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Field-based fire behaviour research: past and future roles

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Abstract: Empirical modelling of fire behaviour based on field data has resulted in significant advances in forest fire science and produced numerous research and operational decision support tools. This field-based research requires measuring of fire behaviour quantities, e.g., rate of spread and flame geometry, in a number of outdoor experimental fires burned under a set of fuels and fire weather conditions. Ensuing modelling relies on regression analysis linking easily measurable fire environment variables with fire characteristics. Costs, safety constraints and the characteristics of the data collected in the field have somehow limited the inferences that can be drawn from the data. This has limited our understanding of some of the processes driving fire spread, namely fine-scale processes and fire-atmosphere interactions.

This paper will discuss a quasi-physical approach to fire behaviour modelling. The focus is combining basic physical processes with carefully planned experimental fires aimed at quantifying specific fire properties (e.g., heat fluxes, flame flow rates, flame temperatures) that are currently unknown, but necessary for modelling and evaluating the physical processes necessary to close the quasi-physical model systems. We will present results from our experimental burning program, discussing new insights into flame phenomena and its integration into new fire behaviour models.

Keywords: *Fire behaviour modelling, rate of spread, experimental fire.*

1. INTRODUCTION

Modelling fire behaviour has followed the empirical vs mechanistic dichotomy. Empirical models, also called statistical models by some authors (Weber 1991), attempt to establish relationships between response and explanatory variables without explicitly considering the controlling physical processes (e.g., Cheney et al. 1998, Cruz et al. 2004). Mechanistic models are formulated as expressions of physical processes and by their comprehensiveness should be able to predict most fire behaviour phenomena and their interaction with small-scale meteorological conditions (e.g., Morvan and Dupuy 2001, Mell et al. 2007). Nevertheless these models cannot be considered as pure physical models. The current state of knowledge in fire phenomenology requires the use of numerous empirically based sub-models or constants to describe phenomena where our knowledge of the driving processes is still incomplete. A further drawback of these models is that they have seldom been subjected to any evaluation against independent field data. The importance of field-based flame geometry and fire behaviour data in the development of quasi-physical models will be discussed.

2. EXPERIMENTAL BURNING PROGRAMS IN AUSTRALIA

The data arising from field based fire behaviour experimental research programmes form the backbone of a number of fire danger and behaviour modelling systems operationally used throughout the world to support fire management decision-making (e.g., prescribed burning planning, assessing fuel management effectiveness, support of wildfire suppression strategies and tactics). In eastern Australia, early work carried out in the late 1950s and early 1960s by A. G. McArthur lead to the development of the Forest Fire Danger Index and Meter for grasslands and forest (McArthur 1966, 1967). His experiments, conducted over a range of grassland and eucalypt fuel types (Fig 1.a) consisted in igniting point source fires that were allowed to spread for 15-60 min while being monitored for the relevant fire weather (e.g., wind speed, air temperature and air relative humidity) and behaviour (e.g., rate of spread, flame height and spotting potential) (Burrows

1991). At about the same time G.B. Peet in Western Australia carried out similar fire behaviour experiments (Fig 1.b) that lead to the development of the Forest Fire Behaviour Tables (Peet 1965, Sneeuwjagt and Peet 1985), a prescribed burning guide. Not much detail exists on the dataset characteristics of these pioneering experimental burning programs. Nonetheless, it is understood that a large proportion of the datasets correspond to relatively small and low intensity burns. Understanding the limitations of these datasets and the fuel type specificity that arises from models derived from them, two major burning programs were conducted by CSIRO Forestry and Forest Products Division in the 1980s and 1990s in grasslands and dry sclerophyll forest with the aim to establish causal relationships between fuel, fire weather variables and fire behaviour quantities.

Figure1. Point source ignition of experimental fires, (a) left: ACT, 1960s, (b) right: Dwellingup, WA, 1959.

2.1. Annaburroo Experiments (Cheney et al. 1993, 1998):

The Annaburroo experiments (Annaburroo, NT, Australia) aimed at investigating the effect of fire front width, wind speed, dead fuel moisture, fuel load and fuel condition (undisturbed grass and distinct fuelbed modification treatments) on the rate of fire spread in grassland fuels. A total of 170 plots ranging in size from 100 x 100 m to 200 x 300 m were prepared, with 121 of then burned and analysed. Wind speed (10-m open wind speed) varied between 7.3 and 40 km/h, and fine dead fuel moisture between 2.7 and 12.1%. Rate of spread and fireline intensity varied between 17.3 and 124.2 m/min, and 1450 and 20,220 kW/m, respectively. As to its main outcomes, this study quantified the effect of wind speed, dead fuel moisture and fire front width on rate of spread, and developed a fire propagation model for grasslands. For the range of conditions in the dataset fuel load was not found to have a significant effect on rate of spread in grasslands (Cheney et al. 1993).

The thorough measurement of fuel characteristics, weather variables and fire behaviour in this experimental burning program yield a high quality dataset that make it suitable for other fire research purposes. Sullivan (2007) analysed fire – atmosphere interaction models to examine the possibility of an effect of this interaction on fire rate of spread and behaviour. Mell et al. 2007 used two of the Annaburroo experimental fires to evaluate the performance of a mechanistic fire dynamics model.

2.2. Vesta project (Gould et al. 2007)

The Vesta project aimed at understanding the effect of wind speed and certain fuel characteristics on fire behaviour in dry eucalypt forest. The experiments (Fig. 2), conducted in jarrah (*Eucalyptus marginata*) forest stands in plots with dimension 200 x 200 m, took place at two distinct sites, McCorkhill (n=60) and Dee Vee (n=45), in Western Australia. Site selection and fuel treatments provided a wide range of fuel complex structures. The McCorkhill site had a tall understorey shrub layer and the Dee Vee site had a sparse and shallow shrub understorey. Application of prescribed burns in the years preceding the experimental fires allowed controlling for fuel age (fuel accumulation since fire), varying from 2 to 22 years. The fires were conducted under fairly dry conditions of moderate to high forest fire danger with a restricted variation in surface fine dead fuel moisture content, for an average of 7% (range 5.6 – 9.6%). On each burnt day sets of fires were burnt simultaneously in plots of each fuel age. Half the experiments were scheduled to be conducted under light winds (10-m open wind speed lower then 12.5 km/h), and the other half with moderate winds (10-m open wind speed between 12.5 and 25 km/h). A total of 105 fires were conducted over three summers, with rates of spread and fireline intensity varying between 0.8 and 22.7 m/min, and 150 and 10570 kW/m, respectively. The main outcomes of this project were the evaluation of prior fire spread models performance (McCaw et al. 2008) and the development of a fuel hazard assessment guide and an operational fire behaviour prediction model for dry eucalypt forest (Gould et al. 2007).

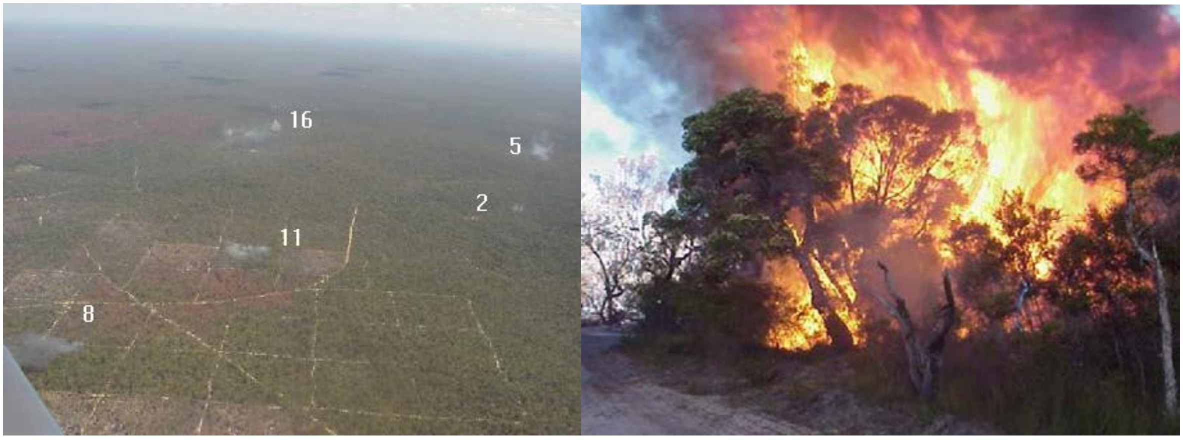

Figure 2. Left: Simultaneous ignition of multiple plots during Project Vesta. Numbers indicate surface fuel age (years since fire). Right: High intensity fire during Project Vesta.

Other recent large-scale fire behaviour experimental programs in Australia include Burrows (1994) in dry sclerophyll eucalyptus forest and McCaw (1997).

The process of the developing fire behaviour prediction models from field experiments has several practical and technical limitations. Burrows and Sneeuwjagt (1991) pointed out the “physical and economical limits to plot size and numbers”, “costs, risks and difficulties of implementing and containing experimental fires”, namely when the experiments are conducted in volatile and spot fire prone fuel complexes, “physical damage to other forest values” and “scaling problems associated with large fires such as fire acceleration, spotting and crown fire development”. As a whole, these limitations decrease the number of replicates within the experimental design and constrain the range in fire behaviour that can be attained within an experimental burning program. Seldom has an experimental fire been conducted within the severe burning conditions for which fire behaviour knowledge is most limited. Fig. 3 summarizes the range of wind speed, fine dead fuel moisture, fuel load and rate of spread in experimental burning programs (E) and wildfire case studies (W), highlighting that experimental burning programs normally cover the moderate to high zones of the fire potential spectrum. This limits our understanding of fire behaviour at the high end of the scale, thus these models were extrapolated to predict those conditions.

In addition, the impossibility in controlling certain variables limits randomisation and can lead to non-orthogonality. Collinearity issues arising from non-orthogonality make it difficult to single out the effect of certain variables. This limits our understanding of fire behaviour processes and the explanatory power of models. As examples, empirical models have failed to find a significant effect of: (1) live fuel moisture on shrubland and crown fire propagation (e.g., Fernandes 2001; Cruz et al. 2005); (2) stand structure on crown fire spread (Cruz et al. 2005); and (3) fuel load on grassland (Cheney et al. 1993) and shrubland rate of fire spread (Fernandes 2001; Fernandes et al. 2000). The limitations associated with collinearity leads to oversimplification of models and result on the absence of important variables from the model. Some empirical models have simplified the fuel parameters represent surrogates of physical fuel attributes to predict fire behaviour e.g. Gould et al. 2007. This reduces their predictive power and limits their application in planning and research scenarios (e.g., effect of climate change and associated fuel complexes in potential fire severity, effect of fuel treatments on modifying fire hazard).

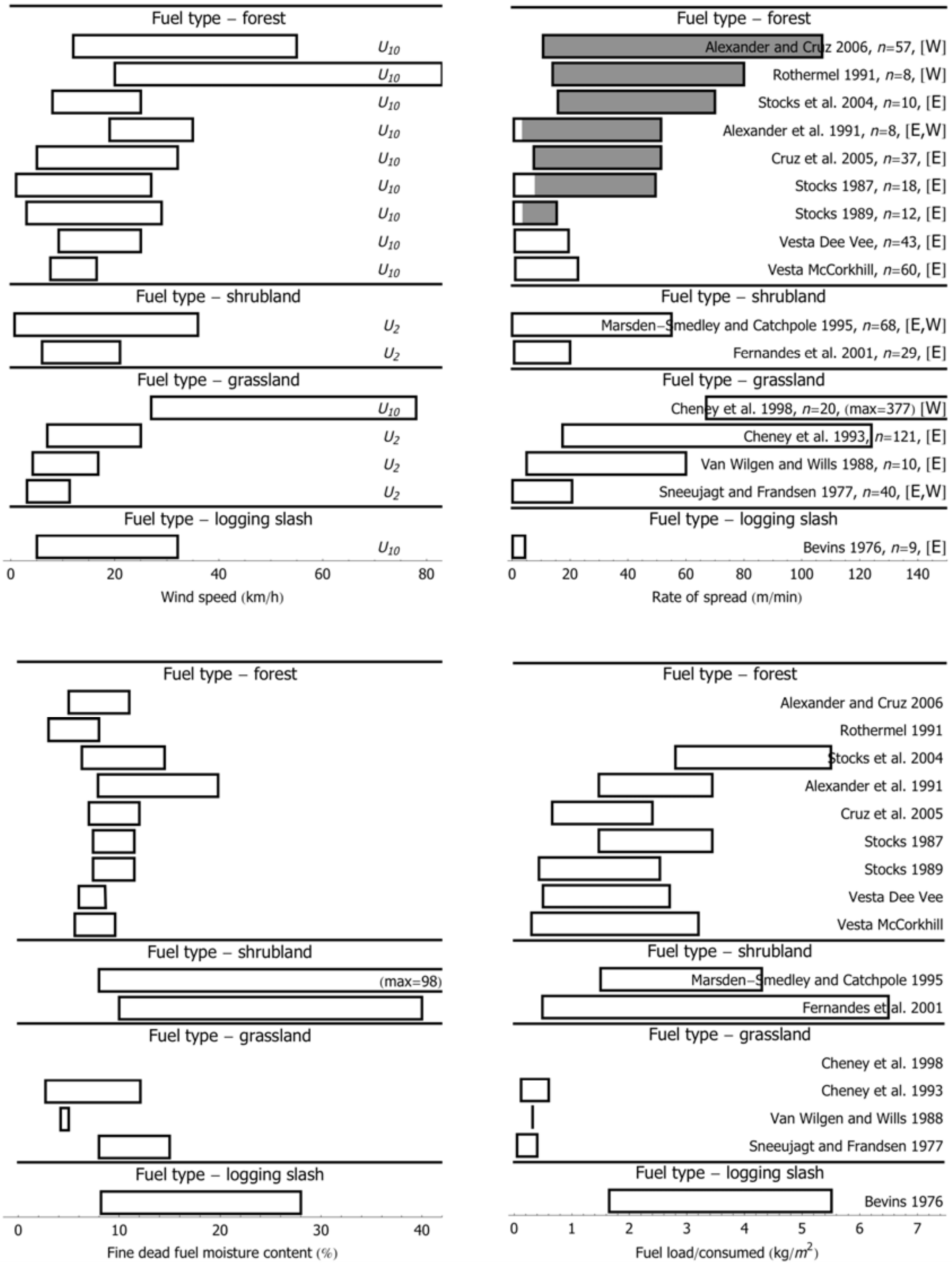

Figure 3. Range of wind speed, fine dead fuel moisture content, fuel load and rate of spread associated with experimental burning programs (E) and wildfire case studies (W). Dark bars indicate crown fire activity.

3. THE QUASI-PHYSICAL APPROACH

The limitations of the fully empirical modelling approach described above emphasise the need to revise the way we integrate field based fire behaviour data with modelling efforts, and ultimately how we develop the fire behaviour models required to answer future fire management questions. The application of a quasi-physical modelling approach to describe fire behaviour can combine the advantages of both the empirical and mechanistic approach. In this approach, the dominant physical processes determining fire behaviour need to be explicitly described, albeit in a simplified form. The role of the field data is to quantify certain fire phenomena and provide linkages between fire processes that theory has not yet satisfactorily described.

The contrast between the data needs required in the empirical and quasi-physical approach is well illustrated by comparing Van Wagner (1977) and Cruz et al. (2004) crown fire initiation models.

Van Wagner (1977), through a combination of physical criteria and empirical observation, defined quantitative criteria to predict the onset of crown combustion. His analysis was based on a relationship developed by Thomas (1964) that linked fire intensity, as defined by Byram (1959), with the maximum temperature attained at a certain height in the convection plume above the fire. This relationship, based on dimensional analysis was rearranged by Van Wagner (1977) to allow the determination of a critical surface fire intensity needed to induce crown combustion, as a function of canopy base height, heat required for ignition, and a proportionally constant, "*best regarded as an empirical constant of complex dimensions*" (Van Wagner 1977). The proportionality constant was estimated in a sole experimental fire in a red pine (*Pinus resinosa* Ait.) stand. Although the data foundation of the model can be considered weak and the proportionality constant has been shown to vary with surface fuelbed structure (Alexander 1998), the discerning idealization of the crown fire initiation process gave robustness to the model. Framing the onset of crowning as a dichotomous problem (presence or absence of crown fire activity), Cruz et al. (2004) modelled the likelihood of crown fire occurrence through logistic regression analysis based on a dataset of 71 experimental fires in conifer fuel types. Although model evaluation suggested good performance for fuel types similar to the ones used in model development, the small number of explanatory variables and the lack of functional relationships call into question the use of the model to fuel complexes and fire weather conditions other then the ones in the original dataset. The model did also not improve our understanding of the processes determining the onset of crowning. The comparison between the outputs of Van Wagner (1977) and Cruz et al. (2004) models show models with similar response for certain weather conditions (high fire potential), but diverging under other conditions (combination of moderate and extreme fire potential). Van Wagner model had better performance under these conditions if the available fuel for combustion and rate of spread of the fire is accurately known. But because Van Wagner's model depends on the outputs of other intermediate models (e.g., within stand wind speed, rate of spread) its use is prone to error propagation. This highlights the importance of understanding model behaviour before relying on its predictions. For a fuel complex where surface fire behaviour predictions are accurate Van Wagner's crown fire initiation model is likely to be the most adequate. In different circumstances, e.g., where there is uncertainty regarding the adequacy of the surface fire behaviour models to the target fuel complex, the Cruz et al. (2004) model might provide a more accurate outcome.

Within the quasi-physical framework, the characteristics of the field data used in model development change considerably from past approaches. Whereas the development of empirical fire spread models is mostly based on a large dataset covering a few coarse fire behaviour quantities, e.g., rate of spread, average flame geometry, energy release rate, the quasi-physical approach will require smaller datasets, up to a few fires, but with a higher level of detail of fire characteristics. Fundamental quantities that need to be measured include amongst others, ignition interface shape, flame gas temperature and velocities resolved in height and time, flame radiative energy profile, flame geometry and nonsteady fire behaviour, and wind turbulence. These are some of the variables that characterize the energy released by the fire and its interaction with the environment. These variables are the outputs of complex and poorly understood phenomena, and their quantification will allow to bypass our knowledge gaps and close the model systems. One of the main difficulties in carrying out these measurements will be to adapt instruments and methods currently restricted to laboratory settings to the harsh environment associated with high intensity experimental fires and wildland fires.

In 2006 we started a project aimed at modelling fire behaviour in Australian mallee-heath vegetation. Mallee-heath vegetation occurring in semiarid and Mediterranean climates develops a vertically non-uniform and horizontally discontinuous fuel complex. The heterogeneity of the fuel layers sustaining fire propagation leads to fire behaviour characterized by nonlinear dynamics where small changes in the drivers of fire spread lead to large changes in observed fire behaviour. Within this fuel complex fire behaviour is not just determined by the effect of fuels and weather, but to a large extent determined by the interactions between those variables and the structure of the flame front. These interactions somehow limit the fully empirical modelling approach based on regression analysis. Hence along with the empirical modelling we are pursuing a quasi-physical modelling approach. A total of 67 fires were completed. The range of fire environment conditions within the experimental fire dataset were: air temperature 15 to 39 C; Relative humidity 7 to 80%; 10-m open wind 3.6 to 31.5 km/h; Forest Danger Index from 1.7 to 53.3. Fire behaviour measurements for the 67 fires included rate of spread, flame geometry, residence time and fuel consumed. In a restricted number of fires we conducted detailed measurements of flame emissive power and temperature. The aim of these measurements was to improve our understanding of how energy is being released by the flame front. An analysis of the mechanisms that allow fire spread in discontinuous fuels indicate that it is the flame characteristics, e.g., height, depth, angle, that will determine if the fire will spread in a certain fuel configuration. We hope our measurements will allow us to better model flame development and the threshold flame characteristics that allow fire to breach fuel discontinuities.

4. CONCLUDING REMARKS

Empirical models of fire behaviour have been widely used by fire management agencies to support fire management decision-making. Despite their usefulness, they possess a number of limitations that restrict their applicability and the type of questions that they can address. Mechanistic models developed from a theoretical description of fire phenomena combined with measurements of fire characteristics will allow to bypass our lack of understanding of some fundamental fire processes and describe fire propagation as a closed model system. Such approach will allow the application of models to a wide spectrum of fire management questions, from meeting the requirements of operational users (e.g., site specific fire potential for a particular prescribed burn) to research (e.g., fire potential under new climate scenarios). The increase in model complexity and robustness that arises from the quasi-physical modelling approach cannot reduce model usability. Model use still needs to rely on fuel and weather inputs that are commonly measured/predicted at the landscape level. The characteristics of the data that needs to be collected change the paradigm of fire behaviour experimentation. The experimental design behind fire behaviour experiments need adapt to focus on the measurement of fundamental fire properties. The benefits of these additional measurements will result in better fire behaviour knowledge, which will have a strong role to play in sound forest fire (bushfire) management.

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