is not necessarily sought (Papadopoulos and Pavlidou 2011). A hybrid approach involving the two main categories of models is viewed by many as the best possible solution for the future of wildland fire behaviour research (Cruz and Gould 2009a).

Some fire behaviour models are made available as very simple and easy- to-use decision support tools (e.g., Bruner and Klebenow 1979, Alexander and Fogarty 2002). In some cases, equation development followed many years later (e.g., Noble *et al.* 1980, Beck 1995). For more complex models (e.g., Rothermel 1972) the complexity is typically, but not always, buried out of sight in the form of prepared tables (e.g., McArthur 1960, 1962, National Wildfire Coordinating Group 1992b), graphical computational aids such as nomographs (Albini 1976a), various types of slide-rule devices (Luke and McArthur 1978, McAlpine 1986, Cheney and Sullivan 2008), and computer programs (Cohen 1986, Andrews 1986).

Computer calculation of wildland fire behaviour for operational and research purposes began to take hold in the early to mid-1970s (Frandsen 1973, Albini 1976b, Albini *et at.* 1977). The use of programmable pocket or hand-held calculators proved popular in the late 1970s and first half of the 1980s (Burgan 1979, Crane 1982, Susott and Burgan 1986).

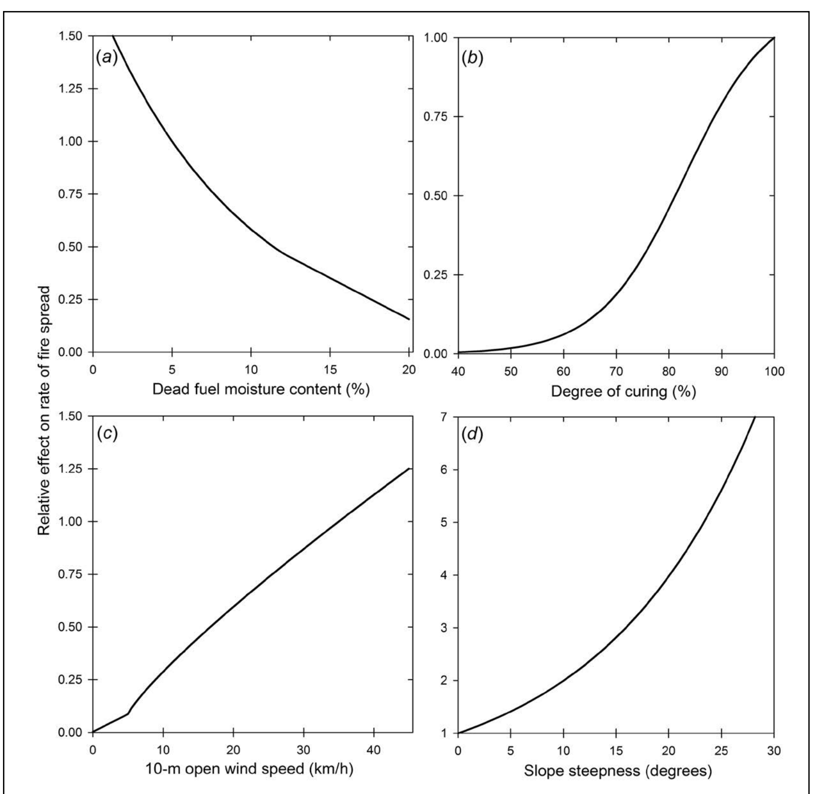

Fig. 2. Graphical representations of the (*a*) dead fuel moisture, (*b*) degree of curing, (*c*) wind speed and (*d*) slope steepness functions incorporated into the model for predicting forward or head fire rate of spread in Australian grasslands (adapted from Cheney *et al.* 1998 and Cheney and Sullivan 2008). The following conditions are assumed constant in (a) and (c): dead fuel moisture content – 5%; degree of curing – 100%; 10-m open wind speed – 35 km/h; and slope steepness – 0%.

Sources of Error in Model Predictions of Wildland Fire Behaviour

All of the fire behaviour prediction tools listed in Box 1 will produce results that do not always agree exactly with observed fire behaviour. In some instances, the disagreement can be quite significant (Brown 1982, Hély *et al.* 2001), as illustrated for example by the large (i.e., almost three times), consistent underprediction trend evident in Fig. 3.

Albini (1976a) pointed out that there are three principal reasons for disagreement between model predictions and observed fire behaviour, no matter which models are being used:

1. The model may not be applicable to the situation.
2. The model's inherent accuracy may be at fault.
3. The data used in the model may be inaccurate.

While much progress has been made in wildland fire behaviour research over the past 35 years or so since the publication of his seminal work on fire behaviour modelling, these same three basic principles still remain valid to this day.

Model applicability

If one applies a model or a system to a situation for which it was not intended to be used,

Box 1 – Examples of Operational Fire Behaviour Prediction Tools from North America, Australasia, and Europe

Tables

- Davis and Dieterich (1976) – Oak–chaparral, Arizona, USA
- Hough and Albini (1978) – Palmetto–gallberry, southeastern USA
- Sneeuwjagt and Peet (1998) – Western Australia
- Alexander and Lanoville (1989) – Black spruce–lichen woodland, Northwest Territories, Canada
- Taylor *et al.* (1997) – Canada
- National Wildfire Coordinating Group (1992b, 2006) – USA
- Alexander and Fogarty (2002) – Grasslands – New Zealand and Canada
- Gould *et al.* (2008) – Dry eucalypt forest, Australia
- Kidnie *et al.* (2010) – southern Ontario, Canada
- Pearce *et al.* (2012) – New Zealand

Graphical and Computational Aids

- McArthur (1962) – Control burning guide for eucalypt forest, Australia
- Roussopoulos (1978) – Boundary Waters Canoe Area, Minnesota, USA
- Rothermel (1991) – Northern Rocky Mountains, USA
- National Wildfire Coordinating Group (1992a)
- Dimitrakopoulos and Dritsa (2003) – Greece
- Leuschen (2005) – Potential Rate of Spread (PROS) Chart, USA
- Bishop (2007) – FireLine Assessment MEthod (FLAME), USA
- Dimitrakopoulos et al. (2007) –Aleppo pine, Greece
- Scott (2007) – USA

Computer Programs

- Alexander *et al.* (2006) – Canada
- Anderson *et al.* (2008) – New Zealand
- Andrews *et al.* (2008) – USA
- Fernandes *et al.* (2012) – Maritime pine, Portugal

Slide-rule Devices

- McArthur (1966) – Grassland Fire Danger Meter, Australia
- McArthur (1967) – Forest Fire Danger Meter, Australia
- Cheney and Just (1974) – Cane Burning Meter, Queensland, Australia
- Muraro (1975) – Prescribed Fire Predictor (clear-cut logging slash), British Columbia, Canada

the error associated with the prediction can in turn be quite large (Kessell *et al.* 1980). Brown and Davis (1973: 183) had this to say about the limitations of fire behaviour models in general:

> "All fire models simulate reality but fall short of it in varying degrees. In meeting the objective of simplifying relationships, minor factors are neglected and the model is usually based on a single set of idealized conditions. If fire-modelling laws are observed, this will permit approximations close enough for many purposes, but it is easy to forget that they are approximations only. Consequently, there is a strong tendency to apply models beyond their field of usefulness. To avoid this, the assumptions on which they are based and the range of conditions under which the model is valid need to be carefully defined and frequently rechecked."

There are for example 18 major assumptions associated with Rothermel's (1991: 36–37) guide to predicting crown fire behaviour and size in the U.S. Northern Rocky Mountains.

Most rate of fire spread models have the following kinds of limitations and should not be expected to predict what they do not pretend to represent (after Albini 1976a):

1. *The fuel complex is assumed to be continuous, uniform, and homogeneous.* The more the actual fuel situation departs from this idealized assumption, the more likely the prediction will not match the observed fire behaviour. While this issue is a matter of scale, subsequent research (e.g., Frandsen and Andrews 1979, Catchpole *et al.* 1989) and other innovations (Fujioka 1985, Finney 2003) such as the two-fuel model concept (Rothermel 1983, Martin 1988), as well as geographic information system (GIS)-based fire growth models (Beck 2000, Finney 2004, Tymstra *et al.* 2010) have not substantially reduced this problem. It thus remains a continuing research challenge (Parsons *et al.* 2011) and involves both the physical fuel characteristics as well as fuel moistures, including differences due to topographic features such as slope exposure (Cheney 1981).

2. *Some models assume that the fuel bed is a single layer and is contiguous to the ground.* In other words, there is no distinct gap between fuel layers (e.g., a forest stand with ground/surface fuels and crown or aerial fuels). As Van Wagner (1985) has so emphatically stated, "The fire world would beat a path to the door of the modeller who could account for vertical gradients and interruptions in moisture content and fuel density." Much progress has been made in recent years to model the step changes in fire behaviour (Fig. 4) due to variations in vertical fuel continuity, composition and structure, both empirically (Van Wagner 1977a, Gould *et al.* 2007, Cruz *et al.* 2008, 2013, Cheney *et al.* 2012) and on a physical basis (Linn *et al.* 2005). Much of our understanding has come about as a result of field experimentation, particularly in Australia (Sullivan *et al.* 2012), subsequently supported by laboratory test fires (Finney *et al.* 2010).

3. *Fire spread by spotting (flying embers or firebrands) is not accounted for.* This includes laboratory or theoretically based rate of fire spread models (e.g., Rothermel 1972) and fire modelling systems that rely upon such models (e.g., Andrews *et al.* 2008). In situations where this form of fire propagation is influential or a dominant mechanism, forecasts or predictions of fire spread are likely to result in underestimates. Even statistical or empirically based models developed from burning small-scale outdoor plots may suffer the same weakness (e.g., Lindenmuth and Davis 1973). Some empirically based models or model systems indirectly include the influence of short- and intermediate-range spotting on rate of fire spread (e.g., Rothermel 1991, Forestry Canada Fire Danger Group 1992) although it is not expected

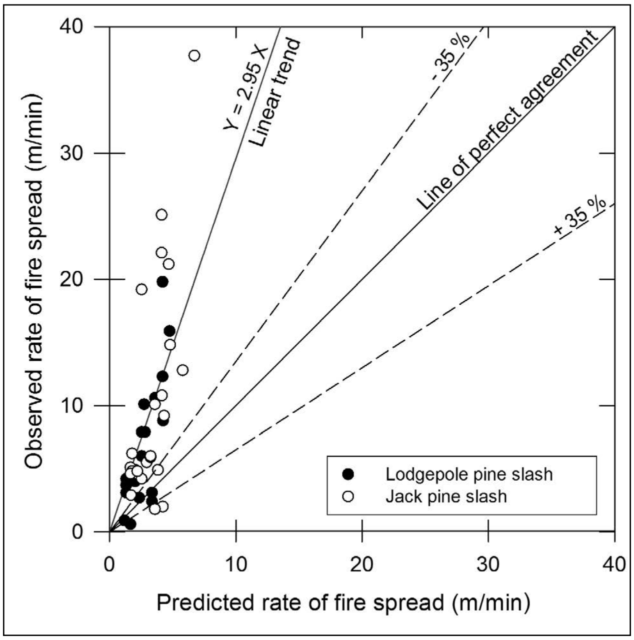

Fig. 3. Observed rates of spread for experimental fires in lodgepole pine logging slash in southwestern Alberta (Quintilio 1972) and jack pine logging slash in northeastern Ontario (Stocks and Walker 1972) versus predictions from Rothermel's (1972) surface fire rate of spread model for Fuel Model 12 – Medium Logging Slash (Anderson 1982) using a wind adjustment factor of 0.4 (Andrews 2012) (adapted from Cruz and Alexander 2013). The dashed lines around the line of perfect agreement indicate the ±35% error interval.

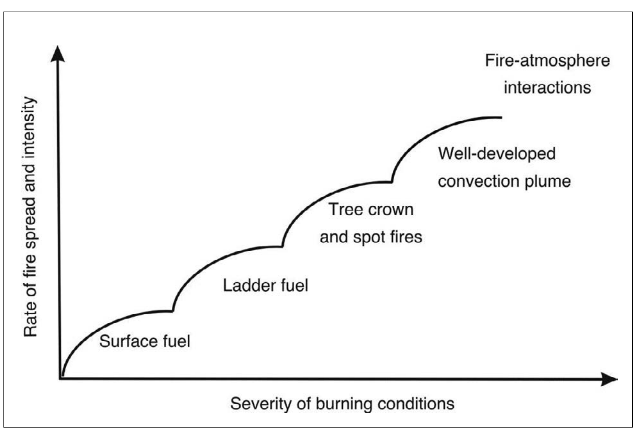

Fig. 4. Stepped-pattern observed in forest and shrubland fuel complexes that are subject to both surface and crown fire propagation (adapted from McArthur 1967).

that these models will be able to account for the effect of short-range spotting over the full spectrum of possible burning conditions. Recent simulation studies have attempted to explicitly model the transport and distribution of firebrands ahead of idealized fires (e.g., Porterie *et al.* 2007, Sardoy *et al.* 2008). The extent that new ignitions ahead of the main fire front result in an increase in the overall rate of fire spread (Fig. 5) depends on a multitude of factors such as the physical characteristics of the fuel type, moisture content of the surface fuels, the number and distribution of firebrands, and fire–atmospheric interactions. Alexander and Cruz (2006) formulated a simple method of estimating the minimum separation distance required for a newly ignited spot fire to avoid being overrun by the main advancing fire front, assuming no interaction between the two flame fronts, in order to judge when this is likely to occur. In situations involving heterogeneous fuel type distributions and complex topography, spotting will allow the main advancing fire front to quickly bypass areas with low spread potential (e.g., downslope runs, pure hardwood stands in summer, discontinuous fuels) thereby effectively advancing the horizontal extent of the fire's "head" (Boychuk *et al.* 2009). Long-range spotting, where viable firebrands are transported over distances in excess of 5 km (Cruz *et al.* 2012), have a more distinct effect on fire propagation than short- to intermediate- or medium-range spotting. In such cases, the fires typically burn independently of the source flame front and thus generally do not contribute to the movement of the main advancing fire edge, although they do contribute to the final area burned in many cases. However, depending on their density, short- to medium-range spotting can effectively serve as a proxy for a backfire and thereby temporarily decrease the head fire's momentum and the potential area burned as a whole (D. Quintilio, Dennis Quintilio and Associates, Glenevis, AB, 2012, personal communication).

4. ***Vertical and horizontal fire whirlwinds are not modelled.*** Amongst these other factors, Albini (1976a) also pointed out that the influence of fire whirls (Fig. 6) and similar extreme, fire-induced vortices (Haines and Smith 1987, McRae and Flannigan 1990) on the rate of spread or growth of a free-burning wildland fire are not considered. While fire whirls have been documented to travel in excess of 2.5 km from the main fire (Steiner 1976, Cheney and Sullivan 2008), it is questionable whether their frequency of occurrence warrants special consideration given the sporadic nature of such events. Site-specific predictions of vertical and horizontal vortex activity in wildland fires are not yet possible (Forthofer and Goodrick 2011). Nevertheless, guidelines do exist as to when and where such fire phenomena are generally thought most likely to occur (Countryman 1971, Haines and Updike 1971, Goens 1978). A quantitative understanding of how these events will specifically affect rate of fire spread for example is lacking.

Accuracy of model input data

Predictive models must be sensitive to those parameters known to readily affect fire behaviour, such as wind speed, dead fuel moisture and slope steepness, amongst others (Salazar 1985, Trevitt 1991, Bachmann and Allgöwer 2002, Jolly 2007). If these input data are not known accurately enough or the user fails to appreciate the spatial and temporal variability of input data, model output can in turn be significantly in error (Albini 1976a).

Given the nonlinear dynamics of free-burning wildland fires (Sullivan 2009d), model output may be highly sensitive to a particular parameter over one range of values and quite insensitive to that same parameter over a different value range (Albini 1976a, Cruz *et al.* 2006). Rate of fire spread models, for example, are comprised of power or curvilinear functions of wind strength, slope angle and fuel moistures (Murphy *et al.* 1966; Van Wagner 1968, 1977b; Thomas 1971; Cheney 1981; Nelson and Adkins 1988). In Fig. 2, we present an example of such relationships for a single fuel complex, namely grass. Similar composite summaries for several different fuel types have

Fig. 5. Spotting activity associated with a wildfire advancing through a maritime pine (*Pinus pinaster* Ait.) forest near Coimbra, Portugal, on the afternoon of August 22, 2005. Photo by M.G. Cruz.

Fig. 6. Fire whirlwinds are the most spectacular of all wildland fire behaviour phenomena and also the most difficult to predict. This particular fire whirl "rope" resulted from the burning of white spruce–subalpine fir logging slash approximately 120 km east of Williams Lake, British Columbia, during the summer of 1990. Photo by S.D. Harvey, British Columbia Forest Service (retired).

been prepared by Cheney (1981), Catchpole (2002) and Sullivan (2009b).

As a result of the non-linear nature of fire behaviour, it is often difficult to make a valid quantitative statement about the relationship between input data accuracy and output accuracy. As such, the model in question must be used to establish its requirements for data accuracy, considering the range of values of the variables used for input (Albini 1976a).

The greatest challenge a fire model user faces in a predictive situation is the accurate estimation of representative input values. A deterministic approach for fire behaviour prediction assumes best estimates of input conditions to represent the fire environment. Nonetheless, the fuel complex is not uniform, continuous or homogeneous. Nor is the wind speed and direction constant, the slope steepness uniform or the moisture content of dead and live fuels the same from place to place (Chandler *et al.* 1963, Crosby and Chandler 1966, Countryman 1977, Rice and Martin 1985, Gibos 2010), especially in complex, mountainous terrain (Schroeder and Buck 1970), making the prediction of fire rate of spread difficult. Yet most methods and guides to predicting fire behaviour generally assume idealized burning conditions (e.g., Rothermel 1991, Taylor *et al.* 1997, Pearce *et al.* 2012).

If standard techniques and procedures (e.g., Rothermel 1983, Norum and Miller 1984, Lawson and Armitage 2008) are strictly adhered to, the error component arising from uncertainty in input data is reduced to acceptable levels. If no direct measurements or observations are made, inaccurate forecasts are used, or predictions are based solely on good "guess-timates", then the error associated with the input data could be the dominant error source.

Internal accuracy of model relationships

Wildfires, being unpredictable as to their timing and location and often occurring in remote locations, are seldom amenable subjects for conventional instrumentation and measurement (Rothermel and Reinhardt 1983) as afforded by a prescribed fire or experimental fire although there is the odd exception (e.g., Norum 1982, Alexander *et al.* 1991). Furthermore, some aspects of wildfire behaviour, such as observations of maximum spot fire distance and associated influences (Albini *et al.* 2012), are difficult to monitor and thus to precisely document.

In the absence of a long-term, concerted effort to systematically monitor and document wildfire behaviour (Alexander and Thomas 2003a,b), data to test theoretical or empirical model formulae against actual wildfire behaviour accumulate slowly from opportunistic high-quality observations (e.g., Butler and Reynolds 1997, Alexander and Taylor 2010, Santoni *et al.* 2011, Cruz *et al.* 2012). As a result, model testing or evaluation is usually based on laboratory experimental fires (e.g., Beaufait 1965, Menage *et al.* 2012), as opposed to operational prescribed fires (e.g., Hough 1968, Doren *et al.* 1987, Custer and Thorsen 1996, Alexander 2010) or outdoor experimental fires (e.g., Stocks *et al.* 2004a,b, Stephens *et al.* 2008, Cruz *et al.* 2010, 2013, McCaw *et al.* 2012).

Albini (1976a) considered that the causal relationships between the driving variables and fire behaviour in most models must be viewed as weakly tested, semi-empirical in nature, and subject to exception. Experimental fires carried out in plots of very uniform fuel complexes involving grasslands, shrublands and conifer forest stands has shown that there will always be some degree of unexplained variation (Cheney *et al.* 1998, Cruz *et al.* 2010, 2013). For example, using the experimental crown fire dataset of Stocks (1987b) consisting of 11 observations in a uniform stand of jack pine (*Pinus banksiana* Lamb.) on level ground, with spread rates ranging from 7.9 m/min to 49.4 m/min, Alexander and Cruz (2006) found that a model based on the main drivers of fire spread, wind speed and fine dead fuel moisture, could explain 84% of the variation in the observed rates of spread. Even with laboratory fires involving constant wind flow in replicated or reproducible fuelbeds (Schuette 1965, Deeming and Elliott 1971), there can be a large degree of unexplained variation in observed spread rates (Fons 1946).

Given the inherent natural variation in wildland fire behaviour, Albini (1976a) suggested that model builders considered models successful if the relationships predict fire behaviour within a factor of two or three over a range of two or three orders of magnitude. McArthur (1977) on the other hand felt that the forest and grassland fire danger meters that he developed for Australia (McArthur 1966, 1967) could predict rate of spread and other fire characteristics to within ±20% of the actual observed fire behaviour (e.g., if the predicted rate of spread was 15 m/min then the observed rate of spread should vary from 12 m/min to 18 m/min). Cruz and Alexander (2013) have on the basis of an extensive review of 49 fire spread model evaluation studies involving 1278 individual rate of spread model prediction–observation pairs, concluded that an error threshold of 35% constitute an acceptable error for model predictions of rate of fire spread (Fig. 3).

Present-day Realities of Wildland Fire Behaviour Prediction

Predicting wildland fire behaviour is a difficult task. Long-range spotting, fire whirl development, and simultaneous ignitions over large areas are characteristics of fire behaviour that are difficult to predict with accuracy (Fig. 5 and Fig. 6). Their occurrence can be forecasted only in a very general way.

The preceding discussion can be taken as roughly representative of the current state of the art in fire behaviour model accuracy, including both the effects of model applicability and internal model accuracy. Until some of the limitations of model applicability as discussed in the previous section are relaxed by further advances in fire behaviour research, improvements in the accuracy of model relationships beyond the current level are unlikely to increase the overall accuracy of model predictions of wildland fire behaviour.

Wildland fire behaviour predictions are inevitably fraught with uncertainty. The most important source of error in any particular prediction of fire behaviour may be difficult to pin down, regardless of the whether the model systematically over- or under-predicts (Albini and Anderson 1982). As Albini (1976a) acknowledged, "The usually dominating error source in model predictions of wildland fire behavior is that the fuel complex is not uniform, continuous, homogeneous, and consolidated into a single layer. Nor is the wind speed constant, the slope everywhere the same, nor the fuel moisture content the same from place to place."

Overall prediction accuracy is also dependent upon the skill and knowledge of the user (Weick 2002, Alexander and Thomas 2004). As Cheney (1981) quite rightly points out, "the reality of fire behaviour predictions is that overestimates can be easily readjusted without serious consequences." On the other hand, "underestimates of behaviour can be disastrous both to the operations of the fire controller and the credibility of the person making the predictions." The "art and science" of predicting wildland fire behaviour includes a multitude of considerations, including being able to correctly assess both the components of the fire environment and the fire's current status (Fig. 7).

Advances in computer technology have greatly aided the operational utilization of predictive fire behaviour models in recent years (Lee *et al.* 2002, Andrews 2007). This has led to a suite of computerized decision support systems (e.g., Tolhurst *et al.* 2008, Anderson 2010, Noonan-Wright *et al.* 2011). These systems are in reality, simply mechanical schemes that involve a whole host of model and specific prediction assumptions and limitations. However, they, like the core models that they depend on, very seldom give an exact answer. As one experienced operational fire behaviour analyst recently remarked, "The products look pretty dazzling, but it remains critical that a fire behaviourist analyze them, provide feedback to the fire geospatial analysts, and interpret the outputs to decision-makers" (R.D. Wilmore, USDA Forest Service, Eagle, CO, 2012, personal communication).

Future Outlook

Few would argue that the management or control of wildland fires will never become a reality until their behaviour can be predicted over the many conditions under which they occur (Underwood 1985). As Van Wagner (1971) has stated:

> "The goal of research on the behaviour of forest fires is presumably to be able to predict with reasonable assurance how a fire will behave in any stated weather and forest fuel. This goal does not, of course, have an absolute form since the prediction of forest fire behaviour can never be an exact process. Performance may someday

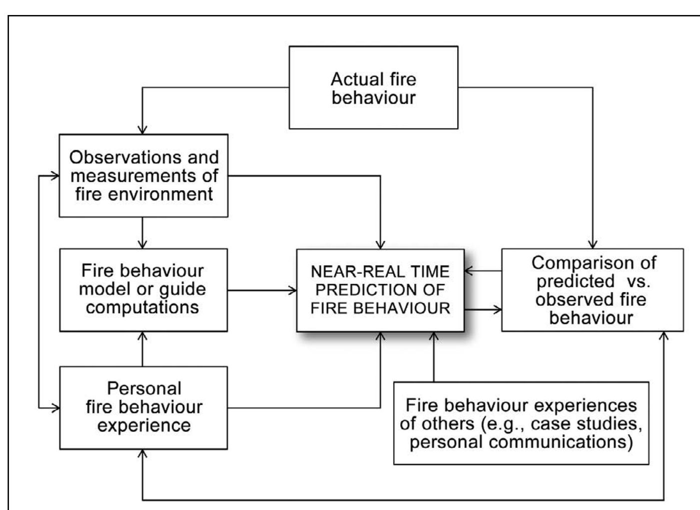

Fig. 7. Flow diagram illustrating that the "science and art" of wildland fire behaviour prediction encompasses the coupling of practical knowledge, professional judgment, and fire behaviour experiences (including local knowledge) with the computational tools produced by fire research.

approach a generally acceptable level of accuracy, but error due to the infinite variety of weather, fuel and topography will always be present."

While there is still much to do from a practical fire behaviour research standpoint (Alexander 2000b, Cruz and Gould 2009a), in the continuing desire for "better" predictions it is easy to lose sight of the fact that model predictions are only a guide and that perfect, near-real time prediction of wildland fire behaviour will probably never be achievable. Nevertheless, fire behaviour model development and training in their use has now evolved to the point that they can be successfully applied in a number of situations that were un-thought of two decades ago (e.g., community evacuation alerts, indirect fire suppression planning).

Van Wagner (1985) was also to note that "Fire behavior predictions may not be infinitely valuable: but as long as the forest fire people continue to want better ones, and there are researchers to work on them, it is safe to say that next year's predictions will be better than last year's." There are, however, undoubtedly limits to what can be expected, which begs the question, are such expectations realistic? Have we in fact reached the limit? From a purely practical operational standpoint, improvements in the field of wildland fire behaviour prediction are more likely to come about from individual self-improvement, using the best available models, local case study work and adaptation, rather than waiting and hoping for yearly advances to be made by wildland fire behaviour research.

Since the publication of Albini's (1976a) seminal work on wildland fire behaviour modelling, experimental fire behaviour field studies have provided new insights into the dynamics associated with the heterogeneity in fuel structure and moisture content, the transient nature of wind speed, and the interaction between the fire and its surrounding environment. We now possess at least a heuristic understanding of the mechanisms driving fire propagation, albeit the implementation of this knowledge into a comprehensive predictive modelling framework is yet to be achieved.

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