FINAL PROJECT REPORT
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FIRE COALESCENCE AND MASS SPOT FIRE DYNAMICS: EXPERIMENTATION, MODELLING AND SIMULATION

Final project report and synthesis

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ACKNOWLEDGMENTS

"Coming together is a beginning, staying together is progress, and working together is success"

– Henry Ford

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EXECUTIVE SUMMARY

The *Fire coalescence and mass spot fire dynamics* project (the *Spotfire Project*) was one of the core research projects within the Bushfire and Natural Hazards CRC's *Bushfire Predictive Services* research cluster. Specifically, the Spotfire Project was focused on enhancing our understanding of the physical processes involved in spot fire development and coalescence and developing computationally efficient mathematical models that can accurately account for these the patterns of bushfire propagation associated with mass spotting and other modes of dynamic fire behaviour. Current operational models and associated simulation platforms are predicated on the assumptions that fires spread in a quasi-steady manner and that different parts of a fire line evolve independently of other parts – both of these assumptions are manifestly untrue during mass spotting events.

The research took a multifaceted approach, which drew upon experimentation, computer simulation and mathematical modelling to develop a new dynamic modelling framework that permits faster-than-real-time simulation of fire propagation incorporating dynamic drivers. Experimentation took place at both laboratory and field scales. Laboratory experimentation was conducted in the CSIRO Pyrotron and in collaboration with Portuguese colleagues at the Centre for the Study of Forest Fires. Field scale experiments were also conducted in Portugal. The experiments provided insights into the dynamic nature of fire behaviour and provided data for calibration and validation of the models under development.

Coupled fire-atmosphere models were used to perform idealized simulations of various scenarios involving dynamic fire propagation. The model output provided detailed quantitative insights into the physical processes driving dynamic fire propagation and were used to inform development of new mathematical models. The mathematical model developed during the project is essentially a two-dimensional version of a coupled fire-atmosphere model – it incorporates the feedback between the fire and the atmosphere but within the two-dimensional Spark fire simulation platform.

The research has yielded many important and significant insights into the behaviour of coalescing spot fires, and these insights have enhanced our understanding of the processes driving fire propagation and the way we model dynamic fire behaviours. These have in turn provided new understanding of violent pyroconvective events and extreme bushfire development.

The most significant research outcome was the development of the pyrogenic potential model, which permits world's first capability to model dynamic modes of fire propagation (e.g., vorticity-driven lateral spread) using a two-dimensional simulation framework. This means that explicitly modelling such effects in operational timeframes is now a feasible option. The research has also examined various other issues related to the spotting process and dynamic fire propagation more generally. These include: the effects of wind-terrain interaction on ember trajectories and the likely distribution of spot fires downwind of complex terrain, the influence of spot fires on the overall rate of spread of a fire, the influence of terminal velocity assumptions on ember trajectory modelling, the influence of fuel characteristics (e.g., bulk density) on spot fire development and pyroconvective feedback, the role of fine scale vorticity effects on dynamic fire behaviour, and development of simple measures of pyroconvective potential.

There is considerable utilisation potential for the research findings. The advances in fire behaviour modelling are easily incorporated within the Spark simulator platform. Given that Spark has been formally chosen by AFAC to be the new national bushfire prediction platform, the project's research findings will eventually be available to all involved in operational prediction of bushfire propagation. Moreover, the insights into dynamic fire behaviours provided by the project will form the basis for new firefighter training and education materials that will equip operational personnel with better knowledge of the full spectrum of possible fire behaviours in given scenarios. This will improve situational awareness, with benefits for firefighter safety.

The project has also developed a new mapping product that identifies regions prone to mass spotting in association with vorticity-driven lateral spread. This will be available to fire management agencies and other relevant organisations, to assist with fire behaviour prediction, with special relevance to anticipating blow-up fire events and extreme bushfire development.

Overall, the *Spotfire Project* has presented a new paradigm for understanding fire behaviour and has made the first significant advances towards the next generation of operational models. The insights gained from the research complements and extends existing fire behaviour knowledge in a way that enhances our ability to deal with the increasing bushfire threat into the future.

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END-USER STATEMENT

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Fire behaviour analysts always want more understanding and more tools so they can provide incident managers with explanations of the situation and risk as well as usable predictions (with confidence levels). The twin challenges of incorporating relevant complexity and faster than real-time computation are always present.

Fire behaviour analysis and prediction struggles as situations become increasingly complex – which of course are the situations where the outcomes can be more damaging and dangerous. This project has taken on the task of unpacking fire behaviour effects seen in the field but not yet included in the working tools and models used by fire behaviour analysts. The researchers combined laboratory and field experiments with coupled fire-atmospheric and two-dimensional mathematical modelling. Different approaches found in the literature were explored and tested for their validity across a range of scales which has increased our understanding of dynamic fire behaviour. It has also required new approaches to be developed as some of the existing simplifications and relationships were found unreliable for both describing fire behaviour or being viable for real-time use.

The research team achieved a lot with the limited resources available. The mapping of terrain with a high potential for Vorticity-driven Lateral Spread (VLS) before and during fires will hopefully be an operational product for future fire seasons. Fire behaviour analysts need to be able to include VLS terrain when briefing incident managers to improve crew and community safety as well as informing fire suppression strategies. The use of the Spark framework by the project has increased our ability to utilise this next generation fire simulator and is a great service to future fire predictive services. The increased understanding of the dynamic processes in fire growth and associated models, especially around the effects of spotting on large fire growth, have great potential for furthering our future fire prediction products. The broader challenge of improving situational awareness of firefighters and agencies through incorporation of the new knowledge into national training products is still to be addressed, especially for those outside the fire behaviour prediction community.

INTRODUCTION

Fire behaviour in dry eucalypt forests in Australia (and in many other vegetation types to a lesser extent) is characterised by the occurrence of spot-fires—new fires ignited by the transport of burning debris such as bark ahead of an existing fire. Under most burning conditions, spot-fires generally play a minor role in the overall propagation of a fire, except perhaps when spread is impeded by breaks in fuel or topography which spot-fires enable the fire to overcome. However, under conditions of severe and extreme bushfire behaviour, spot-fire occurrence can be so prevalent that spotting becomes the dominant propagation mechanism and the fire spreads as a cascade of spot-fires forming a 'pseudo' front (McArthur 1967).

It has long been recognised that the presence of multiple individual fires affects the behaviour and spread of all fires present. The convergence of separate individual fires into larger fires is called coalescence and can lead to rapid increases in fire intensity and spread rate, often in directions at odds with the prevailing wind. This coalescence effect is frequently utilised in prescribed burning via multiple point ignitions to rapidly burn out large areas.

The zone between two coalescing fires is known as the convergence or junction zone and can be a very dangerous place to be for firefighters and may lead to highly erratic fire behaviour as witnessed during the 2003 Canberra fires. Fire behaviour under such conditions may be dominated by dynamic feedback processes between the energy released by each fire and the coupling of that energy with the atmosphere.

All existing operational fire behaviour models assume that a fire will burn at an approximately constant (quasi-steady) rate of spread for a given set of environmental conditions. While prior work has shown that an individual fire starting from a point accelerates to this steady state (e.g., McAlpine and Wakimoto (1991)), little research has been undertaken into the behaviour of multiple simultaneous adjacent ignitions under wildfire conditions or the effects of the dynamic feedbacks involved. No operational fire spread models currently account for the dynamical aspects of fire spread, particularly fire-fire interactions. This inability to accurately predict the behaviour of mass spotting events and the interactions of multiple adjacent fires places firefighters at risk and the general public in danger. With the projected climate change impacts expected to produce more extreme bushfires and a prevalence of mass fire behaviour, this deficiency in our understanding and operational systems represents a considerable knowledge gap.

The effects of dynamic processes on fire spread cannot be calculated using tables, spreadsheets or simple calculators. To comprehensively account for the effects of dynamic fire spread it is necessary to model the phenomenon using a physics-based model that incorporates complete descriptions of the key processes, including interactions between the fire, the fuel, topography and the surrounding atmosphere (e.g., WFDS (Mell et al. 2007), FIRETEC (Linn et al. 2002)). Unfortunately, such a modelling approach is computationally intensive and expensive, with associated model run-times that prohibit operational application (Sullivan 2009).

The *Fire Coalescence and Mass Spot Fire Dynamics* project (aka, the *Spotfire Project*) addressed these issues by investigating the processes involved in the coalescence of free-burning fires using a series of controlled laboratory, field and numerical experiments, quantifying the physical mechanisms involved in these, and investigating the potential of physically simplified proxies for some of the more complicated dynamical effects, particularly those driven by interactions between different parts of the fire(s). This approach enables development of models that are able to run faster-than-real-time, but that can still emulate the important dynamics of fire spread without the need to explicitly model fire-atmosphere or fire-fire interactions in a computationally costly manner.

BACKGROUND

The traditional approach to understanding the propagation of wildfires across a landscape relies on a number of assumptions about the way fires behave and the way their behaviour responds to environmental factors such as weather, fuel and topography. One of the main fundamental assumptions about fire behaviour is the quasi-steady assumption, which asserts that a fire will attain an approximately constant rate of spread that can be uniquely determined by a given a set of environmental conditions. Indeed, the quasi-steady assumption underpins the dominant paradigm of fire behaviour modelling throughout the world. It is embodied in fire behaviour models such as the McArthur Fire Danger Meters, which posits that the rate of spread of a head fire can be uniquely determined from knowledge of the air temperature, relative humidity, wind speed, antecedent rainfall, and the fuel load.

The quasi-steady assumption has a number of important implications, which can influence what is considered 'best practice' in fire management. For example, in the aftermath of the 2019/20 Black Summer fires, public debate naturally focused on ways of mitigating catastrophic fires. Much of this debate was centered around the issue of fuel management, and fuel reduction burning in particular. One of the arguments presented in support of the need for greater fuel reduction efforts was the widely held tenet that fire intensity increases quadratically with fuel load. This notion is based upon two propositions:

1. That rate of spread R is proportional to fuel load, as embodied in formulae developed by early bushfire scientists – e.g. in the McArthur system

$$R = 0.012\, w\, FFDI,$$

   where w is the fuel load and $FFDI$ is the forest fire danger index;

2. That the intensity I of a fire line can be expressed using Byram's formula (Byram 1959)

$$I = H\, w\, R,$$

   where H is the heat of combustion.

Combining these two formulae gives: $I = 0.012\, H\, w^2\, FFDI$, whereby fire line intensity is seen to increase quadratically with fuel load – hence the belief, for example, that reducing the fuel load by half will decrease fire intensity by a quarter.

However, both of the formulae are only valid in the special case where a fire is burning with a quasi-steady rate of spread. This fact appears to be grossly underappreciated, despite it first being pointed out by Albini (1982) and more recently by Dold and Zinoviev (2009). It should also be noted that combining Byram's formula with other quasi-steady fire behaviour models (e.g. the dry Eucalypt (Vesta) model) would also produce super-linear dependence of intensity on fuel load.

Another widely held tenet is that the progression of a fire line can be modelled by assuming that all points on the fire line act as point ignitions that burn independently – for example, this is the assumption underpinning Huygens-based simulation platforms that are widely employed to predict fire propagation (e.g.

FARSITE, PHOENIX Rapidfire). However, the shortcomings of this assumption are easily demonstrated by consideration of a wind-driven fire line.

Consider a straight-line ignition oriented perpendicular to the prevailing wind direction. According to a Huygens-based approach, the straight fire line will propagate as if each point on the fire line were a point ignition that spreads independently according to the prevailing conditions. Assuming uniform conditions, each point of the fire line will spread in an identical manner so that the ends of the straight fire line will spread at the same forward rate of spread as the center of the fire line. The overall result, according to Huygen's principle, therefore, is that the initially straight fire line will remain straight, as all points on the fire line propagate with the same forward rate of spread.

This is of course manifestly at odds with what happens in reality – an initially straight-line fire under the influence of a uniform wind will instantaneously develop a curved parabolic head, with the spread of the ends of the fire line suppressed relative to the spread of the center of the fire line. In reality, a particular portion of a fire line does not spread independently, rather its spread is influenced by other parts of the fire line through the effects of *pyroconvection*.

Pyroconvection is the buoyant movement of fire heated air – all fires are pyroconvective, all the time! While the effects of pyroconvection can be safely ignored when modelling fire propagation for a wide range of scenarios, there are certain scenarios where pyroconvective interactions can result in non-steady fire propagation that is fundamentally different to the type of fire propagation envisaged in the traditional fire behaviour modelling paradigm. This is especially the case under extreme conditions and/or when multiple fires burn in close proximity. Figure 1 provides a schematic illustration of how multiple spot fires can interact with each other to produce different modes of unsteady fire propagation.

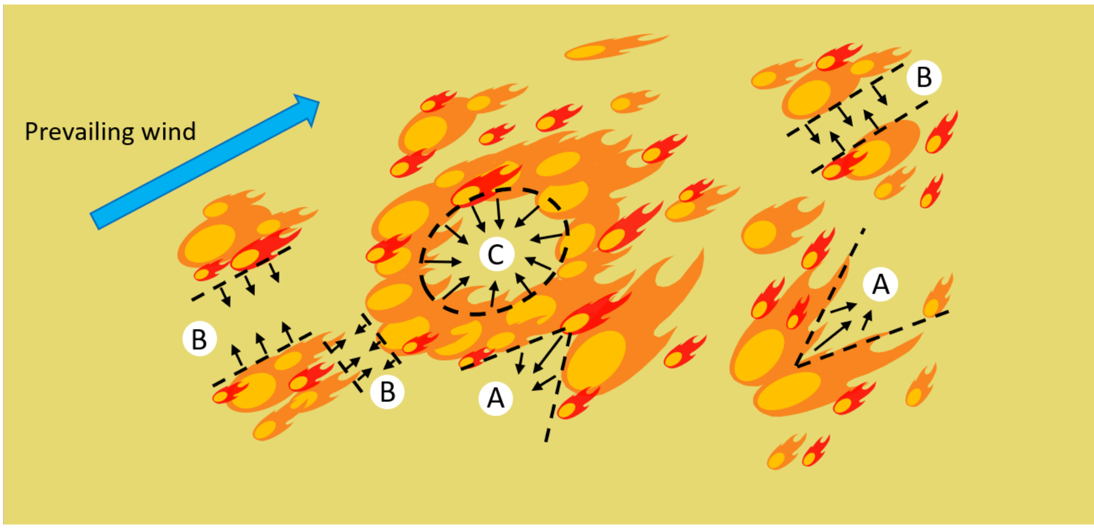

FIGURE 1: SCHEMATIC REPRESENTATION OF COALESCING SPOT-FIRES AND FORMS OF INTERACTION BETWEEN INDIVIDUAL SPOTS. EXAMPLES OF FIRE LINE INTERACTIONS INCLUDE (A) JUNCTION FIRES; (B) PARALLEL FIRE LINE MERGING; (C) PERIMETER COLLAPSE (RING FIRE). ALL OF THESE CONFIGURATIONS INVOLVE PYROCONVECTIVE INTERACTIONS THAT RESULT IN UNSTEADY FIRE SPREAD.

Current operational fire simulators, which are based on the traditional fire modelling paradigm, are not able to account for the types of pyroconvective interactions depicted in Figure 1. At the beginning of this project, the only models capable of accounting for pyroconvective interactions were coupled fire-atmosphere models, which allow for dynamic feedbacks between the fire and the surrounding atmosphere. These coupled models are typically of one of two forms: full physics-based models incorporating computational fluid dynamics, or models that couple a numerical weather prediction model with an empirical or semi-empirical fire behaviour model via a spatial propagation technique such as cellular automata or an interface tracking model. However, the complexity of these models means that the times required for them to complete just a few hours of simulation are operationally prohibitive – often it can take tens of hours, days or even weeks to simulate a fire that in reality may only run for an hour or two.

This project's mandate, therefore, is to develop a modelling capability that can account for pyroconvective interactions, but that still permits faster-than-real-time simulation. Doing so provides end users with a way to model fire propagation that is well within operational requirements and without the need to ignore important dynamic effects that can significantly affect the way a fire propagates across a landscape.

MODES OF DYNAMIC FIRE PROPAGATION

Recent research has identified several modes of distinctly dynamic fire propagation, which cannot be properly accounted for using the traditional fire modelling paradigm. These dynamic fire behaviours served as a starting point for investigation into pyroconvective interactions and provided insights into the development of models of intermediate complexity; that is, models that incorporate dynamic effects but are able to run within operational timeframes. The following modes of dynamic fire propagation have been identified (Filkov et al. 2020):

- Junction fires, or other types of fire line merging – junction fires occur when two fire lines intersect at an oblique angle producing a 'V-shaped' fire line (Viegas et al. 2012) (see Figure 2). In this configuration, the unburnt fuel inside the 'V' receives a greater heat flux than what would be received from a single fire line on its own. This effect is more pronounced near the vertex of the 'V' where the two fire lines intersect, and as a consequence the point of intersection of the two fire lines (the junction point) advances rapidly. Similar effects can occur for different configurations; for example, when two parallel fire lines merge.
- Spot fire coalescence – when many spot fires occur in close proximity, pyroconvective interactions means that the behaviour of each fire is influenced by the other fires (Finney and McAllister 2011). This can result in highly erratic increases in rate of spread and fire intensity, and fire's spreading in directions at odds with the prevailing winds. These spot fires eventually coalesce, which can be seen as a more complex form of fire line merging.
- Vorticity-driven lateral spread (VLS) – VLS involves rapid lateral fire spread across the crest of a steep leeward slope in a direction approximately transverse to the prevailing winds (Sharples et al. 2012; Simpson et al. 2014). It occurs due to an interaction between terrain-modified winds and the pyroconvective plume of a fire, which generates pyrogenic vorticity. VLS is

also associated with intense spotting downwind of the lateral spread zone, with ensuing spot fire coalescence and the formation of expansive flaming zones.

- Wind-driven fire line – while not typically acknowledged as form of dynamic fire behaviour, the evolution of an initially straight fire line into a curved 'parabolic' head occurs due to the influence of a pyroconvective differential along the fire line (Clark et al. 1996), which elicits a dynamic response that ultimately suppresses the rate of spread of the ends of the fire line relative to that of its center.
- Arc fires – these involve fire lines that take the shape of a circular arc and burn in on themselves toward the center of curvature (Thomas 2019). The rate of spread exhibited by arc fires depends on the angular extent of the arc, with more enclosed fire lines exhibiting higher inward rates of spread. The increase in rate of spread is due to enhanced pyroconvective interactions. In the case where the arc forms a closed circle, the evolution of the fire is sometimes referred to as 'perimeter collapse'.
- Eruptive fire behaviour – eruptive fires are fires that occur in connection with canyons or steep slopes and are characterised by a rapid acceleration of the head fire rate of spread (Viegas and Simeoni 2011). Eruptive fires result due to an interaction between the fire's convective plume and a sufficiently inclined terrain surface. This mode of dynamic fire behaviour has been considered by several authors but was not explicitly considered within the scope of this project.

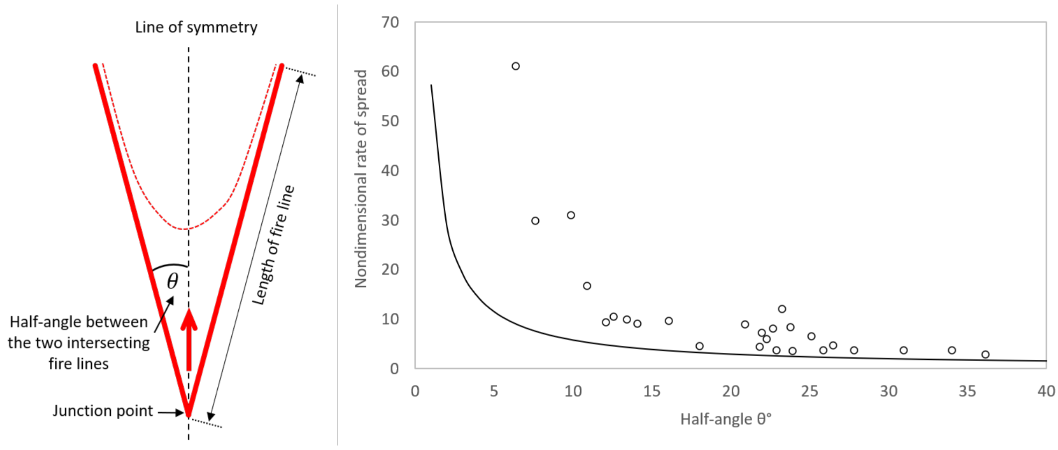

FIGURE 2: LEFT: SCHEMATIC REPRESENTATION OF THE JUNCTION FIRE CONFIGURATION SHOWING THE HALF-ANGLE θ. RIGHT: EXPERIMENTAL CONFIRMATION OF DYNAMIC EHENCEMENT OF THE RATE OF SPREAD. THE POINTS ARE THE OBSERVATIONS OF VIEGAS ET AL. (2012), WHILE THE SOLID LINE REPRESENTS THE ENHANCEMENT OF THE RATE OF SPREAD OF THE JUNCTION POINT EXPECTED DUE TO THE EFFECTS OF GEOMETRY ALONE.

Figure 2 shows a schematic representation of a junction fire configuration, which initially starts as two straight fire lines meeting at some oblique angle (as measured by the half-angle θ) and at some later time has evolved to the dashed fire line. As can be seen, the forward rate of spread of the junction point is enhanced relative to other parts of the fire lines. This behaviour has also been confirmed in laboratory experiments (Viegas et al. 2012). Figure 2 shows results from these experiments, which demonstrate that the forward rate of spread of the junction point is greater than what would be expected in the absence of any interaction between the fire lines and through the effects of geometry alone. The conclusion is that the interaction between the two fire lines enhances the forward rate of spread of the junction point. This interactive effect has also been confirmed using coupled fire-atmosphere models (Thomas et al. 2017).

RESEARCH APPROACH

To enhance our knowledge of the effects of intrinsic fire dynamics on fire spread, the project employed sophisticated mathematical modelling techniques in combination with fire experiments spanning laboratory and landscape scales and coupled fire-atmosphere simulation. The key aim of the project was to develop computationally efficient fire spread models that include physically simplified proxies for complicated dynamical effects.

LEVEL SET METHODS FOR DYNAMIC FIRE PROPAGATION MODELLING

The overarching analytical approach adopted in this project was to treat fire as an evolving interface. This is not new—many researchers have treated fire in such a way, but the methods used have often been confounded due to the changes in topology that can be encountered when fire lines merge or when pockets of unburnt fuel develop (Bose et al. 2009). Such occurrences are rife when spot fires coalesce (see Figure 1), and so employing a methodology that can successfully deal with these types of behaviours is crucial to effectively and efficiently model spot fire development. We therefore employ a level set approach, which is well known to be able to deal with such complexities (Sethian, 1999).

In addition to its ability to deal with topological changes, the level set method also allows for the easy inclusion of additional dynamic drivers, which we aim to include as two-dimensional proxies for more complicated three-dimensional effects. For example, the fire merging configurations illustrated in Figure 1 all involve unsteady fire propagation—as such, commonly used fire simulation techniques that assume a quasi-steady rate of spread or treat different parts of a fire line as mutually inert (e.g. Huygens' Principle), will not accurately capture the ensuing propagation of the fire.

COUPLED FIRE-ATMOSPHERE MODELLING

The dynamic fire behaviours involved in spot fire coalescence, and in other key scenarios, arise due to various interactions between the fire and the surrounding atmosphere. As such, coupled fire-atmosphere models provide a way of directly examining these phenomena, despite their known limitations (e.g., empirical fire spread model formulation, issues with spatial resolution, computational expense). Coupled models permit simulation of idealised scenarios, in which the effects of specific driving factors can be isolated and studied, thereby providing insights into the fundamental physical processes that govern dynamic fire behaviours

Understanding of these fundamental processes informs the development of models of reduced complexity, such as the near-field model that is discussed in the later sections of this report. Indeed, the development of computationally efficient fire propagation models was guided by a number of targeted numerical simulations using the WRF-Fire coupled fire-atmosphere model.

EXPERIMENTAL PROGRAM

To further understand dynamic fire interactions, the project drew upon the findings of an experimental program that included both laboratory experiments conducted in the CSIRO's 'Pyrotron' and in the Centre for the Study of Forest Fires laboratory at Lousã, Portugal, and field experiments conducted by Portuguese researchers as part of Project Firewhirl: Vorticity Effects in Forest Fires (on which Prof Sharples is a co-investigator).

The experiments considered several different fire line configurations, including:

- Junction fires
- Separated V fires
- Parallel fire line experiments
- Ring fire experiments (perimeter collapse)
- Multiple spot fire experiments
- Fire growth from point ignition

The experimental program was also complemented by spot fire experiments conducted in Portugal as part of a collaboration between the University of Wollongong, University of Coimbra and UNSW. The project was run by PhD scholar Michael Storey (Prof Sharples was a co-supervisor).

FINDINGS

The starting point for the project was to investigate junction fires in detail and to propose models of intermediate complexity to model their evolution.

CURVATURE-BASED MODELLING

The question is how to incorporate the dynamics observed in junction fires in a model that runs faster-than-real-time. One way of doing this is to observe which parts of the fire line are exhibiting enhanced rates of spread and identifying features of those parts of the fire line that are distinct from parts of the fire line that don't exhibit enhanced rates of spread.

In the case of junction fires, it is the point of intersection of the two fire lines that exhibits the enhanced rates of spread – this coincides with the part of the fire line with the highest curvature (see Figure 3). Moreover, the parts of the fire line that do not exhibit enhanced rates of spread are straight, and as the fire line straightens out the dynamic enhancement in rate of spread decreases. These observations suggest that fire line curvature may be a good predictor of rate of spread.

With this observation in mind, the following curvature-based model for the evolution of a fire line was proposed:

$$\frac{\partial \phi}{\partial t} + s(\alpha, \beta)\|\nabla\phi\| + \vec{\boldsymbol{u}}(\gamma) \cdot \nabla\phi = 0,$$

with $s(\alpha, \beta) = -\alpha\kappa + \beta$, where ϕ is the level set function, $\vec{\boldsymbol{u}}$ is the ambient wind vector, κ is the curvature of the fire line and α, β and γ are model parameters.

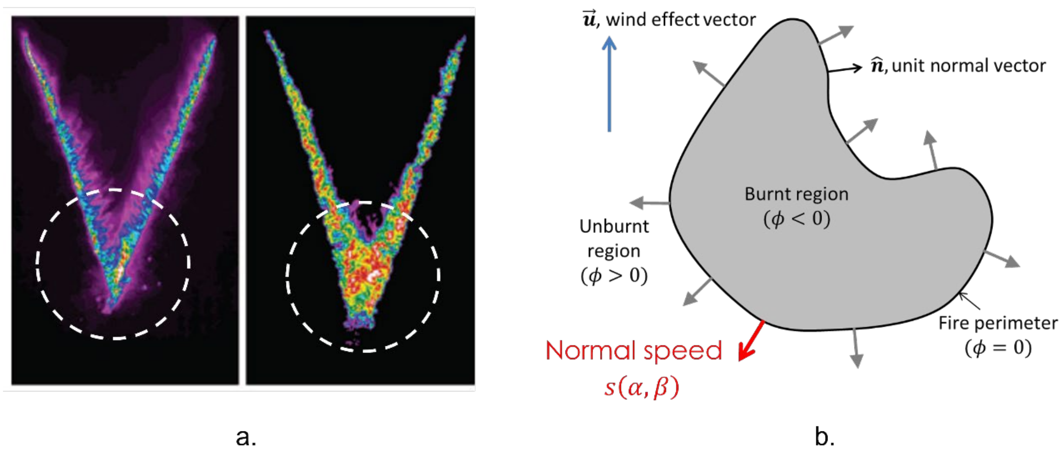

FIGURE 3: (A) IFRARED IMAGERY SHOWING THE ENHANCED RATE OF SPREAD OF THE JUNCTION POINT, WHICH IS ALSO THE POINT OF HIGHEST CURVATURE. FIGURE ADAPETD FROM VIEGAS ET AL. (2012), (B) SCHEMATIC REPRESENTATION OF A FIRE INTERFACE WITH LEVEL SET ϕ, AND NORMAL SPEED $s(\alpha, \beta)$..

This model was found to do a good job of predicting the evolution of the junction fires of Viegas et al. (2012) and the experimental grass fires of Cruz et al. (2015). The details of this are provided by Hilton et al. (2018).

While the curvature-based model was found to perform well in some scenarios, it was not able to account for all of the modes of dynamic fire behaviour outlined above. For example, it is not able to account for the dynamic behaviour of two parallel straight-line fires, or the case where the two arms of a V-shaped fire are initially separated ('separated V' fire) – in both of these cases there is no curvature in the fire line, and so no potential for curvature to describe any dynamic behaviours. Similarly, the curvature-based model is not able to account for the different behaviours observed in circular arc fires, which all have the same fire line curvature but different angular extents. Moreover, a curvature-based model is not able to account for the parabolic rounding of a wind-driven head fire. Therefore, while the curvature-based model is able to account for certain types of dynamic fire behaviour, it is not generally applicable (Thomas 2019).

COUPLED FIRE-ATMOSPHERE MODELLING

The WRF-Fire coupled fire-atmosphere model was used to examine the physical processes associated with dynamic fire spread and spotting. It was led by Dr Chris Thomas as part of his affiliated PhD project, supervised by Prof Sharples. The modelling examined the pyroconvective dynamics of junction fires (V-fires), arc fires and spotting distributions under different terminal velocity assumptions. These results have all been published in scientific journals and refereed conference proceedings (Thomas et al. 2015; 2017; Thomas 2019).

Coupled fire-atmosphere models account for the two-way interaction between a fire and the atmosphere by coupling an empirical fire spread model with a numerical weather model. The heat and moisture released from a fire modifies the atmosphere around it. This results in changes in the local wind field that then influences the spread and intensity of the fire, which then further modifies the atmosphere as part of a feedback cycle. This feedback between the fire and the atmosphere is a critical component of pyroconvective dynamics but are not accounted for in any way in existing operational fire spread simulators.

Junction fires

The modelling considered the detailed wind and vorticity dynamics associated with the enhanced forward rate of propagation of the junction point of two intersecting fire lines. In these numerical experiments the arms of the V were taken to be 1 km long, and a significant enhancement of the forward propagation of the junction point was consistently observed. This study also provides further evidence that the scale of the fire lines plays an important part in the significance of the pyroconvective interactions driving dynamic fire spread.

Figure 4 shows examples of the modelling results. The left panel of Figure 4 shows the evolution of two straight line fires that meet at an oblique angle of 45° (half angle $\theta = 22.5°$). The grey lines show how the two fire lines would have evolved in the absence of any pyroconvective interaction between them, while the black line shows the dynamic evolution of the two fire lines when they interact with each other. In this case, twenty minutes after ignition of the fire lines, the junction point has progressed an additional 750 m in the dynamic simulation compared to when the fire lines evolve independently.

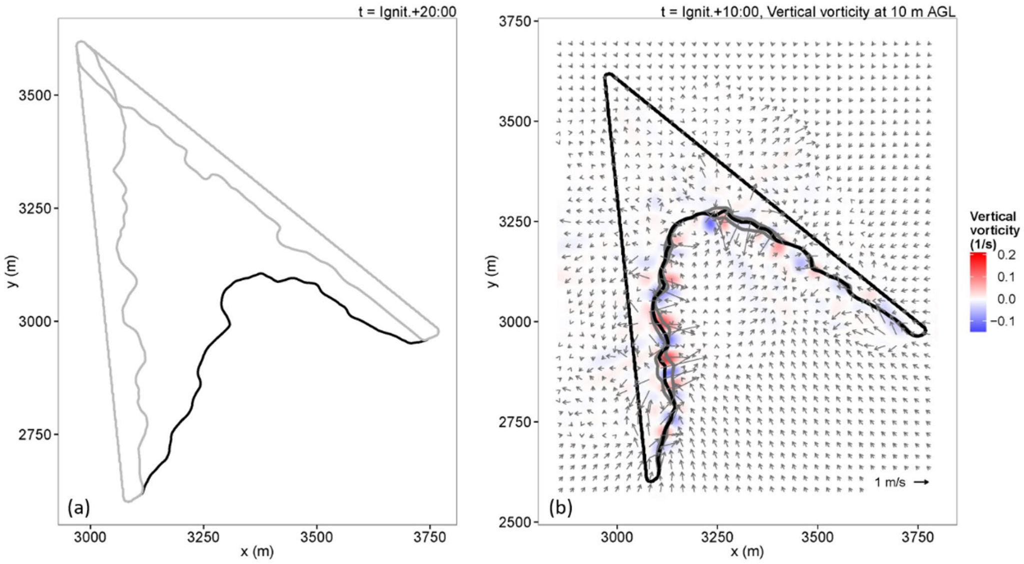

FIGURE 4: LEFT: SCHEMATIC REPRESENTATION OF THE JUNCTION FIRE CONFIGURATION SHOWING THE HALF-ANGLE θ. RIGHT: EXPERIMENTAL CONFIRMATION OF DYNAMIC EHENCEMENT OF THE RATE OF SPREAD. THE POINTS ARE THE OBSERVATIONS OF VIEGAS ET AL. (2012), WHILE THE SOLID LINE REPRESENTS THE ENHANCEMENT OF THE RATE OF SPREAD OF THE JUNCTION POINT EXPECTED DUE TO THE EFFECTS OF GEOMETRY ALONE.

The right panel of Figure 4 illustrates the vorticity dynamics involved in junction fire propagation. The figure shows the formation of localised counter-rotating vortex pairs just ahead of the fire front (seen as pairs of red/blue colouring). The fact these vortex pairs form ahead of the fire front means that they are able to locally enhance the rate of spread, by 'pulling' the fire front forward. In contrast, while vortex pairs were also found to form in association with straight fire lines, they formed directly over or behind the fire line, and so didn't influence the forward rate of spread of the front.

The simulations confirm the role that pyroconvective interactions play in driving the enhanced rate of spread associated with junction fires. The vortex dynamics evident in the right panel of Figure 4 indicate the presence of finer-scale processes driving the propagation of junction fires, which may be difficult to resolve in models of reduced complexity.

Arc fires

Coupled fire-atmosphere simulations were also used to investigate the behaviour of circular arc fires. Some results are shown in Figure 5. The simulations indicated that the angular extent of the circular arc had a significant effect on the inward rate of spread of the fire, with a 60° arc exhibiting rates of spread similar to a straight fire line, and a closed circular arc exhibited much higher rates of spread (see Figure 5). The simulations indicated the general trend that as the arc fire became more closed (i.e., its angular extent increased), the inward rate of spread became higher. Moreover, the simulation indicated that the radius of the circular arc fires also influenced the inward rate of spread, although this effect only became pronounced for the case of the fully enclosed 360° arc fire.

These simulations are significant because they provide a clear refutation of the hypothesis that the dynamic enhancement of the rate of spread is due to fire line curvature. Indeed, the coupled modelling results presented here constituted

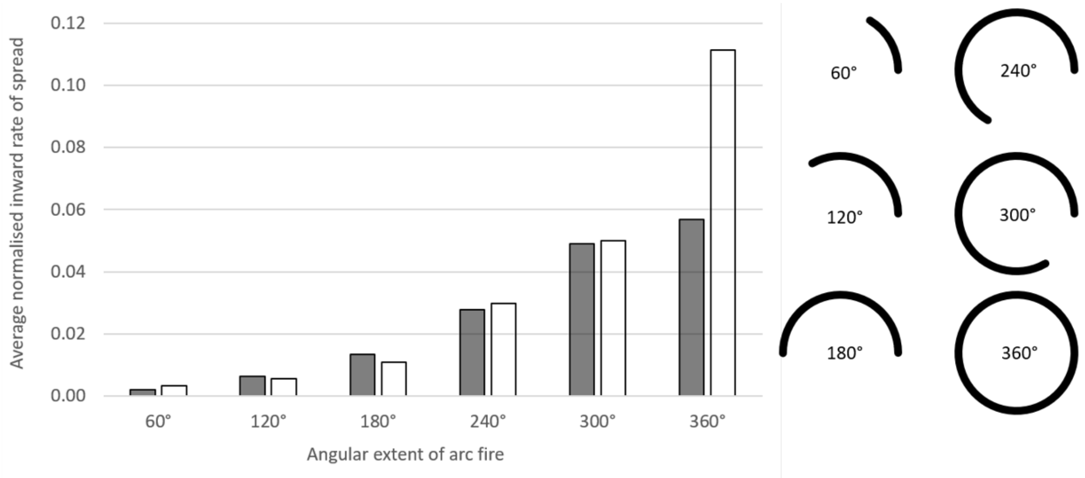

FIGURE 5: INWARD RATE OF SPREAD OF ARC FIRES SIMULATED USING A COUPLED FIRE-ATMOSPHERE MODEL.THE GREY SHADED BARS REPRESENT ARC FIRES WITH AN INITIAL RADIUS OF CURVATURE OF 1000 m, WHILE THE WHITE BARS REPRESENT ARC FIRES WITH AN INITIAL RADIUS OF CURVATURE OF 500 m (THOMAS 2019). THE VARIOUS ARC FIRE S CONSIDERED ARE SHOWN TO THE RIGHT.

a large part of the reason why the curvature-based modelling approached was abandoned. The coupled fire-atmosphere simulations also provided insights that informed the development of the pyrogenic potential model discussed in the later sections of this report.

Other numerical experiments

The WRF-Fire coupled fire-atmosphere model was also used to inform the development of the pyrogenic potential model (next section). Specifically, the model was used to investigate the strength of the pyrogenic indraft produced by a small circular heat source. Some of these results can be seen in Figure 6, which shows how the WRF model compares to the simple pyrogenic potential model for an isolated, static heat source.

PYROGENIC POTENTIAL MODEL

Given the shortcomings of the curvature-based model a new model was sought that could emulate the success of the curvature-based model in the cases where it performed well, and account for dynamic behaviours that the curvature-based model couldn't account for. This led to the development of the pyrogenic potential model. The central idea behind the pyrogenic potential model is that pyroconvective interactions between different parts of the fire line (or fire lines) ultimately arise due to pyrogenic indrafts. These indrafts are modeled as a two-dimensional surface flow with the fire line treated as a sink, whose strength at any given location depends on the intensity of the fire at that point. This is shown schematically in Figure 7. The air flowing horizontally into a fire's plume can be treated as a two-dimensional incompressible and irrotational flow everywhere except along the fire line, where it becomes a purely vertical flow (the two-dimensional flow disappears along the fire line, which is then treated as a 'sink' for the flow). The strength of the pyrogenic indraft can then be modelled by coupling the level set equation with a Poisson equation, which is a standard technique in potential theory.

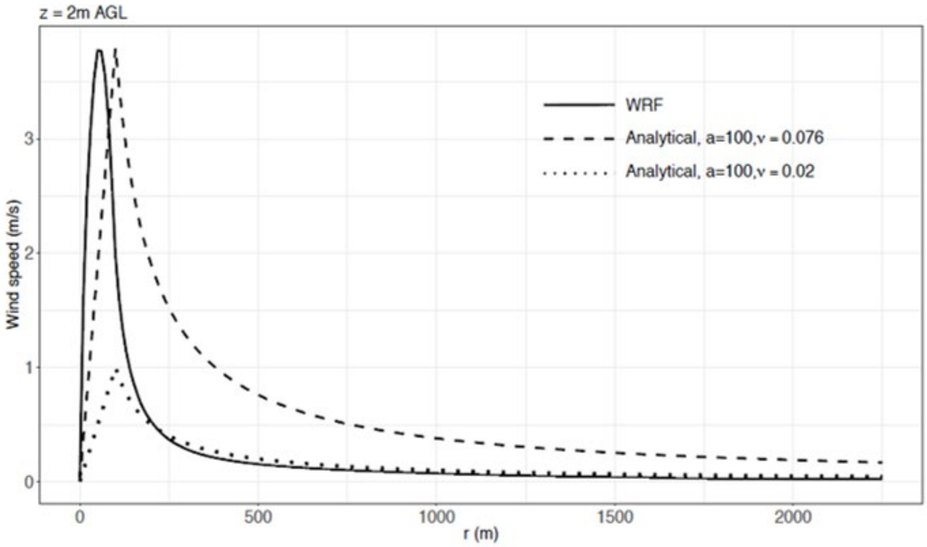

FIGURE 6: COMPARISON OF RADIAL PROFLES OF NEAR-SURFACE WIND SPEED RESULTING FROM STATIC CIRCULAR HEAT SOURCE OF a = 100 METRES RADIUS (MEASURED FROM THE CENTRE OF THE HEAT SOURCE). THE SOLID LINE IS THE WRF SOLUTION AT 2 METRES AGL WITH I = 5 × 10^4 Wm^{-2}. THE BROKEN LINES ARE ANALYTICAL SOLUTIONS CORRESPONDING TO THE SIMPLE PYROGENIC POTENTIAL MODEL. THE VALUES OF ν ARE ARBITRARY: ν = 0.076 MAKES THE PEAK OF THE ANALYTICAL SOLUTION APPROXIMATELY EQUAL TO THAT OF WRF, WHILE ν = 0.02 MAKES THE ANALYTICAL SOLUTION APPROXIMATELY MATCH THE WRF SOLUTION FOR r > 200 METRES.

Fire simulation incorporating pyrogenic potential - irrotational case

The pyrogenic potential model is defined by the parameters α, β and k, and is expressed as the following set of equations (see Figure 7):

$$\frac{\partial \phi}{\partial t} + s(\boldsymbol{x})\|\nabla\phi\| = 0,$$

$$s(\boldsymbol{x}) = \alpha + \beta \max(\hat{\boldsymbol{u}} \cdot \hat{\boldsymbol{n}}, 0),$$

$$\boldsymbol{u} = \boldsymbol{u}_a + \Delta\boldsymbol{u}_p,$$

$$\Delta\boldsymbol{u}_p = \nabla\psi,$$

$$\nabla^2\psi = ks(\boldsymbol{x})\delta_s\big(\phi(\boldsymbol{x})\big)\|\nabla\phi\|.$$

Here $\hat{\boldsymbol{u}}$ is the unit vector in the direction of the wind and $\hat{\boldsymbol{n}}$ is the unit vector normal to the fire perimeter.

The pyrogenic potential model was found to give accurate results for several fire line configurations, many of which could not be adequately modelled using the curvature-based model. These configurations included junction fires, separated V- fires, wind-driven fire lines and parallel fire lines. Further details are presented by Hilton et al. (2018).

Near-field model

One limitation of the pyrogenic potential model, as presented above, is that the pyrogenic indraft is assumed to be irrotational. This means that the pyrogenic model cannot be applied to situations where vertical vorticity is present. However, there are many instances where it will be desirable to incorporate the effects of vertical vorticity; for example, in instances of vorticity-driven lateral spread.

Initial limitations of the model, which required the indraft flow to be irrotational, have been overcome through use of a near-field approximation via the Helmholtz decomposition (Arfken and Weber, 1999). In this sense we assume that we can write the pyrogenic indraft as the gradient of a pyrogenic potential function ψ. Note that the pyrogenic indraft can now include components due to the pyrogenic vertical vorticity. In the presence of an ambient wind, the fire's propagation is then driven by the sum of the ambient wind and the pyrogenic indraft $\nabla\psi$. This gives rise to the upgraded level set formulation, where now the level set equation is coupled with two Poisson equations for the scalar pyrogenic potential ψ and the vector potential $\boldsymbol{\eta}$:

$$
\begin{aligned}
&\frac{\partial \phi}{\partial t} + s(\boldsymbol{x})\|\nabla\phi\| = 0,\\
&s(\boldsymbol{x}) = \alpha + \beta \max(\hat{\boldsymbol{u}} \cdot \hat{\boldsymbol{n}}, 0),\\
&\boldsymbol{u} = \boldsymbol{u}_a + \Delta\boldsymbol{u}_p,\\
&\Delta\boldsymbol{u}_p = \nabla\psi + \nabla \times \boldsymbol{\eta},\\
&\nabla^2\psi = ks(\boldsymbol{x})\delta_s\big(\phi(\boldsymbol{x})\big)\|\nabla\phi\|\\
&\nabla^2\boldsymbol{\eta} = \boldsymbol{\omega}.
\end{aligned}
$$

The term $\boldsymbol{\omega}$ represents sources of vertical pyrogenic vorticity. We refer to the model described by the above equations as the *near-field model*.

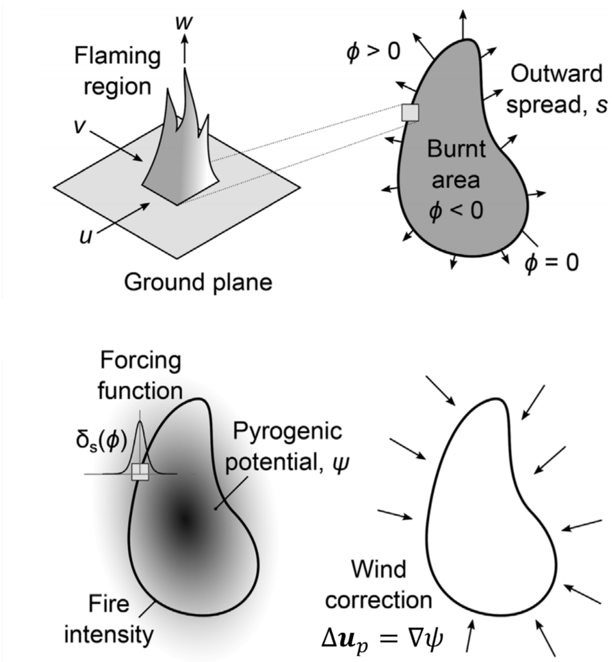

FIGURE 7: SCHEMATIC DIAGRAM OF PYROGENIC POTENTIAL MODEL. TOP LEFT: THE POTENTIAL FORMULATION USES AN IDEALISED MODEL WHERE A VERTICAL AIR FLOW COMPONENT, w, ONLY OCCURS WITHIN FLAMING REGIONS ACTING AS A SINK TERM ON THE HORIZONTAL AIR FLOW, u AND v. TOP RIGHT: THE FIRE PERIMETER (SOLID BLACK CLOSED CURVE) MOVES OUTWARD AT A SPEED s DEPENDING ON LOCAL CONDITIONS SUCH AS FUEL AND LOCAL WIND VECTOR $\boldsymbol{u}$. THE PERIMETER IS REPRESENTED IN THE LEVEL SET MODEL AS THE ZERO SET OF THE DISTANCE ϕ FROM THE PERIMETER. BOTTOM LEFT: THE PERIMETER IS USED TO CALCULATE A LOCAL INTENSITY, REPRESENTED AS A SMOOTHED DIRAC DELTA DISTRIBUTION $\delta_s(\phi)$. THE INTENSITY IS USED AS A FORCING TERM IN A PYROGENIC POTENTIAL MODEL. BOTTOM RIGHT: THE GRADIENT OF THIS PYROGENIC POTENTIAL PROVIDES A CORRECTIVE TERM TO THE WIND VECTOR Δu_p ACCOUNTING FOR AIR INFLOW TO THE FIRE.

In addition to successfully reproducing the observed behaviour of several experimental fires (across scales from 1 metre to 10s of metres), the near-field model is also able to emulate more complex dynamic fire propagation, such as vorticity-driven lateral spread. Figure 8 shows a simulation of vorticity-driven lateral spread using a fully coupled fire-atmosphere model compared with the output from the near-field model (Sharples and Hilton, 2020). It is worth noting that the fully coupled simulation took about 10 hours of computation time on a supercomputer, while the near-field model took about 10 seconds of computation time on a laptop. While the near-field model is not able to perfectly reproduce the behaviour simulated by the fully coupled model (e.g., the flanks on the mid-slopes), it is able to accurately reproduce the extent of the lateral spread, which is one of the key features of this mode of fire propagation.

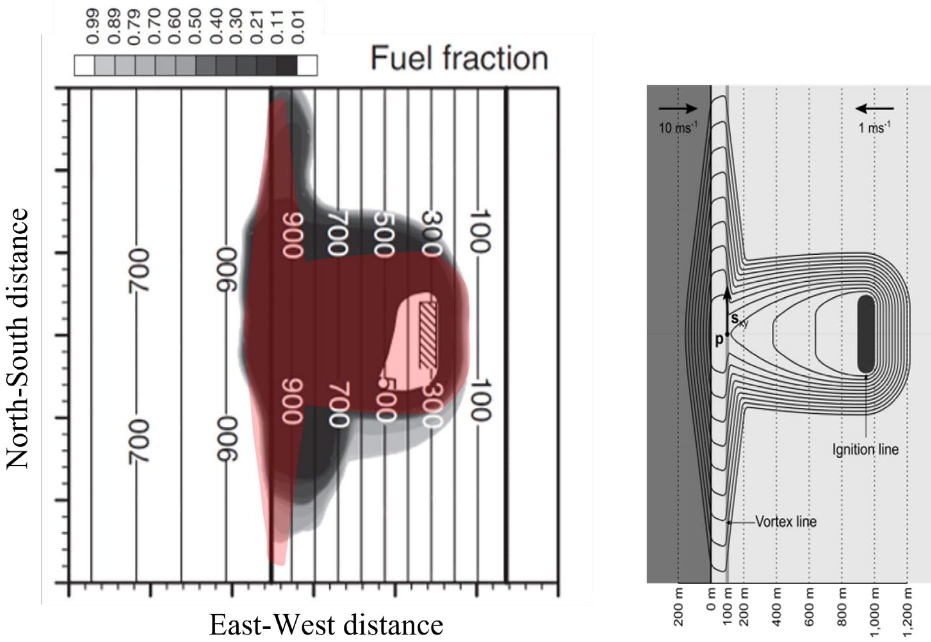

FIGURE 8: SIMULATIONS OF VORTICITY-DRIVEN LATERAL SPREAD TWO HOURS AFTER IGNITION. THE LEFT PANEL SHOWS A COUPLED FIRE-ATMOSPHERE SIMULATION - A FIRE LINE IGNITION ON THE LEEWARD SIDE OF A HILL BURNS BACK UP THE SLOPE AND SPREADS LATERALLY ACROSS THE RIDGE. THE CONTOURS IN THE FIGURE INDICATE THE HEIGHT OF THE HILL (MAJOR INTERVALS ON THE HORIZONTAL AND VERTICAL AXES ARE 100m). THE RIGHT PANEL SHOWS A NEAR-FIELD MODEL SIMULATION OF THE SAME SCENARIO. FOR COMPARISON, THE RED SHADED REGION IN THE LEFT PANEL CORRESPONDS TO THE EXTENT OF THE NEAR-FIELD SIMULATION.

Implications of the pyrogenic potential model

The pyrogenic potential model, and its near-field extension, permit more detailed examination of burning configurations that arise in situations such as prescribed burning and spot fire formation. For example, it could be used to better understand how different ignition patterns might influence prescribed burning objectives in terms of fire intensity thresholds, etc.

The model can also be used to address controversies in the debate around wildfire management. For example, in the aftermath of the Black Summer fires (or indeed as happens after any major fire), many commentators suggested that the intensity of the fires would have been less if more effort had of gone into fuel reduction. As mentioned in the Introduction, this argument is based on the widely held tenet that fire intensity increases quadratically with fuel load.

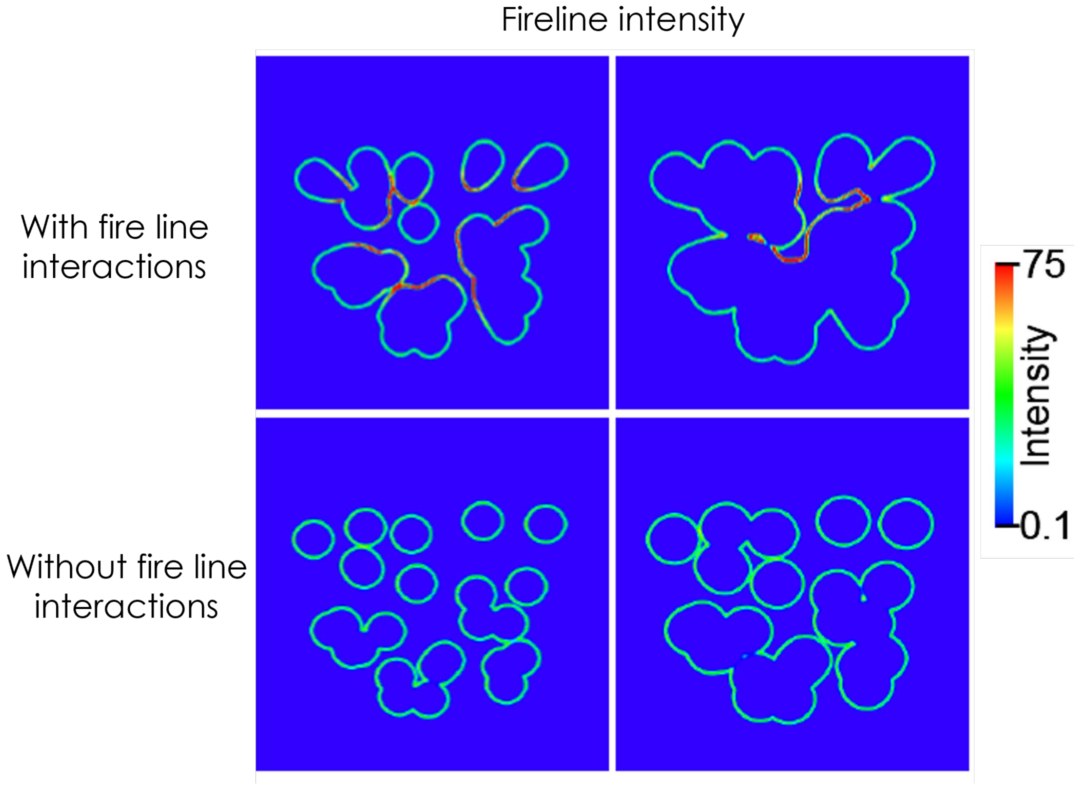

FIGURE 9: COALESCENCE OF 25 SPOT FIRES WITH (TOP ROW) AND WITHOUT (BOTTOM ROW) PYROCONVECTIVE INTERACTION. THE LEFT COLUMN SHOWS THE DEVELOPMENT OF THE FIRES 15 SECONDS AFTER IGNITION AND THE RIGHT COLUMN SHOW THE FIRES 20 SECONDS AFTER IGNITION. RED COLOURS INDICATE LOCAL ENHANCEMENTS IN (NON-DIMESNIONALISED) FIRE INTENSITY DUE TO PYROCONVECTIVE EFFECTS. FIGURE ADAPTED FROM HILTON ET AL. (2017)

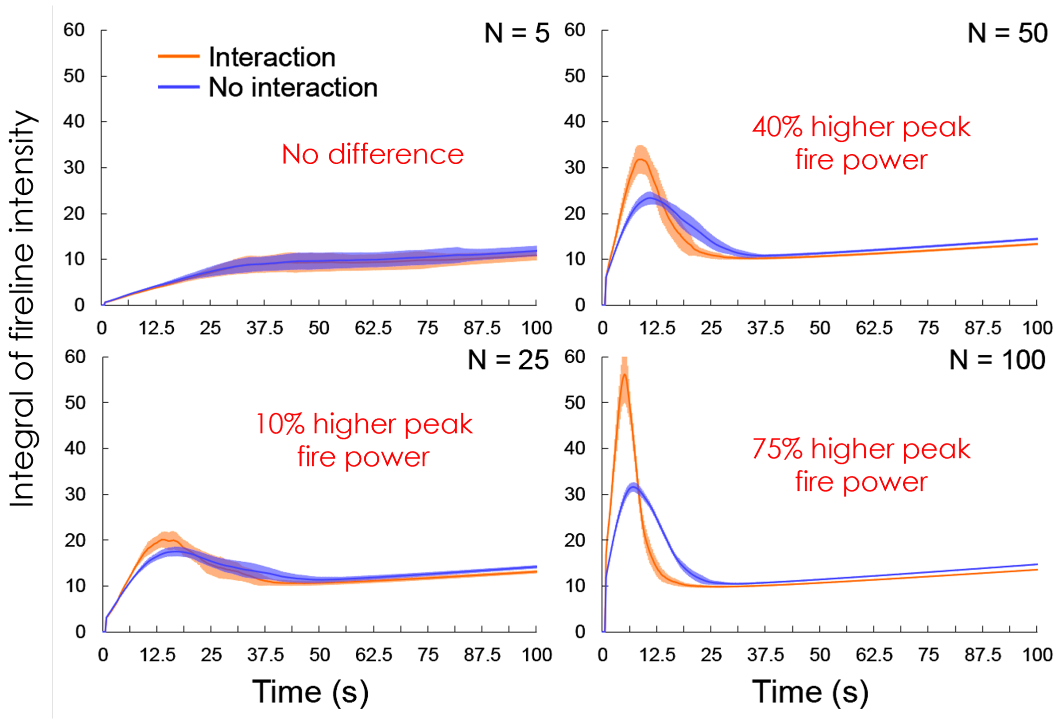

FIGURE 10: POWER PROFILE (INTEGRAL OF NON-DIMENSIONALISED FIRELINE INTENSITY) FOR RANDOMLY DISTRIBUTED COALESCING SPOT FIRES AS A FUNCTION OF DIFFERENT NUMBER OF SPOTS FIRES. THE LINES SHOW THE MEAN VALUE OVER TEN ENSEMBLE SIMULATIONS AND THE CONFIDENCE BAND SHOWS ONE STANDARD DEVIATION. FIGURE ADAPTED FROM HILTON ET AL. (2017).

The pyrogenic potential model can provide additional insight into issues like these, for example through simulations like those portrayed in Figure 9. The figure shows simulations of multiple spot fires under two scenarios. The first (top row of the Figure) shows how the spot fires develop when dynamic fire interactions are included using the pyrogenic potential model, while the second (bottom row) shows how they develop when there is no dynamic interaction between different fires. The pyroconvective interactions act to enhance the rate of spread at different points across the burning domain resulting in an overall increase in fire intensity compared to the case with no fire line interactions. This is despite the fact that the fuel loads in each set of simulations is the same. These results suggest that pyroconvective interactions can dominate fire intensity, overpowering the influence of reduced fuel loads when mass spotting is present.

Figure 10 quantifies this effect and shows that it becomes more pronounced when a greater number of spot fires are involved. In the case of only five spot fires, pyroconvective interactions have practically no effect on the overall peak intensity, but when a hundred spot fires are burning over the same area, pyroconvective interactions can produce a 75% increase in the peak fire intensity.

Finally, Figure 11 gives an example of how the pyrogenic potential model, and its near field extension can be implemented in fire simulators – in this case the Spark framework. The figure shows a simulation involving a line fire ignition and multiple spot ignitions. Figure 11a the left shows the simulated propagation of the fire in the absence of any pyroconvective interactions, while Figure 11b shows the simulated propagation of the fire when pyroconvective interactions are accounted for. It is of interest to note the different ways the line fire ignition evolves in each of the two scenarios: in the absence of pyroconvective interactions the initially straight-line fire remains straight, while in the case where pyroconvective interactions are included, the initially straight-line fire develops a rounded front, as is seen in real wildfire cases.

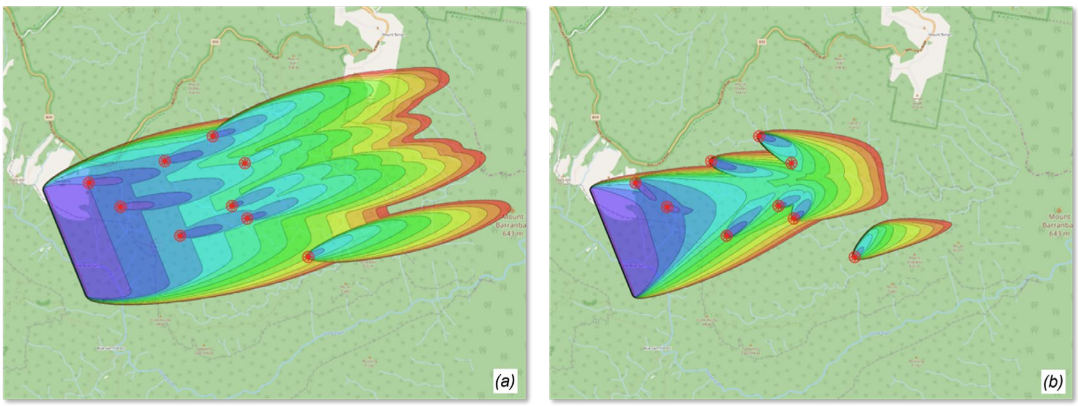

FIGURE 11: SPARK SIMULATION OF FIRE PROPAGATION RESULTING FROM A LINE IGNITION AND MULTIPLE SPOT IGNITIONS. (A) EVOLUTION OF THE FIRE IN THE ABSENCE OF PYROCONVECTIVE INTERACTIONS. (B) EVOLUTION OF THE FRONT INCORPORATING PYROCONVECTIVE INTERACTIONS. NOTE THE PRESENCE OF MULTIPLE JUNCTION FIRES IN THE SIMULATIONS.

EXPERIMENTAL PROGRAM

The project drew upon findings from the experimental program to further inform development of dynamic fire propagation models of reduced complexity. The experimental programs involved both laboratory and field experiments. The laboratory experiments were conducted at two different facilities: at the CSIRO Pyrotron in Canberra, Australia and at the Centre for the Study of Forest Fires at Lousã, Portugal. Field experiments were also conducted in Portugal as part of 'Project Firewhirl' (affiliated with this CRC project, through Prof Sharples involvement in each).

More recently, the project has also drawn upon field experiments conducted by the University of Melbourne as part of the CRC project "Threshold conditions for extreme fire behaviour" (of which Prof Sharples is also a team member). Analysis of the data obtained through these experiments, which consider fire line merging, is still underway and will not be reported on further in this report.

Pyrotron experiments

The CSIRO Pyrotron was employed to examine several different dynamic fire propagation configurations. These included: junction fires, separated V-fires, ring fires and growth from point ignitions.

Junction fires

The main aim of these experiments was to examine pyroconvective interactions between two fire lines that intersect at an oblique angle – we refer to these two fire lines as 'the arms of the V'. Experiments were conducted in the absence and presence of ambient wind, for different arm lengths and for different half-angles (see Figure 2). Dry eucalypt litter was used as fuel for this series of experiments, which comprised a total of 96 experiments – this is different to Viegas et al. (2012) who used straw fuel. The results of these experiments have been published by Sullivan et al. (2019).

Taken as a whole, the experiments conducted in the absence of wind indicated that the forward rate of progression of the point of intersection of the arms of the V was not significantly different from what would be expected if the fire lines did not interact with one another. As such the no-wind experiments did not support the hypothesis that pyroconvective interactions result in enhancement of the forward rate of spread of the vertex of the junction fire.

However, the arms of the V exhibited asymmetrical propagation, which indicated that pyroconvective interactions did have an effect on the overall propagation of the fire. In particular, the arms of the V fire did not spread backwards until later in the burns. This suggests that while pyroconvective interactions were not strong enough to exert a significant influence on the forward propagation of the vertex point inside the V, they were strong enough to slow spread outside the V.

Furthermore, the forward propagation of the vertex inside the V was consistently higher for the 1500 mm experiments than for the 800 mm experiments, which indicates that the scale of the fire plays an important role. This is also consistent with the findings of Viegas et al. (2012), who found a significant enhancement in the forward propagation of the vertex, in the absence of wind and different fuel type, for 6m long arms.

For the experiments in the presence of wind it was found that the forward rate of spread of the vertex was significantly higher than what would be expected if there was no interaction between the fire lines. These findings suggest that the presence of wind alters the pyroconvective dynamics in a way that enhances the interaction between the fire lines.

The results of this series of experiments were also used for calibration and validation of the pyrogenic potential model, as discussed by Hilton et al. (2018).

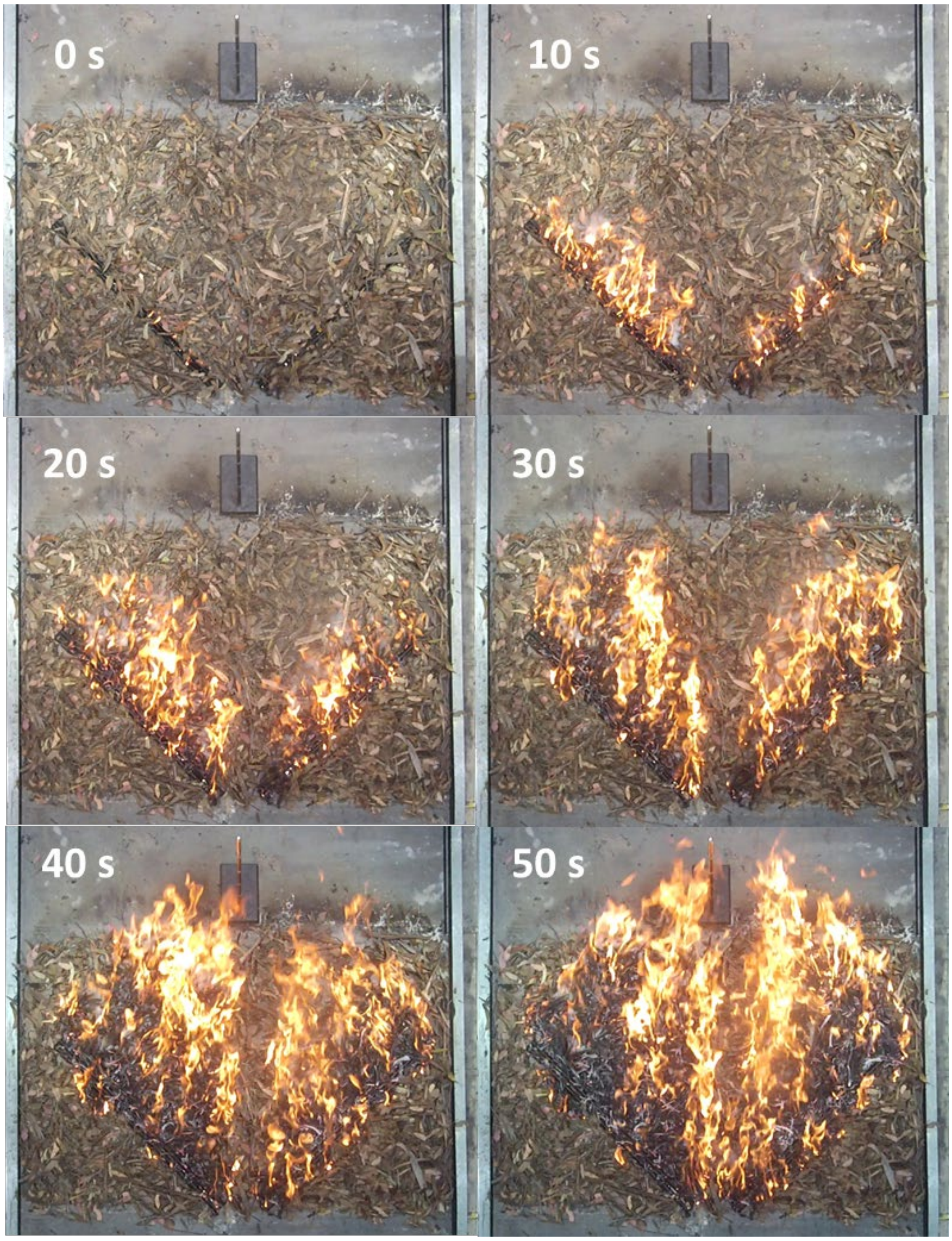

FIGURE 12: EXAMPLE OF A SEPARATED 'V' FIRE AT VARIOUS TIMES SINCE IGNITION IN WHICH TWO 800 MM IGNITION LINES AT AN INTERSECTION ANGLE NORMAL TO THE FLOW OF 1 M/S AIR (BOTTOM OF FRAME TO TOP) IS 45°. AS CAN BE SEEN, THE FIRE FROM EACH IGNITION LINE DEVELOPS INDIVIDUALLY, ONLY MERGING AFTER 50 SECONDS. HOWEVER, THE HYPOTHESIS OF THE EXPERIMENT IS THAT THE BEHAVIOUR OF EACH FIRE IS DIFFERENT FROM THAT OF A SINGLE FIRE.

Separated V fires

The experiments explored the effect of interactions between oblique fire lines that do not intersect. Utilising a similar methodology to the junction fire experiments, but with a 150 mm separation of the arms of each 'V', a smaller range of variables (line length and angle) were studied. However, as a result of the fundamentally different behaviour of these fires, an innovative analysis method was required in order to examine interactions.

Figure 12 illustrates an example separated 'V' fire burning under the influence of an ambient wind of 1 ms^{-1} at various times since ignition. Two 800 mm ignition lines, set at an incident angle 45° (half-angle $\theta = 45°$) and separated at the closest point by 150 mm, results in two individual fires that do not merge until 50 seconds after ignition.

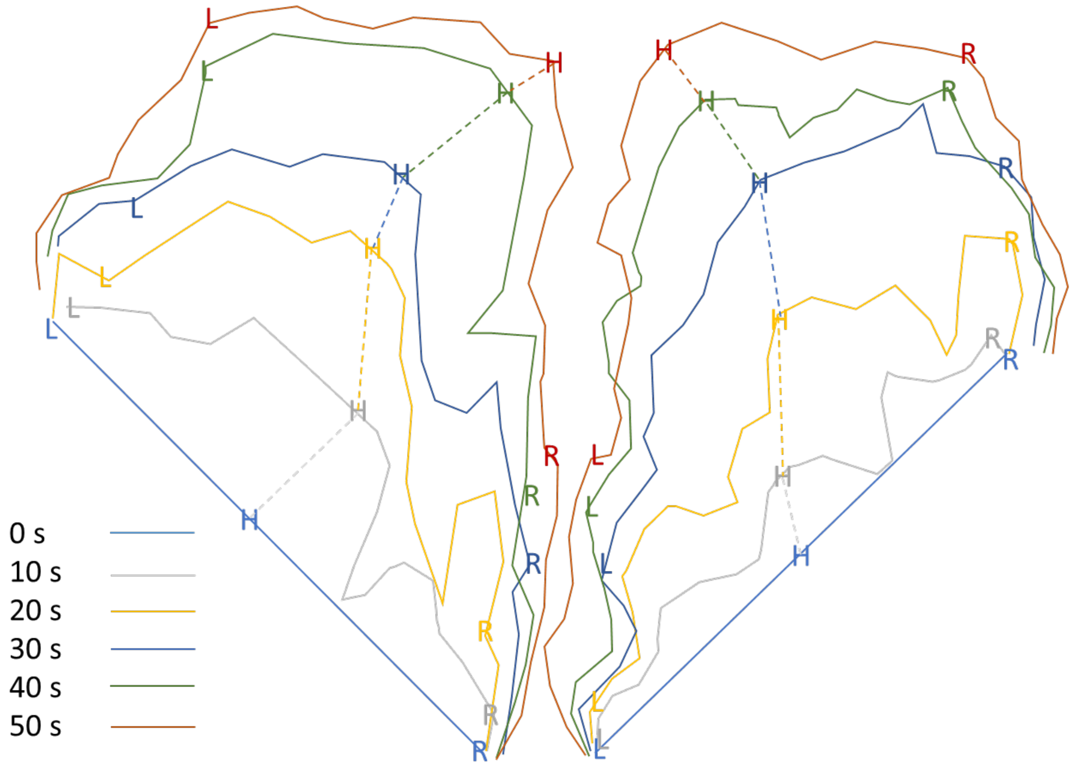

FIGURE 13: SCHEMATIC MAP OF FIRE ISOCHRONES BASED ON THE IMAGES PRESENTED IN FIGURE 1. LEFT FLANK (L), HEAD FIRE (H) AND RIGHT FLANK (R) POSITIONS ARE MARKED. DASHED LINES INDICATE TRAJECTORY OF EACH FIRE'S HEAD PATH BY ISOCHRONE.

Figure 13 illustrates a schematic map of the isochrones extracted from the frames presented in Figure 12. The positions of the left flank, head and right flank are marked for each fire. The analysis currently being undertaken attempts to quantify fire behaviour specific to this ignition configuration in contrast to a control consisting of a single fire in the absence and presence of wind. Of primary interest are the rate of spread and trajectory of the head fire (marked as dashed lines in Figure 13), change in head fire angle (∠LHR), distance between heads, time to closure (left fire R, right fire L conjunction). The analysis aims to correlate these attributes with variables such as wind presence, ignition incident angle, ignition line length, and fuel moisture content.

Ring fires

Following on from the 'V'-fire experiments previously published and discussed above and comparison with similar experiments conducted in different fuel types (e.g. Viegas et al. 2012), it was hypothesised that fuel bulk density (the 'fluffiness' of the fuel) was a critical variable in determining the level of interaction between fires, primarily influencing the rate of combustion and thus height and volume of flame produced. For this experimental program involving ring fires, or annular fires (i.e., fires ignited as circles and allowed to burn inward), fuels with different bulk densities were considered.

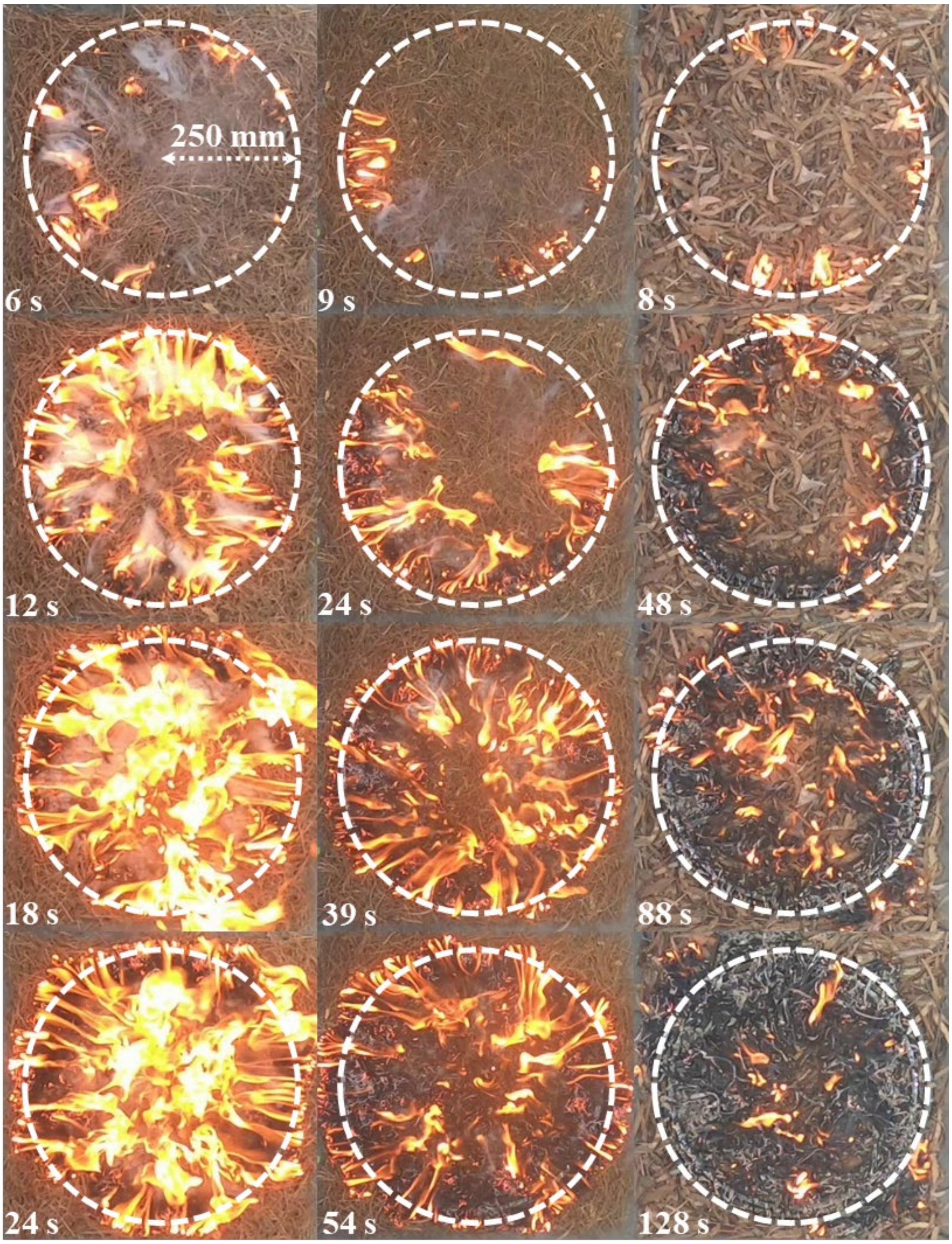

FIGURE 14: PLANAR IMAGERY AT VARIOUS TIMES SINCE IGNITION OF EXAMPLE ANNULAR FIRE EXPERIMENTS USING 500 MM DIAMETER IGNITION RING IN THREE FUEL CONDITIONS. (LEFT COLUMN) UNCOMPACTED PINE NEEDLES (LOW BULK DENSITY). (CENTRE COLUMN) COMPACTED PINE NEEDLES (INTERMEDIATE BULK DENSITY). (RIGHT COLUMN) UNCOMPACTED EUCALYPT LITTER (HIGH BULK DENSITY).

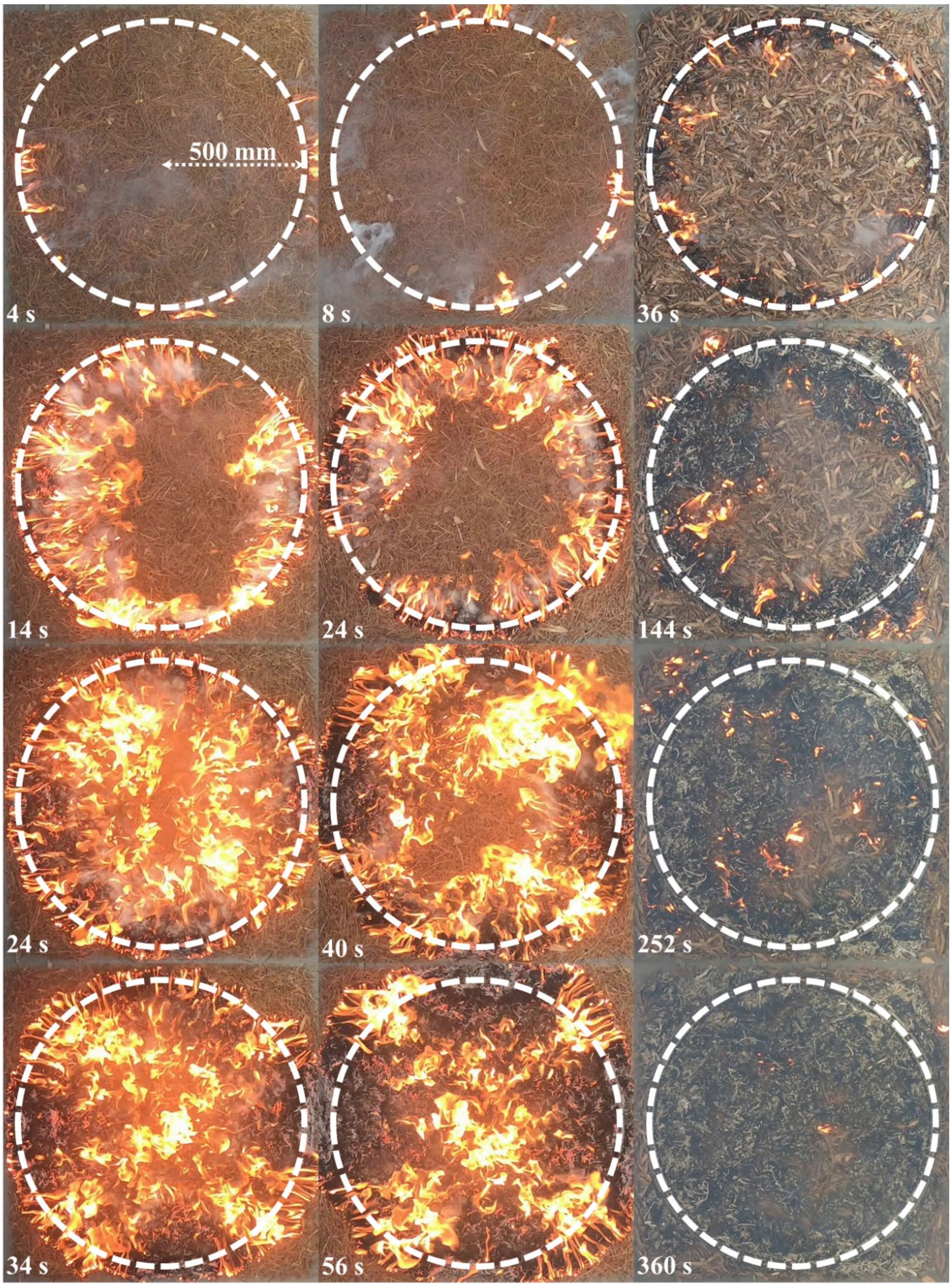

FIGURE 15: PLANAR IMAGERY AT VARIOUS TIMES SINCE IGNITION OF EXAMPLE ANNULAR FIRE EXPERIMENTS USING 1000 MM DIAMETER IGNITION RING IN THREE FUEL CONDITIONS. (LEFT COLUMN) UNCOMPACTED PINE NEEDLES (LOW BULK DENSITY). (CENTRE COLUMN) COMPACTED PINE NEEDLES (INTERMEDIATE BULK DENSITY). (RIGHT COLUMN) UNCOMPACTED EUCALYPT LITTER (HIGH BULK DENSITY).

Two fuel types, radiata pine needles (to facilitate comparison with international studies) and eucalypt litter (to compare with previous results) were used. The bulk density of the eucalypt litter is naturally high (55-70 kg/m^3) whereas the bulk density of the pine needles is generally lower, but depends on the level of compaction. Two levels of compaction were studied, one in which needles were made as fluffy and aerated as possible (lowest bulk density) and one where needles were compacted under weights (intermediate bulk density), producing a cross-over of fuel type and bulk density. Preliminary analysis of these data is currently in progress.

Figure 14 and Figure 15 compare the typical behaviour of annular fires for the three fuel conditions and for two different radii: 250 mm and 500 mm, respectively. The effect of fuel bulk density is clear – the lower the bulk density, the larger the flames and the faster the inward rate of spread of the fire. Figure 16 further illustrates the effect of fuel condition on relative flame height across all fuel conditions and ignition radii. The flame height in the eucalypt litter uniformly had the lowest flame height whereas the uncompacted pine needle generally had the tallest flame.

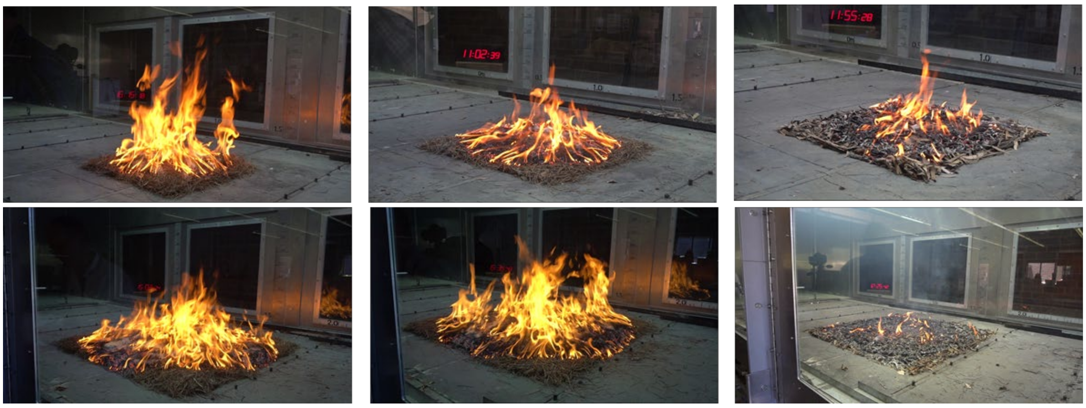

FIGURE 16: COMPARISON OF RELATIVE FLAME HEIGHTS ASSOCIATED WITH THE THIRD ROW OF IMAGES FROM FIGURE 14 (TOP ROW, 500 MM DIAMETER) AND FIGURE 15 (BOTTOM ROW, 1000 MM DIAMETER) FOR UNCOMPACTED PINE NEEDLES (LEFT COLUMN), COMPACTED PINE NEEDLES (CENTRE COLUMN) AND EUCALYPT LITTER (RIGHT COLUMN).

Key fire behaviour metrics for analysis will include rate of spread to centre of ignition circle, flame height, comparison of fire speeds across different radii, backing rate of spread (outside of ignition circle) utilising the following parameters for correlation: fuel type, fuel bulk density, fuel moisture content, ignition radius.

Fire growth

Spot fires develop through an acceleration, or growth, phase before establishing their longer-term behaviour. To better understand this growth phase of fire propagation, the initial growth of incipient fires burning in uniform dry eucalypt forest litter fuel was studied in the Pyrotron. Fifty-eight fires of three ignition patterns (point, 400 mm and 800 mm lines) were carried out under the influence of two different wind speeds (1.25 m s^{-1} and 2.0 m s^{-1}) and two dead fuel moisture groupings (< 5% and >5%).

Rate of forward spread was found to increase with ignition line length with a significant difference in spread rates for both wind speeds. The results were also compared to two theoretical fire growth models to determine the best model to estimate the time for a point ignition to reach steady-state. These results have been detailed by Gould and Sullivan (2021).

Portuguese experiments

The Portuguese funded research project 'Project Firewhirl' involves collaboration between UNSW and the University of Coimbra. Given the complementary aims

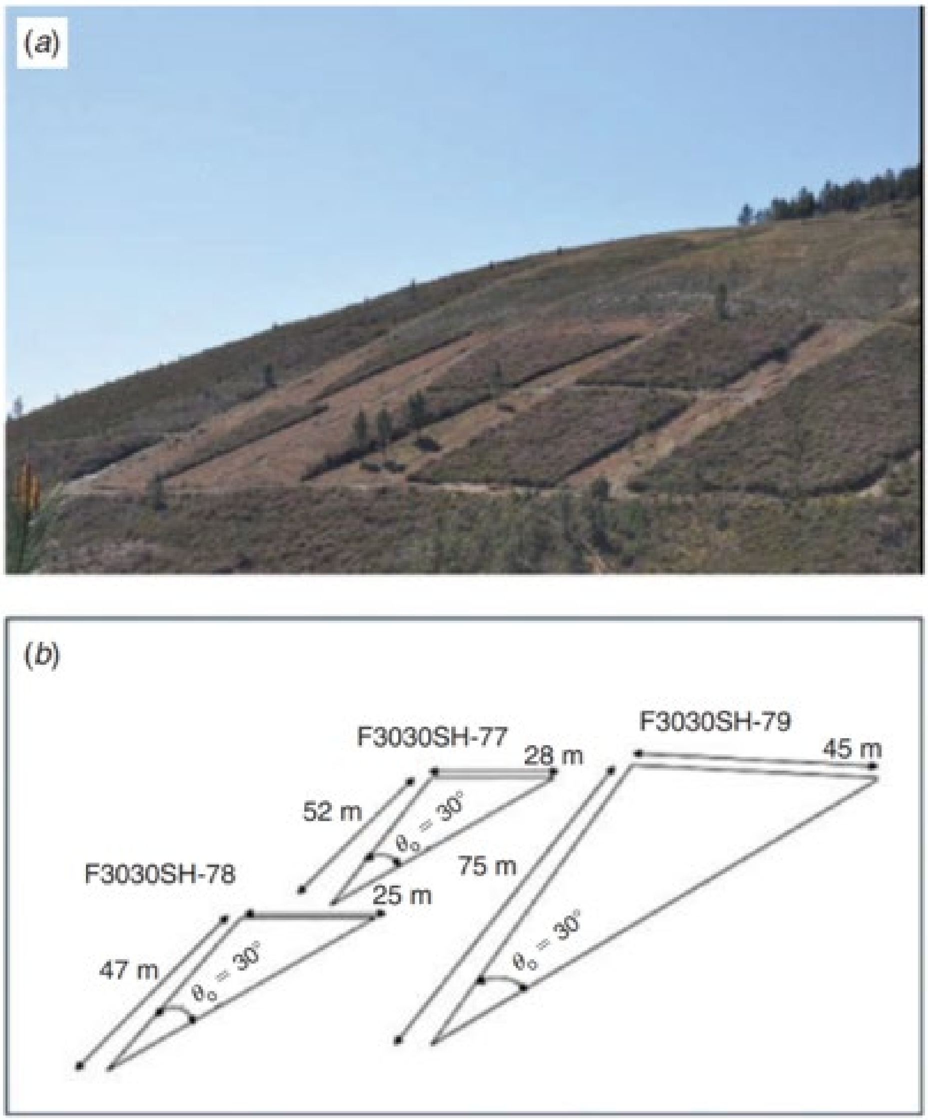

FIGURE 17: GESTOSA JUNCTION FIRE FIELD EXPERIMENTS. (A) GENERAL OVERVIEW; (B) DIMENSIONS OF THE PLOTS. FIGURE HAS BEEN ADAPTED FROM RAPOSO ET AL. (2018).

of Project Firewhirl and the Spot Fire Coalescence project, experiments conducted under the auspices of Project Firewhirl can also be used to inform development of models of reduced complexity, such as the near-field model. These experiments involved both laboratory and field experiments that considered various fire line configurations, such as junction fires, parallel fire lines and multiple spot fires.

Junction fires

The original experimental work that considered junction fires were conducted by Viegas et al. (2012) at the Centre for the Study of Forest Fires in Lousã, Portugal. The pioneering junction fire experiments have been followed up by laboratory and field-scale experiments as described by Raposo et al. (2018).

Results from these experiments, which used various fuel beds and slope angles confirmed that the driving processes are similar over a wide range of scales with little dependence on the initial boundary conditions. Numerical simulations also confirmed the role of pyroconvection in driving the dynamic enhancement of rate of spread. Figure 17 shows the field-scale experimental plots used to examine the behaviour of junction fires burning on slopes.

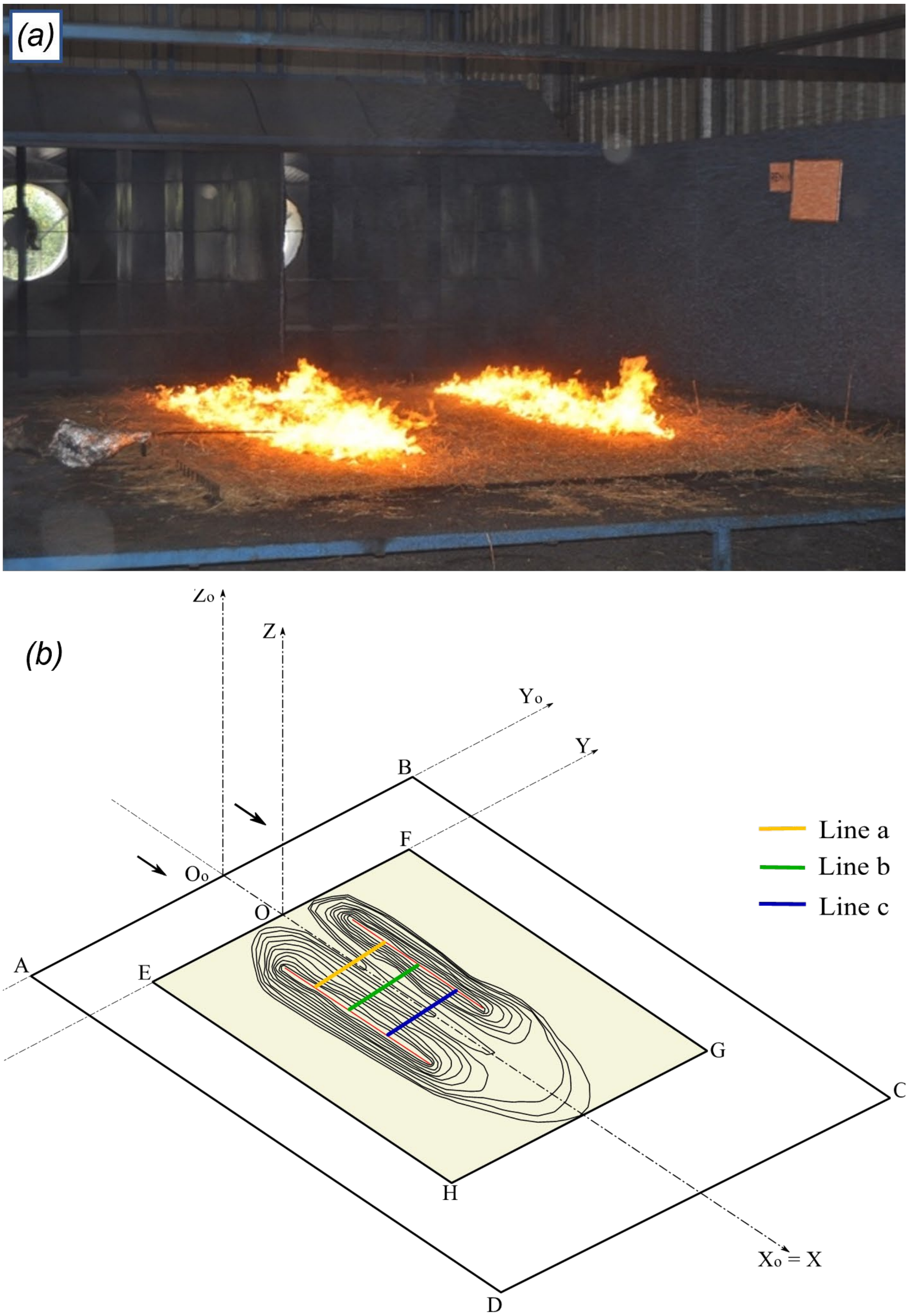

FIGURE 18: (A)VIEW OF THE COMBUSTION TUNNEL OF THE FOREST FIRE LABORATORY OF THE UNIVERSITY OF COIMBRA. (B) THE MEASUREMENT DIRECTIONS USED TO MEASURE THE RATE OF SPREAD OF THE APPROACHING FIRE LINES (LINES A, B AND C). THE ISOCHRONES CORRESPOND TO THE EXPERIMENT WITH THE FIRE LINES INITIALLY SEPARATED BY 1m AND WITH A WIND SPEED OF 3 ms^{-1}. THE FIGURES HAVE BEEN ADAPTED FROM RIBIERO ET AL. (2021).

Parallel line fires

Spot fire coalescence involves the merging of parallel fire lines (see Figure 1), and this pattern of fire merging can also be seen on larger scales when the flanks of two wildfires merge. The merging of parallel line fires, under the influence of wind, was examined in a series of laboratory experiments conducted at the Lousã laboratory.

The two fire lines were initially separated by a certain distance and the fire spread under the influence of a parallel wind on a uniform fuel bed without slope was observed. The results showed that the pyroconvective interaction between the two parallel fire lines and the ambient wind modified the rate of spread (ROS) of the approaching fire lines and their associated fire spread characteristics. The results also exhibited a nonlinear relationship between the wind speed and the rate of spread of the approaching fire line. This effect is likely due to the interaction between the ambient wind and the centre of pyroconvective convergence between the two fire lines. This study is described by Ribiero et al. (2021). An example of one of the experiments can be seen in Figure 18.

Spot fire experiments

The influence of spot fires on the overall rate of spread of a fire was examined in a series of 30 laboratory fire experiments on a 3 m × 4 m fuel bed, subject to wind and in the absence and presence of a model hill. These experiments were led by PhD Scholar Michael Storey and conducted in collaboration with researchers from the University of Coimbra, University of Wollongong, and UNSW. The experiments were carried out at the Centre for the Study of Forest Fires laboratory at Lousã, Portugal.

In the experiments carried out on a flat fuel bed, spot fires (whether 1 or 2) had only a small influence on the combined rate of spread. The slowest overall rate of spread was associated with a downhill run of the fire in the absence of any spot fires. In these cases, the fires crept very slowly downslope and downwind of the hill. In some cases, the downhill rate of spread was up to five times slower than the corresponding rate of spread on flat ground. However, ignition of 1 or 2 spot fires on the lee slope and further downwind on flat ground in the lee of the hill, increased the overall rate of spread to levels similar to those observed on flat ground. This effect was strongest at the head of the fire, where spot fires merged directly with the main fire, but significant increases were also observed in the rate of spread of other parts of the fire line. These findings suggest that under certain topographic conditions, spot fires can allow a fire to overcome the low spread potential of downslopes and that current models, which do not account for these interactive effects, may underestimate wildfire rate of spread and the arrival time of fires burning in and around complex terrain.

Figure 19 shows the schematic and actual experimental set-up for the experiments with the model hill. The full series of experiments and the ensuing results are described in more detail by Storey et al. (2021).

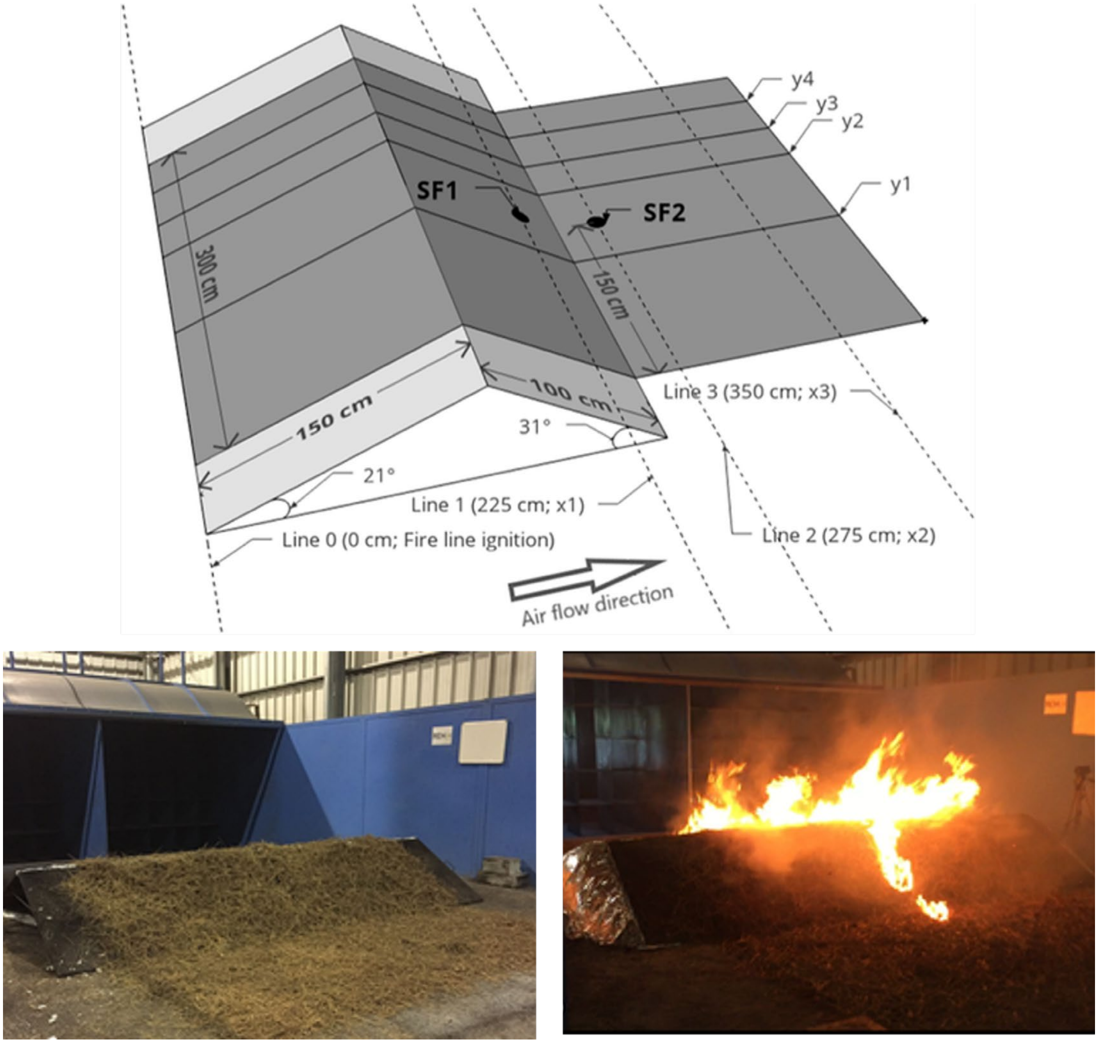

FIGURE 19: SCHEMATIC REPRESENTATION OF THE EXPERIMENTAL SETUP FOR THE EXPERIMENTS IN THE PRESENCE OF A MODEL HILL (TOP), THE ACTUAL EXPERIMENTAL SETUP IN THE WIND TUNNEL AT THE CENTRE FOR THE STUDY OF FOREST FIRES LABORATORY AT LOUSÃ, PORTUGAL, PRIOR TO IGNITION (BOTTOM LEFT), AND A PHOTOGRAPH OF ONE OF THE EXPERIMENTS WITH THE MODEL HILL. SHWING THE INVOLVEMENT OF THE SPOT FIRES (BOTTOM RIGHT). THE FIGURE HAS BEEN ADAPTED FROM STOREY ET AL. (2021).

MODELLING SPOT FIRE PROCESSES

The project also considered the way spot fire processes are modelled. This included an examination of long-range ember transport and, in particular, how the imposition of a terminal velocity assumption for falling embers influenced the overall distribution of embers downwind from a fire. The effect of wind-terrain interactions on ember transport were also investigated, along with techniques for including ember transport and spot fire ignition in the Spark framework.

Terminal velocity assumption

The terminal velocity assumption posits that embers are always falling at their terminal velocity relative to the ambient wind field. To investigate the potential implications of this assumption on model estimates of ember distribution, a numerical weather prediction model (WRF) was used to study the dynamics of ember transport and examine the effect of the terminal velocity assumption.

The equations of motion of an ember moving with velocity $\mathbf{u}$ in a wind field with velocity $\mathbf{w}$ are:

$$\frac{d\mathbf{u}}{dt} = \frac{C_d \rho A}{2m} \|\mathbf{w} - \mathbf{u}\|(\mathbf{w} - \mathbf{u}) - g\hat{\mathbf{k}},$$

where C_d is the ember's drag coefficient, ρ is the atmospheric density, m is the mass of the ember, A it's projected area in the direction of the relative wind velocity $\mathbf{w} - \mathbf{u}$, and $\hat{\mathbf{k}}$ is the unit vector in the $\mathbf{z}$-direction. Tarifa and del Notario (1962) showed that for parameter values typical of an ember, the solution of the equations of motion rapidly (i.e., within a few seconds) approaches the asymptotic solution:

$$\mathbf{u}_\infty^c = \mathbf{w} - u_\infty \hat{\mathbf{k}},$$

where u_∞ is the (constant) terminal speed of the ember, given by:

$$u_\infty = \sqrt{\frac{2mg}{C_d \rho_0 A}}.$$

Here, the parameter ρ_0 is a reference atmospheric density; for example, the atmospheric density at the location of experiments used to determine u_∞, or the approximate atmospheric density at sea level ($\rho_0 = 1.16$).

In their work, Thurston et al. (2017) assumed that embers moved with velocity $\mathbf{u}_\infty^c$, but it is possible to consider different physical scenarios where the embers fall with a terminal velocity that varies with atmospheric density, or where no terminal velocity assumption is made. In the case of a variable terminal velocity, u_∞ can be scaled with respect to actual atmospheric density, leading to the following expression for ember velocity, in which the terminal fall speed is seen to depend on ρ:

$$\mathbf{u}_\infty^v = \mathbf{w} - \sqrt{\frac{\rho_0}{\rho}} u_\infty \hat{\mathbf{k}}.$$

If no assumption is made about the terminal velocity of embers, then their velocity is determined through solution of the equation of motion, which may be written as:

$$\frac{d\mathbf{u}^*}{dt} = g \frac{\rho}{\rho_0} \frac{1}{u_\infty^2} \|\mathbf{w} - \mathbf{u}^*\|(\mathbf{w} - \mathbf{u}^*) - g\hat{\mathbf{k}}.$$

To describe the motion of embers, an idealized heat source was used to emulate the effect of a fire and produce a convective plume. The resulting flow was simulated using the WRF model, which provided the ambient wind field $\mathbf{w}$, required to determine the dynamic trajectories of embers released into the plume as inert particles. The ember trajectories were calculated using the three different assumptions about the ember's terminal velocity, as described above:

1. Constant terminal velocity assumption (i.e., using $\mathbf{u}_\infty^c$);

2. Variable terminal velocity assumption, in which the terminal velocity is allowed to vary with atmospheric density (i.e., using $\mathbf{u}_\infty^v$);

3. No terminal velocity assumption (i.e., using $\mathbf{u}^*$).

The results indicated that the terminal velocity assumption has a significant influence on the density of ember landings, significantly overestimating ember density at long range, and particularly for embers with higher terminal fall speeds. An example of these results can be seen in Figure 20, which shows modelled ember distributions for two different ambient wind speeds and for the three different terminal velocity conditions (Thomas et al. 2020).

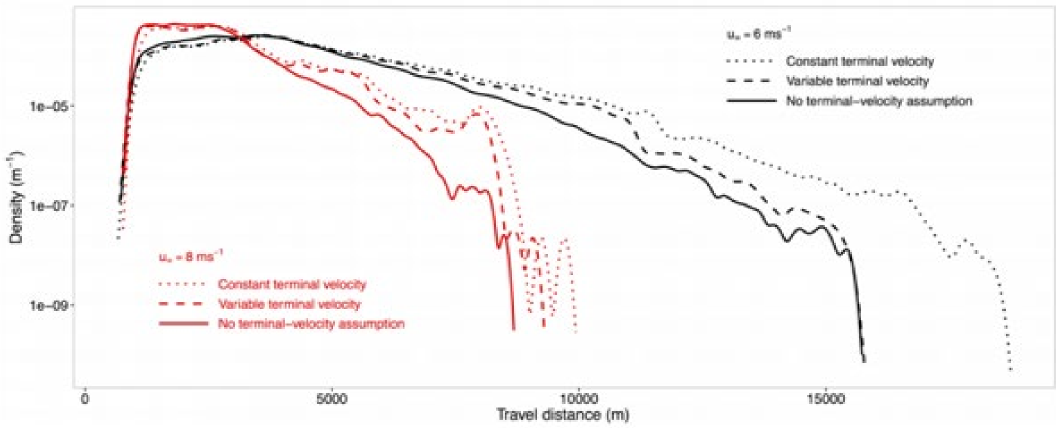

FIGURE 20: EFFECT OF THE TERMINAL VELOCITY ASSUMPTIONS ON EMBER DISTRIBUTIONS DERIVED FROM A COUPLED FIRE-ATMOSPHERE MODEL FOR TWO DIFFERENT AMBIENT WIND SPEEDS: 6 ms^{-1} (BLACK) AND 8 ms^{-1} (RED). DOTTED LINES REPRESENT THE DISTRIBUTION ASSUMING A CONSTANT TERMINAL VELOCITY, DASHED LINES REPRESENT VARIABLE TERMINAL VELOCITY AND SOLID LINES REPRESENT NO TERMINAL VELOCITY ASSUMPTION. FIGURE TAKEN FROM THOMAS ET AL. (2020).

Wind-terrain effects on spotting distribution

Despite its importance in bushfire propagation, firebrand transport and the spotting process are still poorly understood, and there is no definitive model that can adequately emulate the spotting process in general. The dynamics of firebrands are difficult to predict due to the complex flow structure resulting from the interaction of a buoyant plume with a boundary layer wind field.

Understanding the nature of this flow structure, especially for complex terrain, is essential for determining the likely path of firebrands and subsequent distributions of new spot fires and risk levels on structures downwind from the fire. Although several prior computational modelling studies have investigated firebrand transport (e.g., Thurston et al. 2017), the effect of the terrain has not previously been accounted for. It is well known that topography can significantly affect ember generation; for example, the enhanced intensity of a fire running up a slope can increase ember production, the height at which they are launched and the updraft velocity, which affects maximum lofting height. More generally, terrain-modified flows and the strong turbulence associated with leeward slopes and flow around other prominent topographic features may have a pronounced effect on the transport of firebrands. Moreover, modes of dynamic fire propagation such as vorticity-driven lateral spread and eruptive fire spread in canyons involve a coupling between the fire, the terrain and the prevailing winds and so can affect the rate at which firebrands are produced as well as their subsequent transport.

We used a coupled computational fluid dynamics (CFD) model combined with a Lagrangian particle approach to model the transport of firebrands. The model

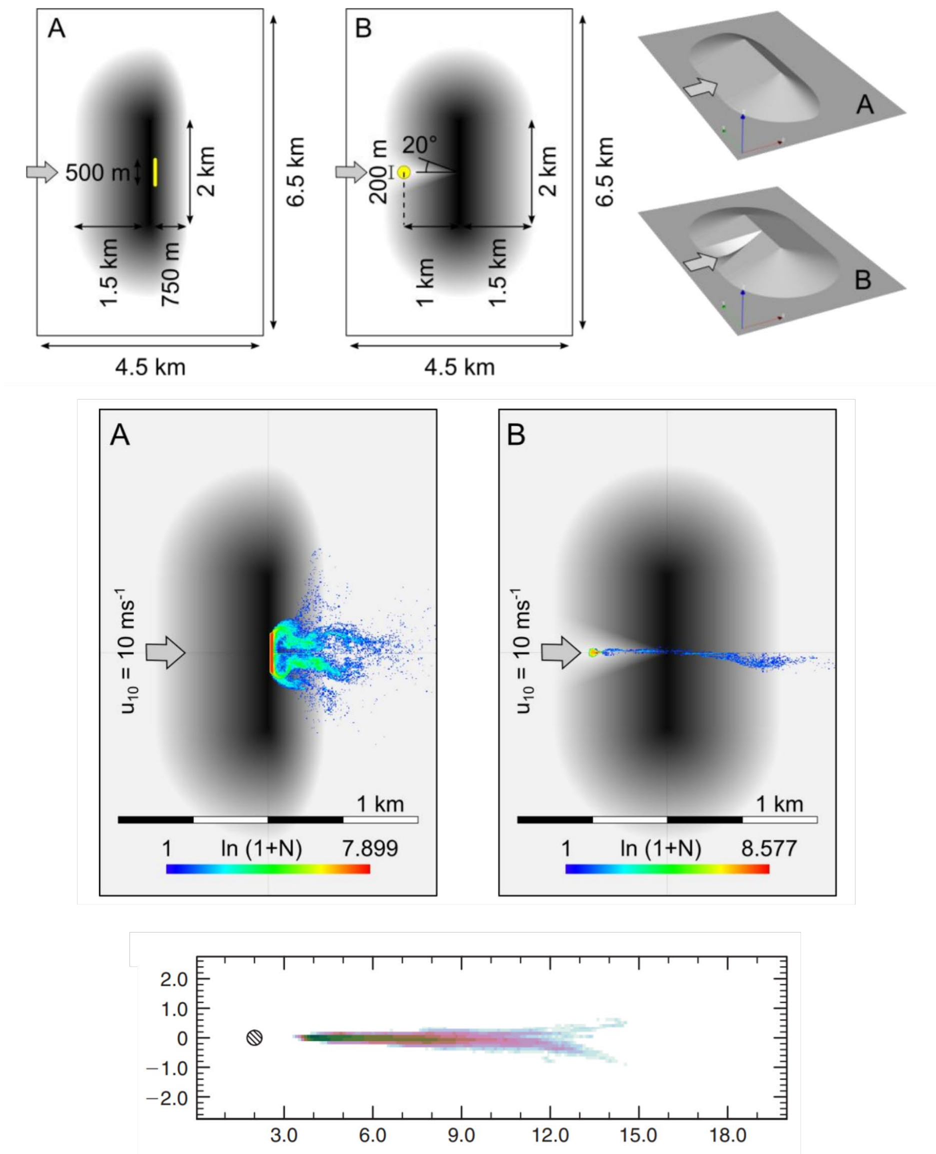

FIGURE 21: TOP ROW: TERRAIN AND FIRE CONFIGURATIONS CONSIDERED IN THE STUDY OF EMBER TRANSPORT IN THE PRESENCE OF COMPLEX TERRAIN FEATURES. THE TWO SCENARIOS ARE LABELLED AS 'SCENARIO A' AND 'SCENARIO B'. MIDDLE ROW: DENSITY MAP OF FIREBRANDS FOR SCENARIO A AND SCENARIO B. BOTTOM ROW: EMBER DISTRIBUTION OBTAINED BY THURSTON ET AL. (2017) FOR THE CORRESPONDING WIND SPEED. FIGURES HAVE BEEN ADAPTED FROM HILTON ET AL. (2019A).

was applied to two different terrain scenarios to investigate the flow dynamics, firebrand trajectories and landing patterns resulting from the interaction with the terrain. These two scenarios are depicted in Figure 21. The first scenario (Scenario A) is a line of fire burning on the lee side of a ridge, oriented parallel to the ridge line but perpendicular to the prevailing wind flow. The second scenario (Scenario B) is a small circular fire burning in a windward canyon aligned with the wind. The simulations indicated that the addition of terrain adds a further level of complexity to the flows generated by interaction between the wind and the fire. The terrain appears to modify the counter-rotating vortex pair in the plume structure. For the fire in Scenario A, the wind-terrain interaction resulted in a flattening and tilting of the counter-rotating vortex pair and enhanced regions of recirculation at the edges of the fire, which were conducive to lateral transport of embers. For the fire in Scenario B, the channelling of the winds up the canyon resulted in the formation of a single jet-like vortex transporting firebrands upwards and over the top of the canyon. This effect is most likely caused by the shape and alignment of the canyon, which forces the counter-rotating vortex pair to merge into a single vortex. These findings were reported by Hilton et al. (2019a).

Figure 21 also shows the ember distribution as modelled by Thurston et al. (2017) for the same wind speed as considered in Scenario A and Scenario B and highlights the distinct differences in ember distributions that result from wind-terrain-fire interactions. The results suggest that ember distributions must be estimated on a case-by-case basis, rather than using a generic kernel. In particular, they suggest that the ember distributions estimated in the absence of terrain should be relied upon to estimate ember distributions for fire burning in complex terrain.

Incorporating spotting in fire simulation

Complex modes of fire behaviour resulting from local coupling between the fire and the atmosphere are a significant challenge for rapid operational wildfire spread simulations. While three-dimensional fully coupled fire-atmosphere models can account for many types of fire behaviour, their computational demands are prohibitive in an operational context. Two-dimensional fire spread models have much lower computational overhead but are generally not able to account for complex local coupling effects and cannot provide a three-dimensional flow structure suitable for modelling the transport of firebrands.

As mentioned in an earlier section, the near-field model has been used to model local coupling effects resulting from wind flow over a ridge that can result in a number of non-intuitive modes of fire behaviour – specifically we demonstrated this capability for the mode of dynamic fire propagation known as vorticity-driven lateral spread (VLS). These models were then extended further to

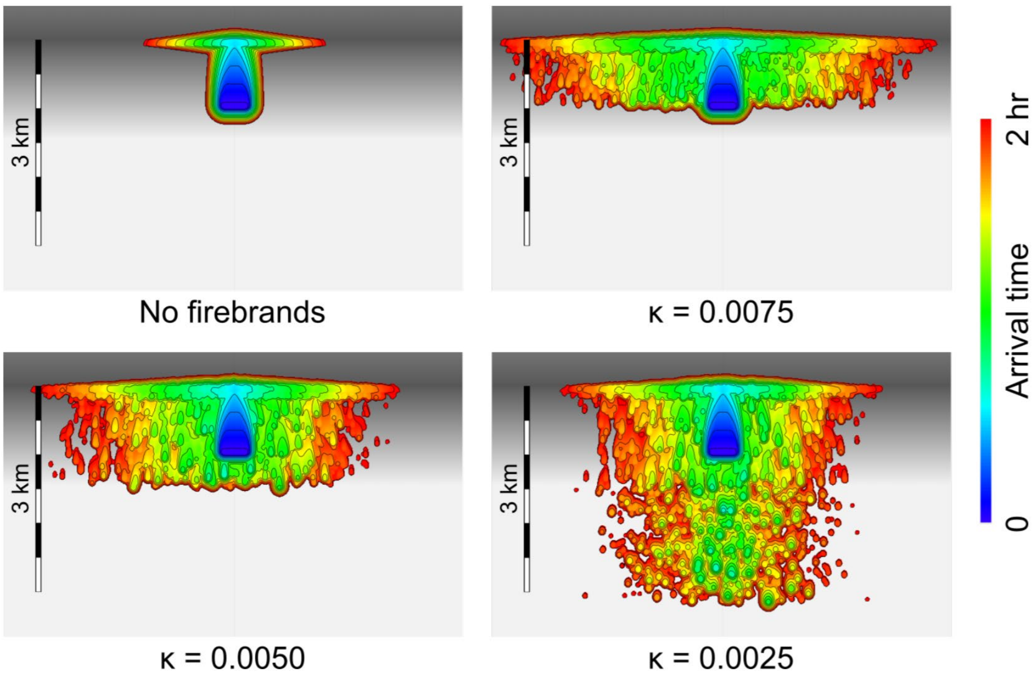

FIGURE 22: MODELLING VORTICITY-DRIVEN LATERAL SPREAD WITH AND WITHOUT FIREBRANDS AND FOR DIFFERENT VALUES OF THE PLUME COOLING PARAMETER κ, WHICH CONTROLS THE STRENGTH/BUOYANCY OF THE PLUME. FIGURE FROM HILTON ET AL. (2019B).

incorporate three-dimensional firebrand transport and to model the patterns of fire propagation that may result due to enhanced downwind spot fire formation associated with VLS.

Firebrands were incorporated using a Lagrangian scheme coupled to the Spark simulator, to model transport through the atmosphere and a sub-scale model for spot fire creation and growth. Note that the intense vorticity associated with VLS can increase the production of embers, but this aspect of the phenomenon was not considered in the project – instead, a generic ember production rate was assumed. The firebrand transport took factors such as drag, gravity and buoyancy into account. As the effect of plume buoyancy on firebrands under real-world conditions is currently unknown, the plume buoyancy was parameterised using an exponential decay model. The sensitivity of the decay parameter was examined in relation to the resulting spot fire distribution and area burnt. All simulations were carried out using the Spark framework.

The coupled VLS and firebrand transport simulations indicated that a higher value of decay parameter, representing a higher cooling rate of the plume, acted to enhance the lateral spread as firebrands were lofted for shorter times and were caught in the vortices at the edge of the lateral spread region. In contrast, a lower value of decay parameter, representing a lower cooling of the plume, resulted in widespread downwind spot fires and larger burnt areas. This appeared to be due to longer lofting times resulting in firebrands being transported further downwind and away from the vortices within the lateral spread region (see Figure 22). The model appears, at least qualitatively, to match lateral spread and 'deep flaming' fire behaviour observed in linescans imagery, for example, although many of the parameters in the model require further research and experimental calibration. Further development of the model may allow these complex modes of fire behaviour to be incorporated into fast-running wildfire simulators for operational and risk assessment usage. This research is discussed in more detail by Hilton et al. (2019b).

ASSESSING EXTREME BUSHFIRE POTENTIAL

Under certain circumstances, wildfires can transition from an ordinary surface fire into an extreme bushfire (Sharples et al. 2016). These fires consistently account for the most severe socioeconomic and environmental impacts. Being able to identify wildfires with the greatest potential to develop into extreme wildfires is therefore crucial for operational and emergency planning and management. The factors giving rise to such extreme wildfires are a complex combination of weather, fire intensity and, crucially, the shape of the fire. Badlan et al. (2021a; 2021b) demonstrated that fires which exhibit 'deep flaming' characteristics; that is, fires that exhibit a large spatial integral of instantaneous intensity, are more likely to produce plumes that reach high enough into the atmosphere to trigger secondary processes associated with violent pyroconvection. Deep flaming events are closely linked with mass spotting and spot fire coalescence (see Figure 22).

However, due the vagaries of fire propagation and the uncertainty about the spatial extent and flaming characteristics of a fire, quantifying the potential for a fire to develop into an extreme wildfire based on its spatial characteristics is a

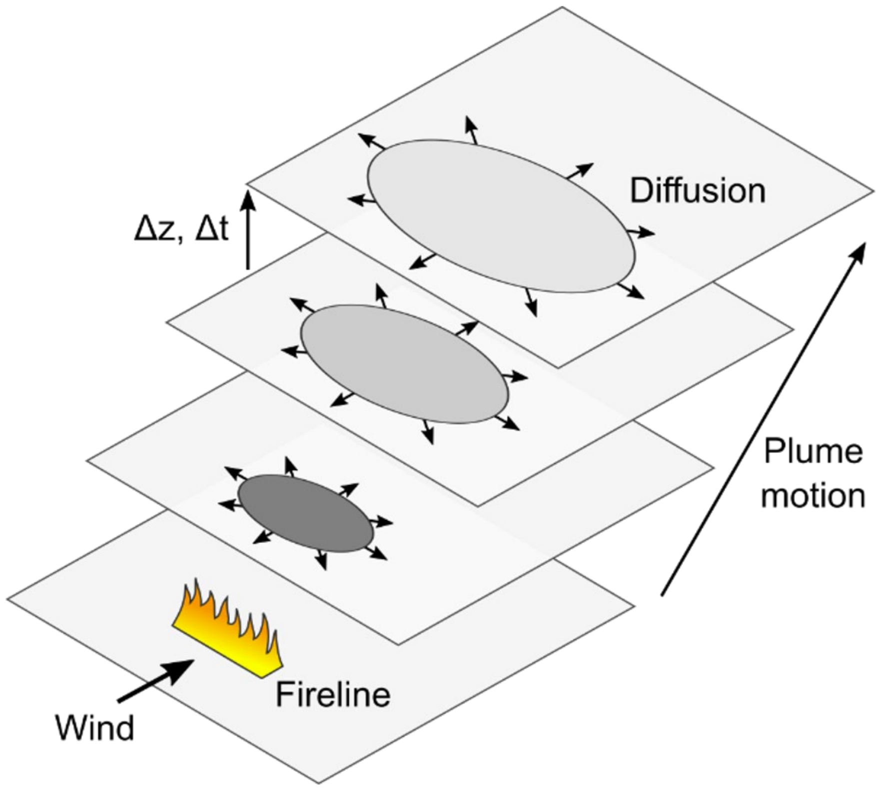

FIGURE 23: SCHEMATIC ILLUSTRATION OF PLUME DIFFUSION MODEL. THE HORIZONTAL TRANSECTS SHOW THE PERIMETER OF THE PLUME AT VARIOUS HEIGHTS AS IT DIFFUSES INTO THE SURROUNDING ATMOSPHERE

challenging problem. To address this issue, a physics-based method was developed using standard techniques of image analysis, which converts remotely sensed thermal infra-red (linescan) data into a measure of the potential for a fire to transition into an extreme wildfire.

The basic idea is to estimate the radial diffusion of a fire's plume as it rises into the air. This idea is illustrated in the schematic in Figure 23. We consider the rate of change of some diffusing quantity, $(\boldsymbol{r},\ t)$, of the plume; e.g. temperature, smoke concentration, turbulent kinetic energy or vorticity, in a frame of reference that moves with the plume. This rate of change can be modelled using a two-dimensional diffusion equation in the horizontal plane:

$$\frac{\partial u(\boldsymbol{r},\ t)}{\partial t} = k\nabla^2 u(\boldsymbol{r},\ t).$$

A solution of the diffusion equation for $u(\boldsymbol{r}, t + \Delta t)$ can be obtained using the Fourier transform and the energy of the associated spectrum compared with the energy spectrum of the initial condition, which is defined by the condition of the fire at the surface. The ratio of these two spectral energies defines an index between 0 and 1, where 1 corresponds to no diffusion and 0 corresponds to complete diffusion. Hence, lower values of the index indicate a distributed fire with greater potential for diffusion and a weak plume, whereas higher values of the index indicate a strong plume with a compact centre, less prone to diffusion and therefore more likely to reach higher levels of the atmosphere, assuming that all other atmospheric factors are the same.

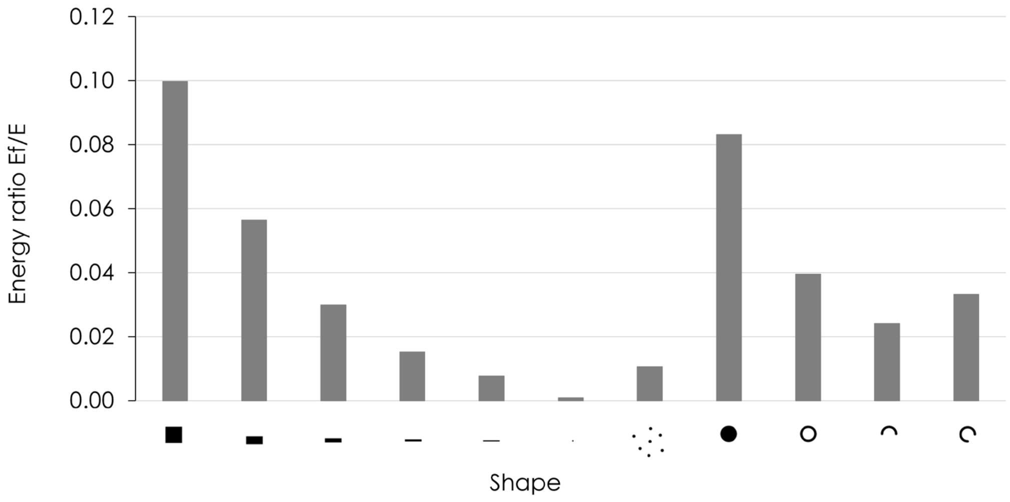

FIGURE 24: ENERGY RATIO INDEX FOR VARIOUS FIRE SHAPES

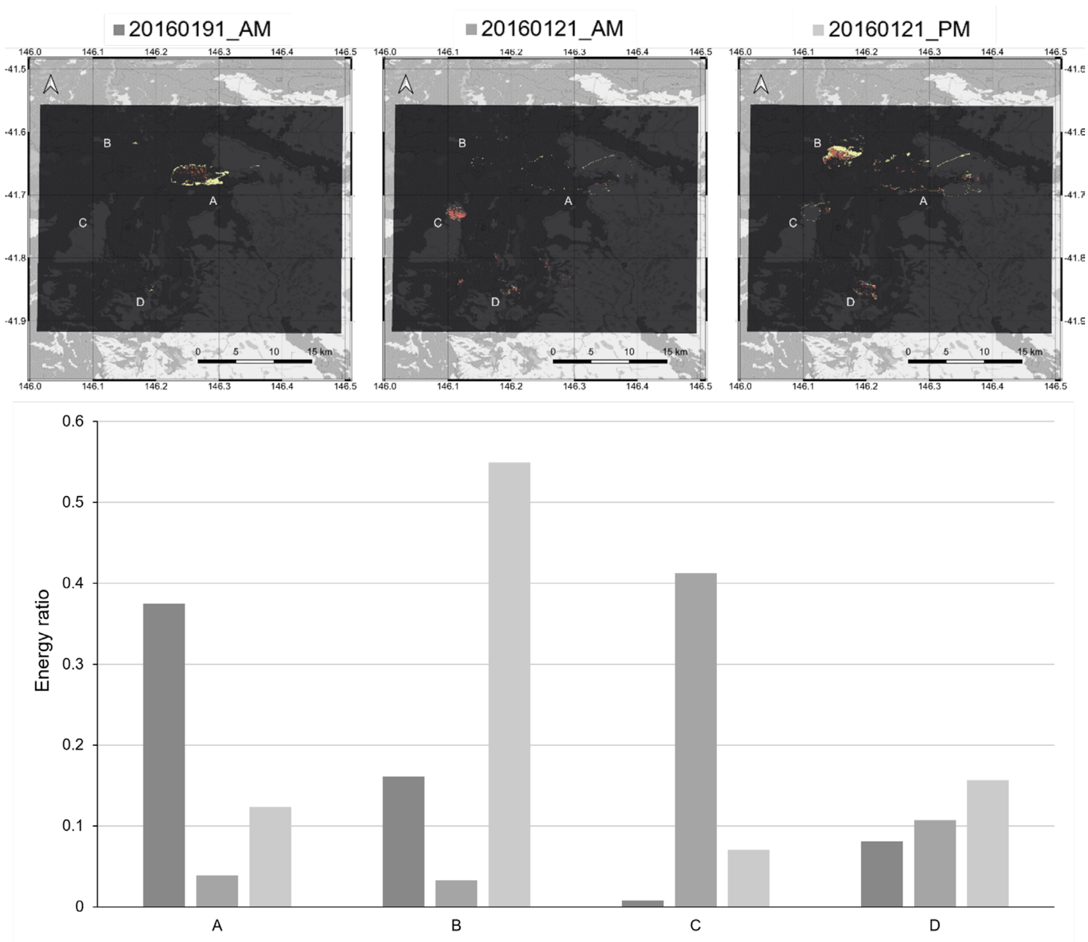

FIGURE 25: ENERGY RATIO INDEX VALUES FOR FOUR MOLE CREEK FIRES, LABELLED A, B, C AND D IN THE LINESCANS FOR THREE DIFFERENT TIMES: 19 JANUARY 2016 AM, 21 JANUARY 2016 AM, 21 JANUARY 2016 PM.

The method was applied to several idealised heat sources (fire shapes), some of which were the same as those considered by Badlan et al. (2021b). The values of the index obtained for each of the fire shapes are shown in Figure 24, which shows that the heat sources that more closely represent deep flaming produce higher values of the index, while more distributed heat sources such as those that more resemble ordinary frontal fire behaviour produce lower values of the index. The values of the index also follow the same trend as the maximum plume heights found by Badlan et al. (2021b).

The method was also applied to linescans of several Australian wildfires. The resulting indices can be seen in Figure 25, which demonstrates the ability of the index to identify dangerous wildfires. The method could be used with high-frequency remote sensed data sources to provide automated indicators of potential danger for operational wildfire management.

KEY MILESTONES

Project progress was defined by several key research and utilisation milestones. The key research milestones focused on publication of peer-reviewed articles, while the key utilisation milestones focused on development and communication of education and training materials for firefighters and fire behaviour analysts.

RESEARCH MILESTONES

1. Submit draft of Paper 1 for CRC approval

This paper was titled "Modelling vorticity-driven wildfire behaviour using near-field techniques" by Sharples, J.J. & Hilton, J.E.

The paper demonstrated the use of the near-field model to model vorticity-driven lateral fire spread in an idealized case study. The milestone was delivered 20 March, 2019.

2. Finalise Paper 1 for peer-reviewed publication

This paper, "Modelling vorticity-driven wildfire behaviour using near-field techniques" by Sharples, J.J. & Hilton, J.E. was finalized for publication, subject to peer-review and published in the journal *Frontiers in Mechanical Engineering*, volume 5, 2020. DOI: 10.3389/fmech.2019.00069

The milestone was delivered 11 April 2019.

3. Submit draft of Paper 2 for CRC approval

This paper was titled "Wind-terrain effects on firebrand dynamics" by Hilton, J.E., Sharples, J.J., Garg, N., Rudman, M., Swedosh, W. & Commins, D.

The paper examined the patterns of ember distribution that result from the interaction wind and terrain for fires burning in complex terrain. The milestone was delivered 8 August 2019.

4. Finalise Paper 2 for peer-reviewed publication

The paper, "Wind-terrain effects on firebrand dynamics" by Hilton, J.E., Sharples, J.J., Garg, N., Rudman, M., Swedosh, W. & Commins, D. was finalized for publication, subject to peer-review and published in the *Proceedings of the 23rd International Congress on Modelling and Simulation*, 2019. DOI: 10.36334/modsim.2019.H7.hilton.

The milestone was delivered 7 November 2019.

5. Submit draft of Paper 3 for CRC approval

This paper was titled "Incorporating firebrands and spot fires into vorticity-driven wildfire behaviour models" by Hilton, J.E., Garg, N. & Sharples, J.J.

The paper demonstrated the incorporation of a spot fire simulator within the Spark framework. It was used to model patterns of fire spread associated with vorticity-driven lateral fire spread in an idealized case. The milestone was delivered 28 August 2020.

6. Finalise Paper 3 for peer-reviewed publication

The paper, "Incorporating firebrands and spot fires into vorticity-driven wildfire behaviour models" by Hilton, J.E., Garg, N. & Sharples, J.J. was finalized for publication, subject to peer-review and published in the *Proceedings of the 23rd International Congress on Modelling and Simulation*, 2019. DOI: 10.36334/modsim.2019.H7.hilton2

The milestone was delivered 16 November 2020.

7. Submit draft of Paper 4 for CRC approval

This paper was titled "An index for identifying the potential for extreme wildfires" by Hilton, J., Sharples, J., Badlan, R., Mangeon, S. & Chen, Y.

The paper introduced and discussed a novel index for assessing the potential for fires to develop into extreme wildfires. It is based on Fourier analysis of linescan imagery. The milestone was delivered 20 April 2021.

8. Finalise Paper 4 for peer-reviewed publication

This paper, "Initial growth of fires in eucalypt litter, from ignition to steady-state rate of spread: Laboratory studies" by Gould, J.S. & Sullivan A.L. was finalized for publication. This paper details a study into the initial growth phase of spot and line fires under the influence of wind. It has been submitted to the *International Journal of Wildland Fire* and is now under review.

Close-off for this milestone was initiated 14 July 2021. It is currently pending CRC approval.

Note that due to COVID interruptions the paper mentioned in research milestone #7 could not be finalised, and so this paper was submitted in its place.

UTILISATION MILESTONES

1. Hold initial discussions with relevant end-users on possibilities for including research findings in firefighter training course material

These discussions were held with Simon Heemstra (NSW RFS) and Stuart Matthews (NSW RFS) at NSW RFS HQ on 12 April 2018. Discussion included an overview of project aims and development of education and training products that could be derived from the project and from related ARC funded work. The milestone was delivered 1 August 2018.

2. Hold initial discussions with FBAN working group coordinator on possibilities for including research findings in FBAN training courses

These discussions were held with Simon Heemstra (NSW RFS) in Coimbra, Portugal, and with end-users at the CRC RAF in Brisbane. The project research was subsequently presented at the NSW RFS Fire Behaviour Analyst workshop. The milestone was delivered 26 February 2019.

3. Meet with relevant end-users to draft scoping document on implications of research findings to firefighter training courses – First draft

This meeting was held in conjunction with the 2019 Fire Behaviour and Fuels conference in Sydney. The purpose of the meeting was to canvass end user's opinions regarding how outputs arising from the project could/should be incorporated into firefighter training materials.

A number of issues were highlighted and discussed. The main ones were as follows:

- Firefighter training should be pitched at two levels: 'Awareness' – relevant to advanced fire fighters; and 'Understanding' – relevant to crew leader and above.
- Enhanced firefighter training materials should provide:
  - Awareness of the potential for individual fires and different parts of a fire line to interact with one another.
  - Understanding of the basic processes that drive those interactions; i.e. the effects of pyroconvection.
  - Awareness of the dangers posed to firefighters from mass spotting events.
  - Awareness that certain types of dynamic fire behaviours arise during mass spotting events, and that mass spotting is more likely under some dynamic modes of fire propagation (e.g. VLS).
  - Understanding which parts of the landscape are more prone to dynamic modes of fire propagation and mass spotting events.
  - Awareness that the potential for mass spotting and dynamic fire behaviours may require enhanced observance of concepts such as 'LACES' and 'WATCHOUT'.
  - Understanding the implications for dynamic risk assessment of dynamic fire behaviour and mass spotting; for example, how options for safe egress may be affected under such circumstances.
- In designing modifications for firefighter training materials, it is important to properly appreciate what Fire Behaviour Analysts will be required to know. Firefighter training packages can then be designed so that they provide the prerequisites for establishing FBAN competency. In this sense, it is probably better to start with developing material for FBANs first, and then develop firefighter training material to 'bridge the gap' in an appropriate way.
- Training materials for firefighters and FBANs will require careful use of language and context setting. It needs to be developed in such a way that

respects the chain of command that exists in operational environments – for example, new knowledge conveyed by training materials

- Probably best to develop 'Extreme Fire Behaviour' training module(s) but figuring out where and at what stage this would fit in with the various other competencies already in existence would require some thought. Moreover, formally altering firefighter training materials (via AFAC) is difficult, and likely requires a time frame (i.e. decadal) far beyond that associated with the research project.

The milestone was delivered 21 May 2019.

4. Meet with FBAN working group coordinator to draft scoping document on implications of research findings to FBAN training courses – First draft (RUA)

This meeting was with Laurence McCoy, Bushfire Analyst Supervisor at NSW RFS. Discussions focused on the potential for the project research to be developed into training materials for fire behaviour analysts, and some initial suggestions were covered. The following items were specifically discussed:

- Education and training material on mass spotting potential for increasing pyroconvective plume strength.
- Material on fire line merging, particularly for back burning operations.
- Identification of regions prone to mass spotting (this already being addressed through a specific BHCRC utilisation project).
- Potential for dynamic Spark fire simulator to support decision making.

The milestone was delivered 9 September 2019.

5. Meet with relevant end-users to revise scoping document on implications of research findings to firefighter training courses– Second draft

As discussed with Desiree Beekharry and others at the CRC, this milestone was fulfilled through development of the extreme and dynamic fire behaviour Firepedia entry, which involved extensive elicitation of end-user feedback. In developing the Firepedia, it was not possible to account for all the elements discussed during the first phase of the scoping process, but care was taken to account for as many as possible.

The milestone was delivered 12 January 2021.

6. Meet with FBAN working group coordinator to revise scoping document on implications of research findings to FBAN training courses – Second draft

12 January 2021 As discussed with Desiree Beekharry and others at the CRC, this milestone was also fulfilled through development of the extreme and dynamic fire behaviour Firepedia entry, which involved extensive elicitation and feedback from the NSW RFS Bushfire Analyst Supervisor.

The milestone was delivered 12 January 2021.

7. Summary of scoping engagement with end users on inclusion of research findings in firefighter training course material

As discussed with Desiree Beekharry and others at the CRC, this milestone has been fulfilled through the delivery of the extreme and dynamic fire behaviour Firepedia entry, which involved extensive engagement with end users.

The milestone was delivered 10 February 2021.

8. Summary of scoping engagement with end users on inclusion of research findings in FBAN training course material.

In addition to the delivery of the extreme and dynamic fire behaviour Firepedia entry, which involved extensive engagement with end users, this milestone was also fulfilled with the presentation Prof Sharples presented to the NSW RFS Fire Behaviour Analyst workshop on 5 August 2021. This presentation provided a summary of the project findings and the operational implications of the research.

Close-off for this milestone has been initiated and is currently pending CRC approval.

UTILISATION AND IMPACT

SUMMARY

The Spotfire Coalescence project was mainly concerned with improving our understanding of dynamic fire behaviour and extreme fire occurrence, and the development of new fire simulation techniques that permit consideration of dynamic fire propagation within operational time frames. As such the utilisation potential and impact of the project is mainly found in the form of enhanced education and training materials that can improve situational awareness and operational response in the face of dynamic fire behaviour, and the provision of tools that can enhance operational capabilities.

The main impact of the project is the significant amount of new knowledge about how pyroconvection drives dynamic fire behaviour. Much of this knowledge is still the subject of scientific review and communication and has not yet been distilled into a form that is suitable for immediate operational use. However, this knowledge has laid the foundations for the next generation of education and training materials and operational fire simulators. Indeed, the Spark framework, which is already able to incorporate many aspects of the project's research output will become the operational benchmark for fire simulators in Australia.

In terms of utilisation, the project has delivered on several fronts, as described in the following sections.

DYNAMIC FIRE BEHAVIOUR – 'FIREPEDIA'

Output description

The Firepedia is a compendium of curated entries brought together as an online product. The intent is that they can be downloaded as individual entries or as an integrated PDF. The Firepedia will primarily be used as a reference and learning tool and will contain entries on modes of dynamic fire behaviour that have featured in the CRC's research projects. In particular, the Firepedia will contain information on junction fires and spot fire coalescence, pyroconvective interactions, vorticity-driven lateral spread and extreme bushfire development.

Extent of use

The Firepedia is still yet to be published online in its final form, but when it is it will be a key resource for operational personnel across Australia. In particular, primary users of the Firepedia will be fire behaviour analysts, those providing teaching and training to fire behaviour analysts, and fire simulator developers and programmers. Secondary users will be people like: fire incident commanders, fire crew leaders, prescribed burning managers and crew leaders, firefighters interested in maintaining their knowledge and situational awareness, and interested members of the public.

Utilisation potential

The Firepedia has the potential to serve as an ongoing source of information for members of the firefighting industry. In particular, it will increase situational awareness and improve operational understanding of dynamic fire behaviour.

The Firepedia also has the potential to form the basis for new and improved education and training materials for fire behaviour analysts and firefighters, more generally.

Utilisation impact

While the Firepedia is still yet to formally appear, there has been interest from Australian fire services. This includes extensive feedback during the drafting stages on document preparation. Indeed, many fire practitioners are already using terms and concepts that are described in the Firepedia.

Utilisation and impact evidence

During the 2019/20 Black Summer fires, many of the researchers that contributed to the Firepedia were called upon to serve in the NSW State Operations Centre. This is evidence that the knowledge that is going into the Firepedia is, and will continue to be, of use to firefighting response around Australia.

VLS SPATIAL MAPPING

Output description

The occurrence of vorticity-driven lateral spread (VLS) is subject to certain environmental thresholds. These include sufficiently steep terrain, topographic aspects that sufficiently align with the wind direction, and winds that are sufficiently strong. Research has provided reasonable estimates for the threshold values for topographic slope and aspect, and this provides the basis for mapping parts of the terrain that are prone to VLS. Given the association of VLS with mass spotting and the formation of deep flaming, the ability to identify parts of the terrain prone to VLS also provides insight into the potential for fires to escalate into extreme bushfires.

This ultilisation project involved the development of a VLS spatial mapping system to provide fire behaviour analysts with enhanced intelligence about the likelihood of VLS occurrence and extreme bushfire development. It takes the form of a library of Geographical Information System layers that identify parts of the landscape prone to VLS for various wind direction (16 points of the compass) and different resolutions DEM (90 m and 250 m).

Extent of use

The VLS map layers are still in the process of being made available through the CRC, but the mapping product covers the following states:

- New South Wales
- Victoria

- Tasmania
- South Australia
- Queensland

Maps for Western Australia are also being prepared.

The maps have been prepared in a way that are easily implemented in the Geographic Information Systems used in jurisdictions around Australia.

Utilisation potential

The VLS maps can be added as GIS layers in compatible systems (e.g. ICON), which enable practitioners to gauge whether a particular fire is approaching parts of the terrain that are prone to VLS occurrence, given current or forecast conditions. This permits the user to gauge the likelihood of dangerous escalations in fire activity and to pass this information along to better inform warnings to fire crews and the public.

There is also considerable potential to further automate the mapping system and to incorporate other variables such as wind speed and estimates of fuel moisture content, which can provide deeper insights into the potential for mass spotting.

Utilisation impact

While the system is yet to be used in an operational capacity, it was used to inform the analysis of the 2019 Badja fire complex, which was conducted by UNSW under the auspices of the CRC's Black Summer research program.

Utilisation and impact evidence

The VLS mapping system has been documented in a utilisation project report and in a training manual. A training video is also in preparation. Moreover, the Badja fire analysis has been synthesized into a summary report (references below).

1. Sharples, J.J., McRae, R.H.D., Zazali, N. (2021) *Badja Fire Report*. Bushfire and Natural Hazards CRC.
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TRAINING AND EDUCATION

Output description

The Spotfire Coalescence project has produced a considerable amount of new knowledge regarding dynamic fire behaviour and pyroconvective interactions, which needs to be incorporated into the next generation of formal firefighter education and training modules (beyond the Firepedia). The development of these materials is ongoing and involves collaboration with AFAC and the various fire agencies. Dr Hilton and Prof Sharples have also branched into other projects such as the ARC-funded *iFire Program*, which is part of the UNSW iCinema Research Centre (Sharples is Deputy Director of the Centre). The iFire program is designed to provide an immersive, 3D virtual reality experience of dynamic fire behaviour and extreme wildfire development. iFire is also being conducted in collaboration with AFAC and the fire agencies.

Extent of use

New education and training modules will be designed for inclusion in national firefighting curricula. They will be designed to cater for the different levels of firefighting training (e.g. Advanced Firefighter, Crew Leader, Fire Behaviour Analyst)

The iFire Program is also being developed with the aim of it being available nationally to firefighters and to communities living on the wildland urban interface.

Utilisation potential

Existing firefighter training materials do not cover recent insights into fire behaviour. As such, development of new education and training materials has the potential to significantly improve firefighter's situational awareness and the ability of fire behaviour analysts to anticipate dangerous escalations in fire activity.

Utilisation impact

There is a growing awareness (nationally and internationally) of dynamic fire behaviours and their connection to extreme wildfire development. Indeed, many firefighters, sections of the media and the general public are already using and discussing terms and concepts that have become known and/or better understood through the research conducted by the Spotfire Coalescence project team.

Utilisation and impact evidence

Not really applicable yet, although much of the new vernacular around dynamic fire behaviour and extreme fire development is already being used by firefighters, the media and the general public (though often in a manner that it is not entirely correct).

SPARK – A NEW OPERATIONAL SIMULATOR

Output description

Spark, developed by CSIRO Data61, is an advanced fire simulation platform that employs a level set interface modelling approach. It is modular in design and is able to accommodate many different fire behaviour models and modes of spatial propagation. For example, it is able to emulate the functionality of other fire simulators such as PHOENIX RapidFire but is not restricted to Huygens-based propagation algorithms. Spark is also able to incorporate dynamic modes of fire propagation. The Spotfire Coalescence project has contributed to the development of several Spark modules, which can now be implemented as part of the broader workflow.

Extent of use

AFAC have formally chosen Spark as the new national bushfire prediction platform. It is also used for wildfire risk assessment by government and commercial agencies both in Australia and overseas.

Utilisation potential

Spark is able to offer the same level of functionality as current operational simulators but has the added advantage of being able to incorporate dynamic modes of fire propagations and account for pyroconvective interactions – it can essentially operate as a reduced-complexity, two-dimensional coupled fire-atmosphere model that is able to run in near real-time (in fact, it can run faster than real time in many cases).

Spark has an operational demonstration available on the internet, and improvements are now being made to the technical back-end, along with modifications to the user interface. An online 'sandbox' is also being developed, where models and data processing can be tested and demonstrated as a bridge to operationalising new components such as the VLS model.

Spark is still undergoing development in some respects; for example, in relation to its use in connection with the new Australian Fire Danger Rating System.

Utilisation impact

Spark is used for wildfire risk assessment by government and commercial agencies both in Australia and overseas. The key impacts from an operational sense would be reduction of loss of life, reduction of damage to homes, infrastructure and environmentally or culturally sensitive areas though accurate predictions, which enable informed suppression and evacuation measures. From a risk perspective, the platform can be used test mitigation measures, such as fuel reduction or urban design, with the aim of preventing house loss or damage from fires in peri-urban or urban areas. Spark will also have beneficial environmental impacts through its ability to help us understand and account for long-term projections of future wildfire behaviour.

Utilisation and impact evidence

AFAC carried out an internal cost-benefit analysis for Spark adoption. They found that from an AFAC perspective, a full featured national simulation capability, applicable to all major landscape types across the country is an excellent investment. AFAC have consequently formally chosen Spark as the new national bushfire prediction platform.

CONCLUSION

The Spotfire Coalescence project used targeted and multifaceted investigations to provide new knowledge about the key dynamic processes involved in mass spotting events and spot-fire coalescence. These have also provided insights into dynamic fire behaviours more generally. In particular, the role of pyroconvective feedback was examined in detail and found to be a significant contributor to the enhancements in rate of spread and intensity.

Pyroconvective interactions were investigated using laboratory experiments and coupled fire-atmosphere modelling to provide insights into the physical processes underpinning dynamic fire behaviours. The coupled fire-atmosphere simulations were most illuminating and directly informed the development of models of reduced complexity able to run faster-than-real-time while still incorporating important features of dynamic fire propagation. This facilitates a paradigm shift in the way fires are understood and modelled, and in the way decisions are made regarding their management. Specifically, the pyrogenic potential model was developed as an approach to incorporate a variety of pyroconvective interactions and modes of dynamic fire propagation.

The coupled fire-atmosphere model simulations also confirmed that coupled fire-atmosphere models are still too immature for operational use, and that real-world simulation of fires using coupled fire-atmosphere models must be carefully considered, especially with respect to the use of an appropriate spatial scale (100 metres or less). Use of coupled models at courser resolutions will not be able to resolve the most significant governing processes (e.g., pyrogenic vorticity) driving dynamic fire behaviour. Moreover, the limitations of coupled models need to be clearly articulated in relevant forums.

The model developments ensuing from this research project were tailor made to fit within the CSIRO Spark simulator, and as such are ready to be implemented as part of the new national operational simulation platform. However, it is important that validation and evaluation of the findings of this research against independent field observations (experimental and wildfire, as appropriate) are properly conducted before final operational recommendations are made and adopted.

Combining CRC research with ARC funded research has provided new insights into how we can better account for fire behavioural drivers of violent pyroconvective events and a suite of tools that can be used to assist bushfire operations. Development of operational tools will continue beyond the project.

NEXT STEPS

Although the project is complete, there are still a number of areas that require further investigation. There is also a need for continued effort (and support for such effort) to fully realise the utilisation potential of the research. Much of this effort needs to be addressed towards institutional change; for example, an audit and redesign of national firefighting curricula is required to understand how new fire behavioural insights can be incorporated effectively.

Some of the main research/utilisation gaps that need to be addressed are as follows:

- Modelling the spotting process and ember laden flows, especially in and around the wildland-urban interface. Developing multi-scale modelling capability, with appropriate automation (e.g. machine learning) to assist operational decision making.
- Better understanding of critical fire weather events and their impacts on fuel moisture across all fuel size classes. Developing a scientific foundation for the role that live fuel moisture content plays in fire behaviour. Both of these are critical for developing a comprehensive understanding of spotting processes.
- Developing new national education and training materials with a well-defined place in the national curriculum, and increasing the level of technical understanding and professional qualification (e.g. tertiary micro-credentials) across the bushfire industry.
- Investigating the expected impacts of climate change on frequency and behaviour of extreme bushfires.

PUBLICATIONS LIST

The following list includes all publications arising directly from the project research as well as publications that the project research indirectly contributed to. Publications that arose directly from the project research are marked with an asterisk*.

SPECIAL JOURNAL ISSUES EDITED

1 Sharples JJ, Moinuddin K. (2020). *Coupled fire-atmosphere simulation*. Atmosphere, 11.

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TEAM MEMBERS

The project team comprised members of UNSW Canberra, CSIRO Data61, CSIRO Land and Water, and the following end-user agencies: NSW Rural Fire Service, Country Fire Authority, Country Fire Service, Queensland Fire and Emergency Services, Tasmania Fire Service and ACT Rural Fire Service.

The project team also benefitted from collaboration with colleagues from the UNSW Bushfire Research Group, University of Coimbra (Portugal), Victoria University, University of Melbourne, University of Wollongong, Bureau of Meteorology, University of Western Sydney, University of Tasmania, NSW National Parks and Wildlife Service, and the WA Department of Fire and Emergency Services

RESEARCH TEAM

Prof Jason Sharples, UNSW Canberra

Jason is Professor of Bushfire Dynamics, Director of the UNSW Bushfire Research Group and Project Leader of the Fire Coalescence and Mass Spot Fire Dynamics project. He provided overall research and administrative leadership for the project.

Dr James Hilton, CSIRO Data61

James is a Senior Research Scientist in the Data61 business unit in CSIRO. He provided leadership in simulator development, particularly in the development of the propagation models within the Spark framework, as well as research into the fundamental behaviour of fire propagation.

Dr Andrew Sullivan, CSIRO Land and Water

Andrew leads the CSIRO Land and Water Flagship's Bushfire Behaviour and Risks team. He led the experimental program, which was conducted in the CSIRO's Pyrotron facility.

Dr Rachel Badlan, UNSW Canberra

Rachel is a Post-doctoral Fellow at UNSW Canberra working with Prof Sharples using the WRF model to understand pyroconvective dynamics and on the development of spatial mapping tools to identify parts of the landscape prone to dynamic fire behaviour and mass spotting events.

Dr Chris Thomas, UNSW Canberra

Chris joined the team as a PhD Scholar working with Prof Sharples on implementing the WRF-Fire coupled fire-atmosphere model to better understand the pyroconvective interactions involved in junction fires and circular arc fires.

Mr Richard Hurley, CSIRO Land and Water

Richard is a technical officer working at the CSIRO Pyrotron facility with Dr Sullivan. Richard is extensively involved in conducting the experimental program and as such is a crucial member of the project team.

Mr Will Swedosh, CSIRO Data61

Will is a graduate research officer working at CSIRO with Dr Hilton. Will is involved in implementing the level set models including pyrogenic potential and has played a critical role in analyzing the Pyrotron experimental data. He has also contributed significantly to publications and to the experimental program, working with Dr Sullivan.

Contributions to the experimental work in were also provided by Dr Jim Gould, Dr Matt Plucinski and Mr Vijay Koul.

END-USERS

The research team regularly engaged with the end-user advisory committee, which provided advice and feedback on key research outputs and key utilisation activities. The membership of the end-user advisory committee varied over the course of the project, but the table below lists those that made significant contributions to the project.

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
NSW Rural Fire Service	Dr Simon Heemstra	Lead end-user. Extensive discussion about project outcomes and utilisation potential.
NSW Rural Fire Service	Brad Davies	Lead end-user. Extensive discussion about project outcomes and utilisation potential.
NSW Rural Fire Service	Melissa O'Halloran	Extensive discussion about research direction and utilisation opportunities, especially in the latter stages of the project
NSW Rural Fire Service	Laurence McCoy	Fire Behaviour Analyst representative. Extensive discussion about utilisation potential and engagement through FBAn workshops
NSW Rural Fire Service	Dr Stuart Matthews	Discussion about project outcomes, especially in relation to potential inclusion in the Australian Fire Danger Rating Project

Country Fire Authority	Dr Sarah Harris	Extensive discussion about research direction and potential for utilising research output.
Country Fire Authority	Alen Slijepcevic	Discussion about strategic research direction and potential for utilizing project outcomes.
Queensland Fire and Emergency Services	Andrew Sturgess	Extensive discussion about research direction and potential for utilising research output.
Tasmania Fire Service	Mark Chladil	Extensive discussion about research direction and potential for utilising research output.
Country Fire Service	Andrew Stark	Extensive discussion about research direction and potential for utilising research output.
ACT Rural Fire Service	Rohan Scott	Discussion about research outputs.
ACT Rural Fire Service	Joe Murphy	Extensive discussion about research direction and potential for utilising research output, especially in the context of new education and training modules.
ACT Parks and Conservation Service	Brian Levine	Extensive discussion about research direction and potential for utilising research output.
ACT Parks and Conservation Service	Adam Leavelsey	Extensive discussion about research direction and potential for utilising research output.

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