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Assessing improvements in models used to operationally predict wildland fire rate of spread

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ABSTRACT

The prediction of fire propagation across landscapes is necessary for safe and effective fire management. We analyzed the predictive accuracy of models currently used operationally in Australia for predicting fire spread rates in five different fuel types (grasslands, temperate and semi-arid shrublands, dry eucalypt and conifer forests) compared to their previous counterparts. We calculated error statistics and contrasted model predictions against observed spread rates of field observations of wildfires and prescribed fires. We then compared the changes in error metrics of older models to newer ones. Evaluation results show newer models to have improved prediction accuracy. Mean absolute errors were reduced by 56%, 68% and 70% in dry eucalypt forests, grasslands and crown fires in conifer forests, respectively. The most significant improvement was the reversion of under-prediction bias achieved with newer models. This study has highlighted the value of continuous improvement when it comes to developing operational wildland fire spread models.

1. Introduction

A wildland fire is a free-moving combustion reaction spreading across the landscape (Fig. 1) as determined by fuel availability, topography and atmospheric variables (Barrows, 1961). Under favourable environmental conditions, fast spreading, high intensity wildfires can be responsible for large burned areas (Stocks and Walker, 1973; Cheney, 1976; Alexander and Cruz, 2016), widespread destruction of life and property (Harris et al., 2012; Blanchi et al., 2014; Alexander et al., 2017), and at times undesirable ecological and environmental consequences (Mobley, 1974). Free-burning wildland fires are characterized by energy release rates spanning several orders of magnitude, from 10 kW m^{-1}, an approximate lower limit for sustainable fire propagation, upwards to around 100 000 kW m^{-1} (Byram, 1959), only observable under the most extreme burning conditions (Anderson, 1968; Kiil and Grigel, 1969; Cruz et al., 2012). Within this range, direct fire suppression action is only effective in halting a fire in the lower 4–5% portion (i.e. less than 4000–5000 kW m^{-1}) of the spectrum (Cheney, 1991). Fires that become large will only stop when a change in fuels, weather and/or topographic conditions leads to a decrease in its intensity to suppressible levels or via self-extinguishment (Schaefer, 1957; Underwood et al., 1985; Salazar and González-Cabán, 1987).

The ability to predict the direction and spread rate of a wildland fire and its associated flame front characteristics allows land and fire managers to develop and implement safe and effective suppression strategies and to release timely and effective public warnings and evacuation orders (Scott et al., 2014; Cruz et al., 2015b). Mathematical models aimed at describing the behaviour of wildland fires, namely the forward or head fire rate of spread – arguably the most important fire behaviour characteristic from an operational standpoint (Alexander, 2000) – have been under development for the past 80 years (Scott et al., 2014; Weise and Fons, 2014). Models have been developed with a range of purposes, from improving our theoretical understanding of particular aspects of fire behaviour to specifically addressing an applied research need, such as modelling how fast a fire with an idealised flame front will move across the landscape or how tall the flames will be under a given set of fuel, weather and topographic conditions (Albini, 1984). A question one might ask when examining the accumulated body of research (e.g. Weber, 1991; Pastor et al., 2003; Sullivan, 2009b) is: "Has the capability of fire spread models to accurately predict fire propagation improved in the last couple of

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Fig. 1. Examples of the types of fire data used to develop and evaluate fire rate of spread models in dry eucalypt forests in Australia: (a) early phase of an experimental fire conducted at Black Mountain, ACT in the 1960s typical of the ones used to develop the McArthur (1967) fire rate of spread model; (b) well-developed, high intensity experimental fire conducted in south-western Australia used to develop the Cheney et al. (2012) model; and (c) detailed view of flame front characteristics and associated spotting behaviour of a high intensity wildfire (photo: Wayne Rigg, Country Fire Authority, VIC, Australia).

decades?" Or alternatively, "are the newer fire spread models substantially better than the older models at quantifying the effect of the environmental variables controlling the spread rate of wildland fires?".

This line of questioning is especially pertinent to global wildfire science and management in regions of the world where wildfires threaten life and property and fire spread models are used operationally to support wildland fire control and fuel management. In the particular case of Australia, wildland fire behaviour research has been continuously conducted to develop operationally applicable models that would overcome well documented (Burrows et al., 1991; McCaw et al., 2008) or perceived (Cheney and Gould, 1995; Catchpole et al., 1998a) limitations of existent fire spread models.

Cruz and Alexander (2013) conducted a comprehensive survey of studies where rate of fire spread models were evaluated against independent data derived from field observations of wildfires, prescribed fires and experimental fires (Fig. 1). Using this database comprised of 49 data sets corresponding to 1278 paired observations *vs* model predictions, they were able to characterise the error metrics for several wildland fire rate of spread models. They did not however conduct a temporal analysis of how the errors had changed over the years with the evolution of fire behaviour models. Data recently published by Anderson et al. (2015) and made available by Kilinc et al. (2012) have presented an opportunity to assess model performance, and look at how newer operational models perform relative to their previous, older counterparts.

In this paper we aim to analyse the predictive performance of a number of fire rate of spread models used operationally in Australia and quantify the improvements (or lack thereof) in model accuracy resulting from ongoing model developments over the past 30 years or so (Fig. 1a and b). This was done using commonly accepted error statistics based on an analysis that relied upon independent datasets of wildfire (Fig. 1*c*) and to a lesser extent, prescribed fire observations.

2. Methods

2.1. Model evaluation data

We compiled all fire spread model evaluation studies known to us where there was a direct comparison between model predictions and field observations, and where the evaluation datasets were independent from the model development process. This included the 49 studies used in Cruz and Alexander (2013, 2014) complemented with additional data from Kilinc et al. (2012) and Anderson et al. (2015). Data origins included wildfires, prescribed fires, and experimental fires purposely conducted to develop or evaluate fire spread models. We then scrutinised the available data pool for studies that allowed for the evaluation of both older and newer fire spread models, or provided information from which simulations for models not considered could be undertaken. It was assumed that a fire run occurred in a single general fuel type and that the fire had reached a quasi-steady state spread condition, i.e., fire was not spreading in its "build-up phase" (McArthur, 1968).

To the best of our knowledge, the selected wildfire runs represented a free-burning linear flame front unaffected by fire suppression action, and in the case of prescribed fires, by their ignition pattern (Johansen, 1987). Each evaluation study selected included a minimum of five fire spread rate observations.

2.2. Models examined

An initial examination of the data available revealed five pairs (older *vs* newer) of fuel-type specific fire spread models identified as suitable for analyses (Table 1). This included models for four common fuel types found in Australia, namely grasslands (McArthur, 1966 *vs* Cheney et al., 1998), temperate shrublands (Catchpole et al., 1998a *vs* Anderson et al., 2015), semi-arid shrublands (McCaw, 1997 *vs* Cruz et al., 2013), and dry eucalypt forests (McArthur, 1967 *vs* Cheney et al., 2012), in addition to a pair of models for predicting crown fire spread in North American conifer forests (Rothermel, 1991 *vs*; Cruz et al., 2005); this latter model has been applied to Australia's exotic pine plantations (Cruz et al., 2008). All of the newer, or most current, models listed by fuel type in Table 1 are presently used to predict fire propagation operationally in Australia (Plucinski et al., 2017). A more in-depth description of these models can be found in Cruz et al. (2015a, b).

As a benchmark for the analyses carried out on the models referred to in Table 1, we also incorporated a similar assessment of studies evaluating the Rothermel (1972) semi-empirical surface fire spread model. This model, with additions devised by Albini (1976), is globally the most widely used fire spread model, either through the BehavePlus Fire Modelling System (Andrews, 2010, 2014) or through different implementations in spatially-explicit fire spread simulators (see Sullivan, 2009c for a review).