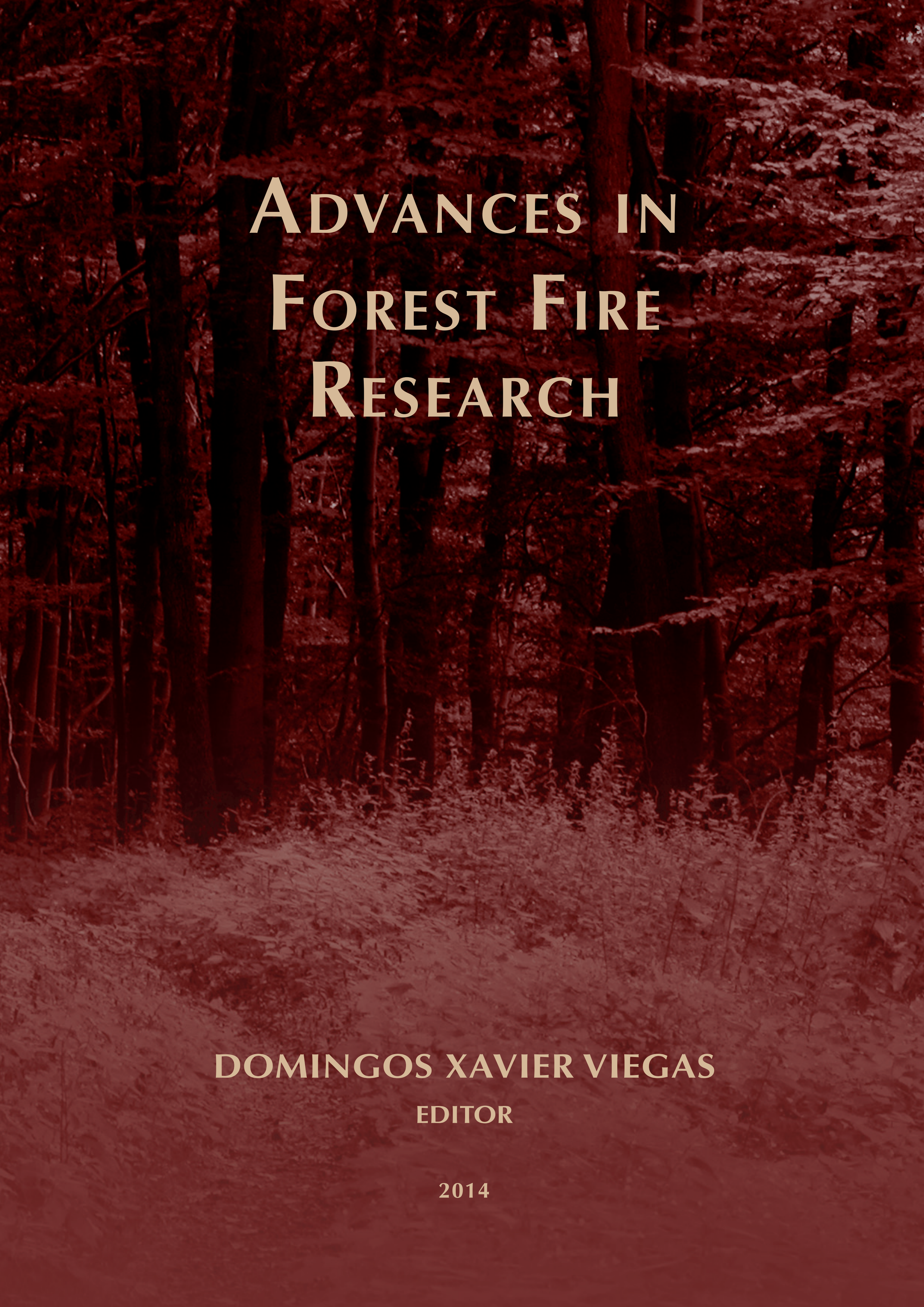

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Uncertainty in model predictions of wildland fire rate of spread

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Abstract

This paper highlights the results obtained from a comprehensive survey recently published by the authors on the error statistics associated with studies that have used independent data derived from field observations of wildfires, prescribed fires and experimental fires to evaluate the performance of 13 models used operationally to predict head fire rate of spread. Answers to the following kinds of questions were sought:

- How accurately can one expect to predict the spread rate of wildland fires with currently available models?
- Can models based on experimental fire data be used to predict wildfire behaviour?
- Are wildfires inherently more difficult to predict the spread rates of than prescribed fires or crown fires compared to surface fires?
- How realistic is it to expect an exact prediction of rate of fire spread?
- What is an acceptable error for rate of fire spread models?

A total of 49 studies, comprising 1278 paired observations vs. model predictions of fire spread rates for four forest fuel types (hardwood, mixedwood, conifer, eucalypt) and three non-canopied fuel types (grassland, shrubland, logging slash) from four continents (North America, Australia, Europe, Africa) were assembled. The answers to the five questions asked above are as follows:

- Mean absolute percent error varied between 20 and 310% and was homogeneous across fuel type groups. Slightly more than half of the evaluation datasets had mean absolute percent errors between 51 and 75 percent. Under-prediction bias was prevalent in 75 percent of the case 49 datasets analysed.
- Empirical-based fire spread rate models founded on solid field observations and well accepted functional forms, can adequately predict rates of fire spread well outside of the bounds of the data used in their development.
- There was no evidence to be found that predicting the rates of spread of wildfires was any more difficult than that of prescribed fires. Spread rates of crown fires were no more difficult to predict that surface fires.
- Only three percent (i.e. 35 out of 1278) of model predictions were considered to be exact (i.e. ±2.5 percent of the observed rate of fire spread).
- A ±35 percent error interval constitutes a reasonable standard for model adequacy.

Keywords: *fire spread models; fire behaviour; error; surface fires; crown fires; wildfires; prescribed fires.*

1. **Introduction**

There are a variety of aspects associated with the subject of wildland fire behaviour (Scott *et al.* 2014) and reasons to increase our knowledge on the subject through continuing research and improvements in operational practice (Cruz *et al.* 2014a,b). However, if one could boil down the whole science of wildland fire behaviour to its most practical essence, it might very well be to provide fire operations personnel with a decent estimate of just how fast a free-burning fire (Figure 1), either of planned or of unplanned origin, would likely spread based on the prevailing fire environment conditions (Van Wagner 1985).

This paper highlights the study undertaken by Cruz and Alexander (2013) that addressed the following kinds of questions:

- How accurately can one expect to predict the spread rate of wildland fires with currently available models?
- Can models based on experimental fire data be used to predict wildfire behaviour?
- Are wildfires inherently more difficult to predict than prescribed fires or crown fires compared to surface fires?
- How realistic is it to expect an exact prediction of rate of fire spread?
- What is an acceptable error for fire spread models?

It is fully recognized that the degree of accuracy in model predictions of rate of spread in wildland fires is 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 (Alexander and Cruz 2013b).

Figure 1. Photo of the Millers Reach #2 Fire near Anchorage, Alaska, during its major run on June 3, 1996 that involved extensive crowning in black spruce forests. Photo by: Anne Raup, Anchorage Daily News. For further information on this wildfire, see Hufford et al. (1998).

2. **Methods**

2.1. **Compilation of datasets**

In order to address the questions poised in the Introduction, a comprehensive effort was made to locate as many evaluation studies of rate of fire spread rate model performance in the literature as possible. The sources included:

- Scientific peer-reviewed journal articles
- Conference and workshop papers
- Technical reports from government agencies
- Post-graduate university theses

The principal requirements for inclusion in the analyses were that the evaluation data be (i) collected on outdoor experimental fires, operational prescribed fires and (or) wildfires, involving a “line fire” pattern similar to that observed on the head of a free-burning wildfire (Figure 1), as opposed to strip-head fires or point-source fire(s) (e.g. Sapsis and Kauffman 1991; Jupen *et al.* 2013) and (ii) that the dataset could not have been used in the model development (i.e. completely independent observational data) as Albini and Stocks (1986) did in their analysis. For example, Cruz *et al.* (2005) used the datasets of Alexander *et al.* 1991, Stocks *et al.* (2004) and Alexander *et al.* (2006) to test their crown fire rate of spread model.

Experimental fires carried out in fuelbeds or with head-fire widths judged too narrow to yield realistic pseudo-steady state rates of spread were excluded (e.g. Neuenschwander 1980; Schimmel and Granström 1997). This also included laboratory studies (e.g. Weise and Biging 1997; Menage *et al.* 2012). To ensure that each study included in the analysis had sufficient data to discern model adequacy for the particular fuel type and burning conditions, we restricted the analysis to studies that had at least five paired observations. Thus, studies like Brown (1982), Pickford *et al.* (1992) and Fogarty *et al.* (1997), for example, were excluded from the analysis. Finally, studies where model outputs were not fully independent, as a result of investigators fine tuning model predictions in relation to the observed rates of fire spread (e.g. Woodall 1998; Beavers 2001), were also not selected for analysis.

It was readily acknowledged that the data quality between studies would vary, especially between data obtained from experimental burning programs versus wildfire monitoring. Experimental fire studies are characterized by detailed sampling of fuel structure, weather and fire behaviour (e.g. Everson *et al.* 1985; Alexander *et al.* 1991; Stocks *et al.* 2004) whereas observations associated with wildfires tend to rely on broad assumptions regarding fuels and representativeness of weather data (e.g. Fogarty *et al.* 1997; Alexander *et al.* 2013).

2.2. **Calculation of statistics**

Error statistics on the rate of fire spread observations versus predictions were calculated for each of the model performance studies that qualified for inclusion. These included the root mean square error (RMSE), the mean absolute error (MAE), the mean absolute percent error (MAPE), and the mean bias error (MBE) as described by Willmott (1982). In most cases, these error statistics were not reported in the studies that we examined so it became necessary to compute them from the data contained in the associated publication or by contacting the study investigators directly for the data pairs.

The percentages of exact, under- and over-predictions were also calculated. To our knowledge, a definition for what constitutes an exact model prediction does not exist. Thus, for the purposes of this study, we elected to consider an exact model prediction as one where the error was less then ±2.5 percent of the observed rate of fire spread.

3. **Results**

3.1. **Assembled database**

Our extensive search for evaluation studies of rate of fire spread model performance resulted in the compilation of 49 suitable cases. At least two studies were overlooked, one consisting of eight low-intensity experimental fires (with spread rates less than 1.5 m/min) in an Australian eucalypt forest (Davis 1976) and a second one involving 28 observations (with spread rates of 1.0 to 89 m/min) garnered from a single wildfire in southern California chaparral (Weise and Fujioka 1998). The number (*n*) of studies by geographic distribution were as follows:

- Africa (*n* = 3)
- Australia (*n* = 14)
- Europe (*n* = 3)
- North America (i.e. Canada and US; *n* = 29)

The combined database ended up amounting to a total of 1278 individual observed rate of fire spread observation – model prediction pairs. This included three types of data (Figure 2):

- Experimental fires (*n* = 892)
- Operational prescribed fires (*n* = 182)
- Wildfires (*n* = 204)

The data encompassed a wide range in fire behaviour and fire propagation regime types, including low- to high-intensity surface fires in both canopied and non-canopied fuel complexes as well as passive and active crown fires (Van Wagner 1977) in several forest and other vegetation types that are prone to crowning (Table 1 and Figure 3). Seven broad fuel type groups could be identified in the 49 studies (Figures 4 and 5):

- Grasslands (*n* = 6)
- Shrublands (*n* = 9)
- Logging slash (*n* = 3)
- Conifer forest (*n* = 17)
- Hardwood forest (*n* = 3)
- Mixedwood forest (*n* = 2)
- Eucalypt forest (*n* = 9)

All of the studies involved either empirical (*n* = 11) or semi-empirical rate of fire spread models (*n* = 2). The lack of any physics-based models involvement simply reflects the fact that any performance evaluation studies carried out to date with these type of models has involved four or less paired cases of observation and model prediction (Alexander and Cruz 2013a).

Table 1. Sample size, range in rate of fire spread (ROS), and summary of error statistics by type of fire involved in the 1278 pairs garnered from the 49 comparison studies as compiled by Cruz and Alexander (2013)

Type of fire	No. of fires	ROS range (m/min)	Exact predictions	Under-predictions			Over-predictions		
				No. of fires	Mean MAPE (%)	Standard deviation	No. of fires	Mean MAPE (%)	Standard deviation
Surface fires	1009	0.1 – 150.9	32	631	48%	25%	346	99%	137%
Crown fires	269	3.4 – 175	3	180	51%	22%	86	61%	63%

3.2. **Mean absolute percent errors**

The mean absolute percent error (MAPE) is a very popular measure of the accuracy of a predictive model or system. It represents the summed differences between the individual predicted versus observed values divided by the observed value; multiplying it by 100 makes it a percentage error. MAPE values were found to vary between 20 and 310 percent and were homogeneous across the seven fuel type groups. The distribution of model comparisons by MAPE classes were as follows:

- 30 percent or less (*n* = 7)
- 31 to 50 percent (*n* = 9)
- 51 to 75 percent (*n* = 26)
- 76 percent and greater (*n* = 7)

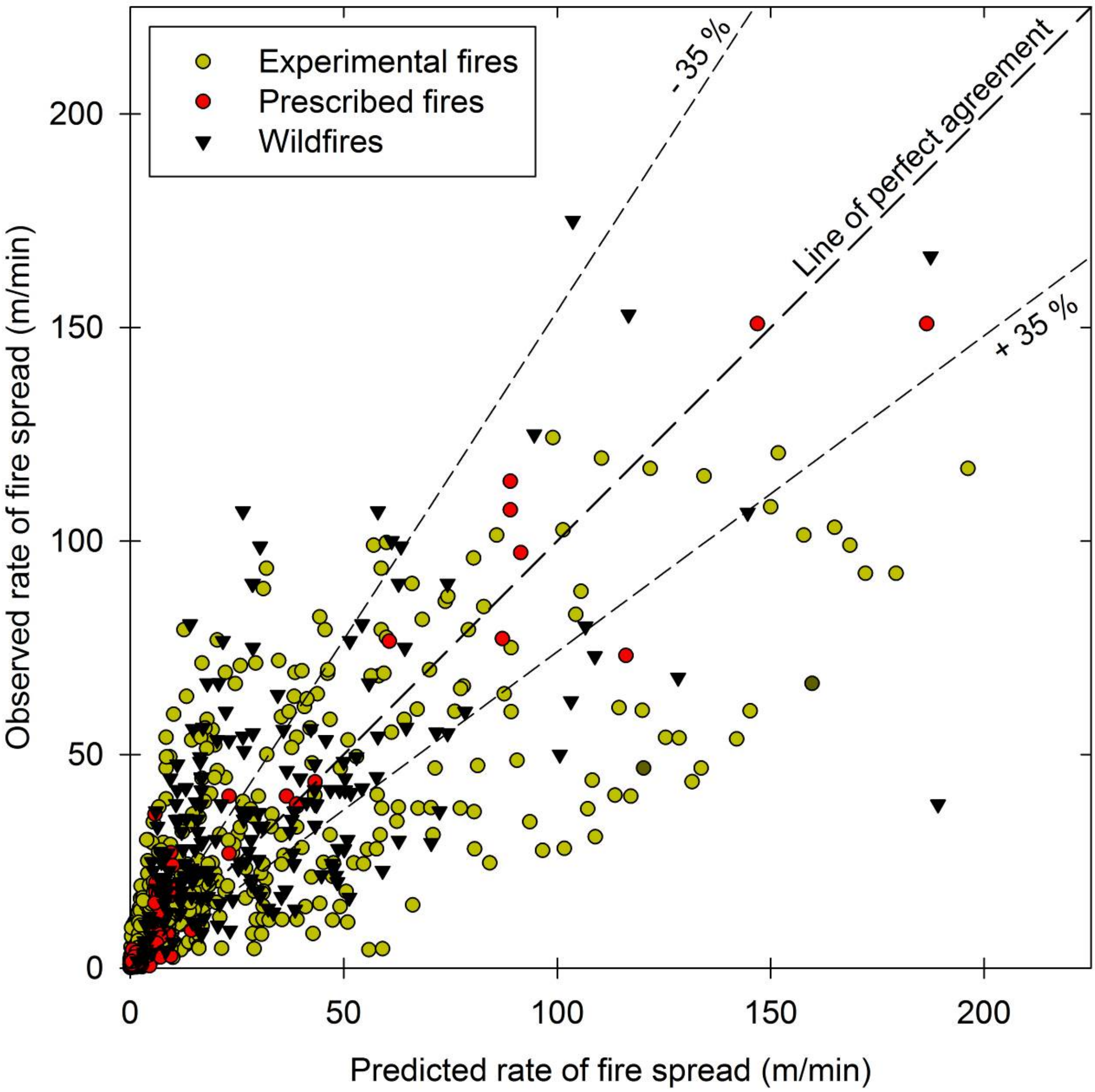

Figure 2. ***Observed rates of fire spread versus model predictions by type of data involved in the 1278 pairs garnered from the 49 comparison studies as compiled by Cruz and Alexander (2013). The two dashed lines around the line of perfect agreement indicate the ±35 percent error interval.***

The lowest errors (i.e., from 20 to 30 percent) were associated with seven studies involving experimental fires and prescribed fires where fuel and weather inputs would have been measured onsite. For comparisons dealing exclusively with wildfires, errors varied from 33 to 59 percent.

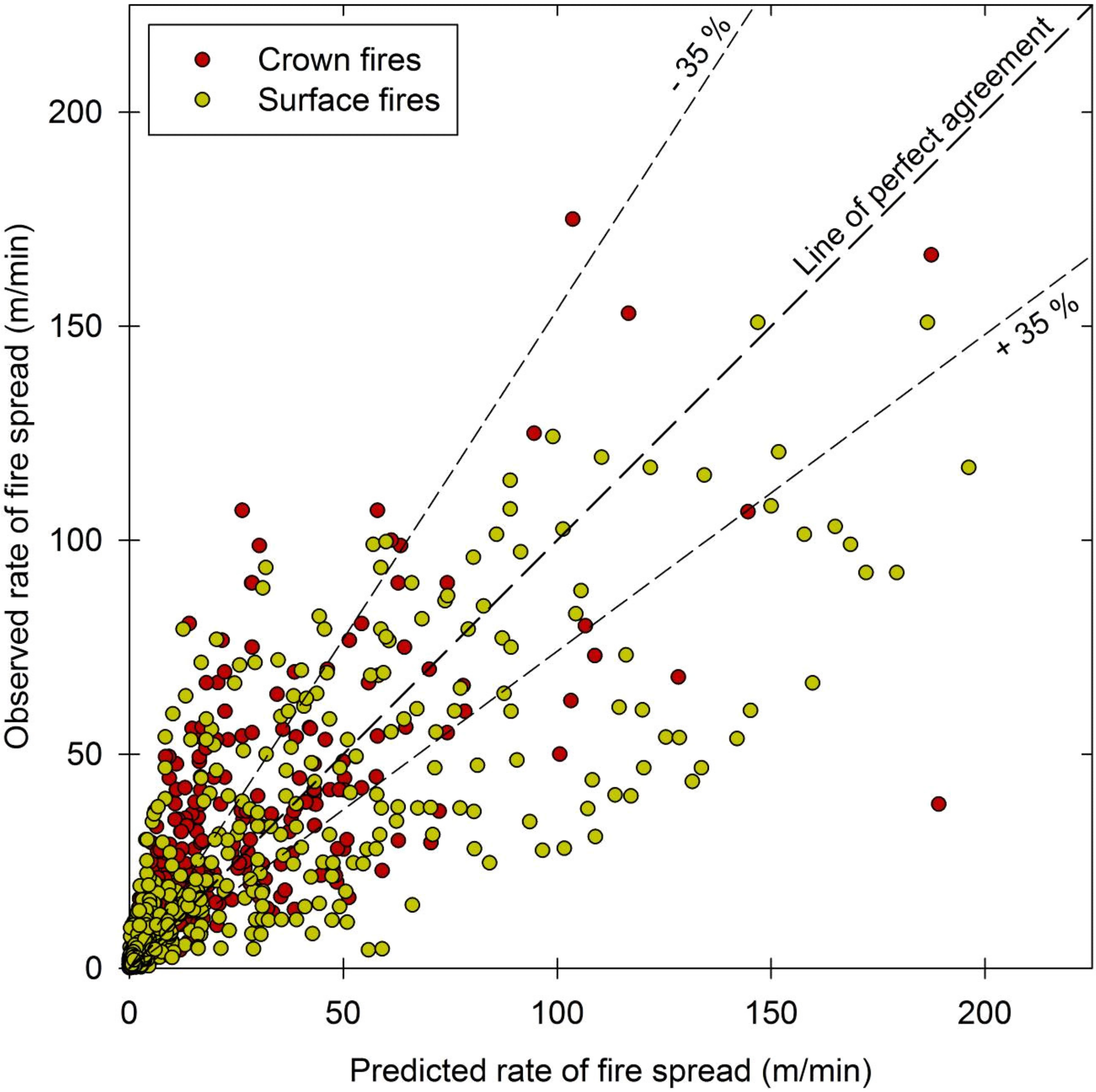

Figure 3. Observed rates of fire spread versus model predictions by type of fire involved in the 1278 pairs garnered from the 49 comparison studies as compiled by Cruz and Alexander (2013). The two dashed lines around the line of perfect agreement indicate the ±35 percent error interval.

4. Discussion

4.1. How accurately can one expect to predict the spread rate of wildland fires with currently available models?

No significant differences were found for under- and over-prediction errors by the type of data source (Figure 2). However, it was found that the rate of fire spread models examined under-prediction occurred in 818 of the 1278 model comparisons (i.e. 64 percent).

Although the range in rate of fire spread in the independent wildfire datasets was much higher than in the datasets used in model development, the model structure allowed for consistent predictions over the full range of observed fire behaviour. In most cases, under-prediction bias was small. There were, however, combinations of model and fuel type that resulted in a predominant, if not total, under-prediction bias. This included, for example, Rothermel's (1972) surface fire rate of spread model in conifer forests and in logging slash, and both the Rothermel (1991) and Schaaf *et al.* (2007) crown fire rate of spread models.

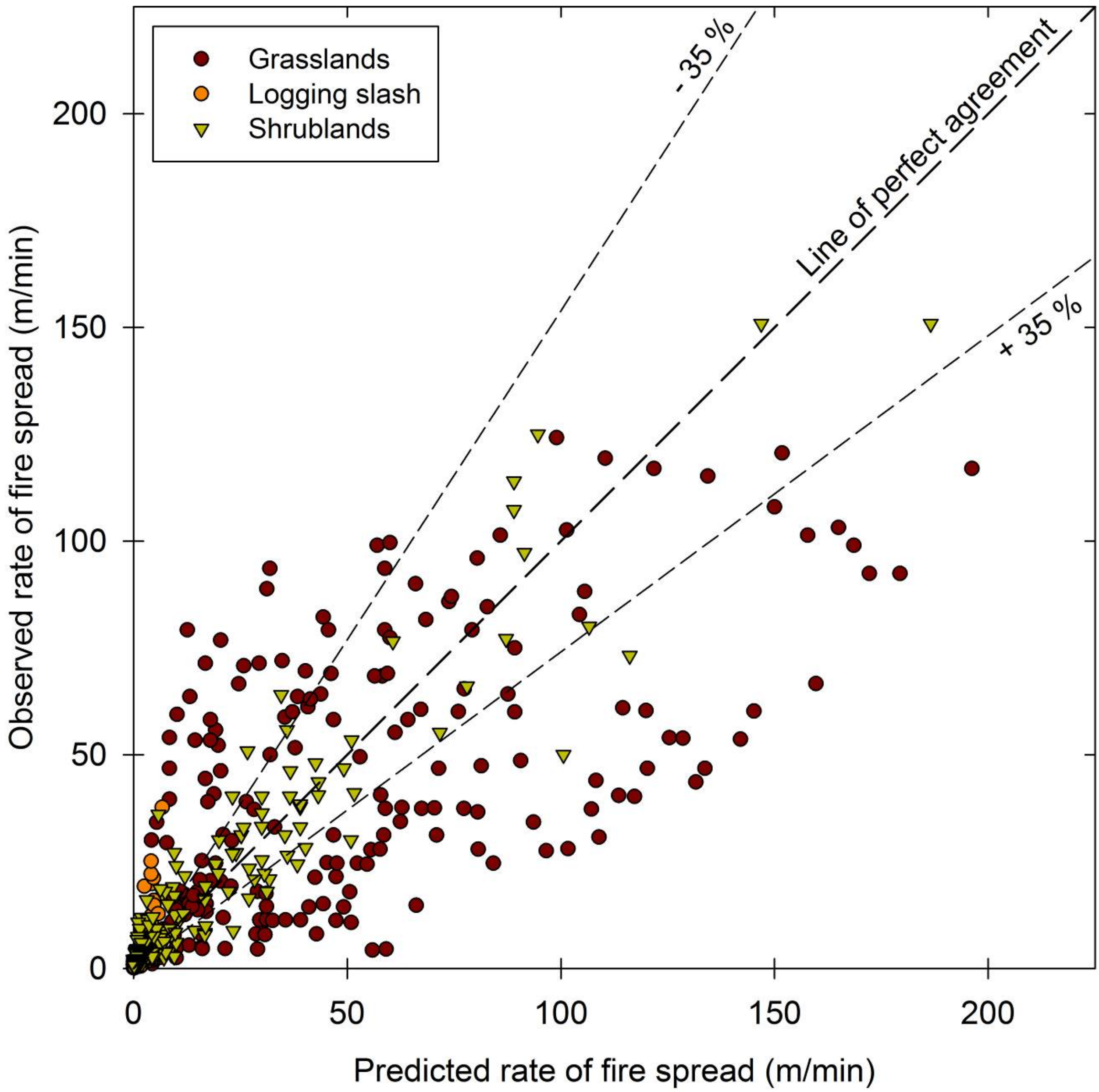

Figure 4. Observed rates of fire spread versus model predictions for non-canopied fuel types (grassland, shrubland and logging slash) involved in the 441 pairs garnered from the 17 comparison studies as compiled by Cruz and Alexander (2013). The two dashed lines around the line of perfect agreement indicate the ±35 percent error interval.

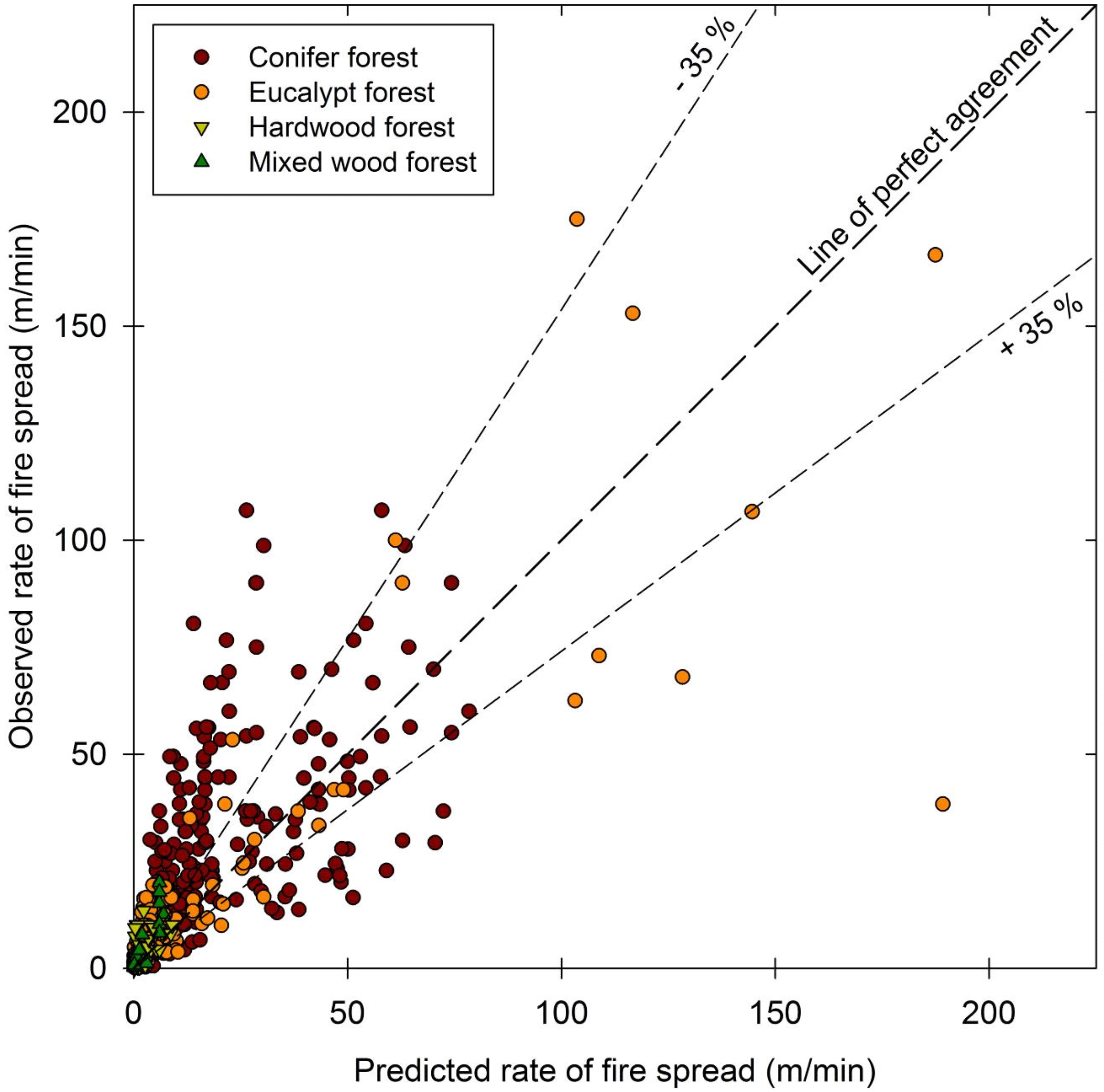

Figure 5. Observed rates of fire spread versus model predictions for forest canopied fuel types (hardwood forest, mixedwood forest, conifer forest and eucalypt forest) involved in the 837 pairs garnered from the 32 comparison studies as compiled by Cruz and Alexander (2013). The two dashed lines around the line of perfect agreement indicate the ±35 percent error interval.

4.2. **Can models based on experimental fire data be used to predict wildfire behaviour?**

Only two of the 13 rate of fire spread models considered in the study were separately evaluated against both experimental fire and wildfire datasets. This included the models developed by Cruz *et al.* (2005) and Cheney *et al.* (2012) where the MAPE values for the experimental fires where 26 and 35 percent, respectively. In turn, the Cruz *et al.* (2005) model yielded MAPE values of 46 and 52 percent for two separate wildfire datasets, while for the Cheney *et al.* (2012) model, the MAPE was 54 percent.

The increase in MAPE is expected given the uncertain nature of the exact environmental conditions associated with the wildfires. In these evaluations against wildfire data, both the Cruz *et al.* (2005) model, which is the basis for the *Crown Fire Initiation and Spread* (*CFIS*) system (Alexander *et al.*

2006), and the Cheney *et al.* (2012) model were extended well beyond the bounds of dead fuel moisture content, wind speed, and rate of fire spread used in their development. This implies that the underlying functional relationships in these models are valid for far drier and windier wildfire conditions than those involved in the model development, a conclusion that Fernandes (2014) has also recently shown to be valid.

4.3. **Are wildfires inherently more difficult to predict the spread rates of than prescribed fires or crown fires compared to surface fires?**

Examination of error statistics revealed no discernible difference in the ability to predict wildfire rates of spread from those associated with prescribed fires.

Some fire researchers have contended on the basis of the dynamic nature of crown fires that their behaviour is more unpredictable than that of surface fires (e.g. Cohen *et al.* 2006). However, according to the error statistics computed for surface and crown fires, there appears to be no differences, at least with respect to predicting rate of fire spread (Table 1). In fact, the highest MAPE values were obtained for surface fires rather than for crown fires.

4.4. **How realistic is it to expect an exact prediction of rate of fire spread?**

On the basis of the 49 studies and 1278 paired observations versus model predictions complied and analyzed, we found that the concept of an exact prediction of rate of fire spread to be an elusive one. Only three percent of the predictions (i.e. 35 out of 1278) were considered to be exact. It thus appears that the only certainty about rate of fire spread predictions is that it is extremely unlikely that a prediction will exactly match the observed fire spread rate.

4.5. **What is an acceptable error for fire spread models?**

McArthur (1977) considered that the fire danger meters he had developed for Australian grasslands and eucalypt forests could predict rate of fire spread and other fire behaviour characteristics to within ±20 percent of the actual observed value. Kilinc *et al.* (2013) have recently shown this assertion to have been quite optimistic.

From a statistical standpoint one might think that a ±1.0 standard deviation as a reasonable measure for an acceptable error. Assuming a normal distribution, such a quantity corresponds to a 34.1 percent departure from the mean. Richard C. Rothermel (USDA Forest Service retired, personal communication, 2012) was to remark to the authors that "I do like your suggestion of one standard deviation being used as a criteria for evaluating what can be expected in model prediction". This error threshold is also consistent with the average errors associated with several experimental field studies of fire behaviour.

According to the present study only two out of the 49 model performance studies (i.e. 4 percent) had a MAPE of 20 percent and no study had any less of a value. Eight of the 49 model comparisons (i.e. 17 percent) had a MAPE equal to or less than 35 percent suggesting that this could constitute a realistic benchmark by which to judge good model performance when accurate input data is available. On the basis of this outcome and the aforementioned considerations, it would appear that a ±35 percent error would constitute a reasonable and conservative standard for fire spread rate model performance.

Of course a ±35 percent error benchmark is only deemed applicable to research studies. In operational practice, given the uncertainty in the estimation of the input data, often times involving large spatial (e.g. >1000 ha) and temporal (i.e. from one to several hours) scales, would understandably, result in wider error intervals.

5. **Conclusions**

A comprehensive survey of the error statistics associated with evaluation studies of rate of fire spread models was undertaken by Cruz and Alexander (2013) in order to gauge the general predictive ability

of such models. This has led to new insights into some of the uncertainties associated with model predictions of free-burning wildland fire behaviour. This survey has also accordingly highlighted the importance of model evaluation (Cruz *et al.* 2003) based on independent datasets and encouraged others to do so (e.g. Anderson *et al.* 2014 in review).
It is worth noting that our evaluation study focused on models of forward or head fire rate of spread (i.e. in one dimension). More recent studies evaluating spatially explicit fire propagation models have relied on a distinct number of metrics to quantify the error associated with wildland fire growth simulations (e.g. Filippi *et al*. 2014a,b). These were not considered in our analysis as the spatial outputs are only partially dependent on the fire spread rate.

6. Acknowledgment

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