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FIRE COALESCENCE AND MASS SPOTFIRE DYNAMICS: EXPERIMENTATION, MODELLING AND SIMULATION

Annual project report 2016-2017

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EXECUTIVE SUMMARY

This report outlines the progress of the *Fire Coalescence and Mass Spot Fire Dynamics* project, which is one of the projects within the Next Generation Fire Modelling cluster.

The project has now been running for approximately 2.4 years. Phase 1 of the experimental program has now been completed and initial results are in the process of being published. Phase 2 of the experimental program is being considered. The project has continued to yield important and significant insights into the behaviour of coalescing fires, and these insights have broader implications for our understanding of the processes driving fire propagation and the way we model dynamic fire behaviours.

In particular, the research has continued to address the role that fire line geometry plays in the dynamic propagation of wildfires. The project team has identified a number of circumstances where the curvature-based models that they previously developed do not provide accurate simulation. This included a number of the particular experimental scenarios considered in Phase 1 of the experimental program. However, coupled fire-atmosphere simulations provided a number of fundamental insights that motivated the development of more broadly applicable two-dimensional models. These new models are able to explain why the curvature-based models worked when they did, and are able to provide accurate predictions in a broader number of circumstances, including those for which the curvature-based models had failed.

At this stage the project has published three journal papers and three conference papers. Three more journal papers and four more peer-reviewed conference papers are in the final stages of preparation. Several conference posters have also been produced. In addition, the project team has delivered a significant number of presentations to stakeholders and researchers

After providing some background information on the project's aims and methodology, this report provides details on the progress of the project to date. In particular this includes:

- Update on milestone delivery;
- New research developments;
- Details on presentations that have been delivered by members of the project team;
- Details on publications and publications in preparation;
- Progress of the PhD scholar.

At the time of writing, the project is several months behind schedule. However, the project team is confident that all milestones will be successfully delivered along with a number of unscheduled, yet significant research outputs.

A/Prof. Jason Sharples
Project Leader
School of Physical, Environmental and Mathematical Sciences,
UNSW Australia

END USER STATEMENT

Brad Davies, *New South Wales Rural Fire Service, NSW*

The project is making good headway using an innovative multi-streamed approach including laboratory experiments, coupled fire-atmosphere physical modelling and simplified analogue modelling. I expect that the results of the research will lead to operationally applicable tools that will improve our ability to predict fire spread. I am very pleased with the level of end user engagement from the project team, which will be key to technology transfer later in the project. The number and quality of research publications coming out of the project is excellent.

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 recent work showed that an individual fire starting from a point accelerates to this steady state, 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).

This project addresses these issues by investigating the processes involved in the coalescence of free-burning fires under experimentally controlled conditions, quantifying the physical mechanisms involved in these, and investigating the potential of geometric drivers of fire line propagation with the aim of developing a physically simplified proxy for some of the more complicated dynamical effects, particularly those driven by pyroconvective interaction between different parts of the fire(s). This approach enables development of models that are able to effectively emulate the dynamics of fire spread without the need to explicitly model fire-atmosphere or fire-fire interactions in a computationally costly manner.

PROJECT BACKGROUND

To enhance our knowledge of the effects of intrinsic fire dynamics on fire spread this project employs sophisticated mathematical modelling techniques in combination with fire experiments spanning laboratory and landscape scales. In particular, the project will develop computationally efficient fire spread models which include physically simplified proxies for complicated dynamical effects.

The overarching analytical approach adopted in this project is to treat fire as an evolving interface. This is not new – many researchers have treated fire in such a way, but the methods they have 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 is able to 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 variables such as fire line curvature, which we aim to include as a two-dimensional proxy for more complicated three-dimensional effects.

This project builds on initial work by members of the project team, who have investigated the use of curvature-based models to simulate instances of dynamic fire propagation such as fire line merging (Sharples et al. 2013; Hilton, 2014).

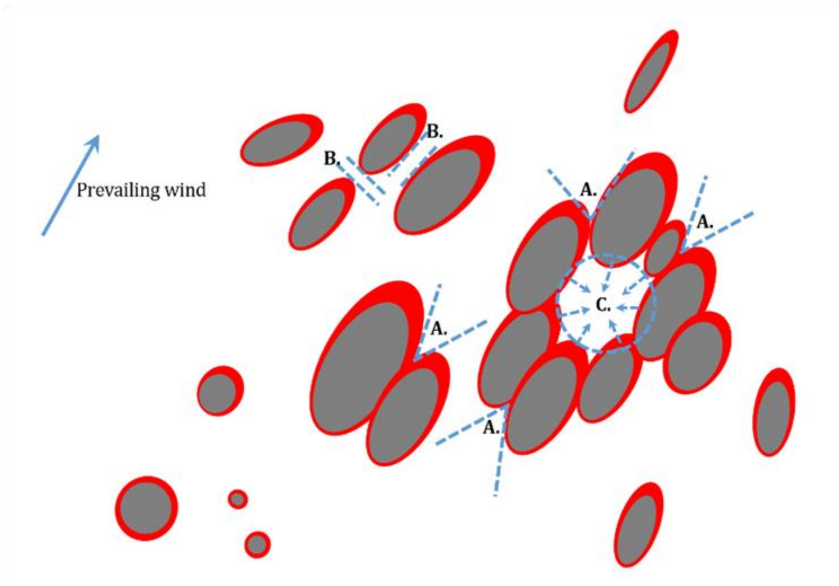

Figure 1: Schematic representation of coalescing spot-fires and forms of interaction between individual spots. Examples of fire line interactions include (A) intersecting oblique lines, non-intersecting converging fire edges (B) and collapsing or constricting perimeters (C). These can be oriented at any angle to the prevailing wind.

To complement model development the project will also include a targeted experimental program. This will involve analysis of experimental fires burning under controlled laboratory conditions as well as analysis of field experiments.

LEVEL SET METHODS FOR INTERFACE MODELLING

Level set methods provide a feasible method for dealing with the types of behaviours encountered when spot fires coalesce. Figure 1 shows a schematic representation of coalescing spot fires and the types of topological issues that can arise due to the discontiguous nature of spot fires.

Dynamic behaviour and curvature dependence

Viegas et al. (2012) noted that when two obliquely intersecting fire lines merge, their point of intersection will advance more rapidly than what would normally be expected. This is due to dynamic interactions that enhance radiative and convective heat transfer in a way that causes the fires to burn faster in regions surrounded by fire. Such regions can be characterized as having negative fire line curvature. Sharples et al. (2013) showed how using a curvature dependent rate of spread can successfully emulate the types of behaviour observed by Viegas et al. (2012). This approach allows for the effect to be modelled in two-dimensions despite the complicated three-dimensional processes that are actually driving it.

The level set method employed is formulated as follows:

$$\frac{\partial\varphi}{\partial t} + \alpha\nabla^2\varphi + N(\varphi) = 0, \tag{1}$$

where

$$N(\varphi) = \alpha\frac{\nabla\varphi}{|\nabla\varphi|}\cdot\nabla(|\nabla\varphi|) + \beta|\nabla\varphi|. \tag{2}$$

In this model a simple affine dependence of rate of spread on fire line curvature has been assumed; that is,

$$R = \alpha\kappa + \beta,$$

where R is the rate of spread (normal speed), κ is the fire line curvature and α and β are model parameters.

The project aims to extend these initial investigations to consider more appropriate mathematical formulations of geometric dependence and also the inclusion of extrinsic factors such as wind and slope.

EXPERIMENTAL PROGRAM

The modelling techniques outlined above will be complemented by a series of laboratory experiments using the CSIRO Pyrotron facility (Sullivan et al. 2013). In addition the research will also draw upon available data from field-based experiments. Empirical information will be complemented with information gained from targeted numerical experiments using a coupled fire-atmosphere model. The use of such modelling enables a deeper insight into the physical mechanisms driving the observed dynamic behaviours.

Laboratory experiments

A series of experiments using the CSIRO Pyrotron facility will be conducted. These experiments will be broken down into four categories:

- Parallel fire line experiments
- V-shaped fire experiments
- Ring fire experiments
- Multiple spot fire experiments

The specifics of this experimental program are provided in detail in the Project Science Plan.

Field experiments

In addition, the project will analyse data collected as part of the CSIRO-led Project Aquarius (1983-1985), which examined the behaviour of a number of point ignitions set in close proximity to each other. Again, the Science Plan provides more detail.

Also, if and when opportunities arise, data arising through other collaborative research will be used to help inform the project research. For example, the collaborative arrangement between UNSW and the University of Coimbra, Portugal, which is further supported through the MOU between the Bushfire and Natural Hazards CRC, has already produced experimental data of relevance.

Numerical experiments

A number of numerical simulations will be carried out in order to better understand the physical mechanisms driving spot fire coalescence, to provide information of the scale dependence of the effects under consideration, and to provide additional information for two-dimensional model development.

Moreover, the numerical simulations will also provide information relating to ember trajectories that are being driven by an evolving heat source. As such they will provide information that will be used as part of the development of an end-to-end model for spot fire development.

These simulations will make use of the WRF-Fire coupled fire-atmosphere model, which will be run on the supercomputer at the NCI National Facility at the ANU.

WHAT THE PROJECT HAS BEEN UP TO

MILESTONE DELIVERY

At the time of writing the project has completed all milestones up to (and including) quarter 3.2, with the exception of milestone 3.2.4 (establish project website). Although milestones 3.3.3 and 3.3.4 have been completed, the project has a number of overdue milestones for quarter 3.3 and 3.4. However, it is expected that these milestones will be delivered before the due date for quarter 4.1 milestones.

As part of delivering milestone 3.3.4 (review of remaining milestones) it was decided to shift the delivery of milestones 4.1.3, 4.1.4, 4.2.5 and 4.2.6 to March 2018, which will allow more continuity with the current project and the project refresh.

RESEARCH PROGRESS

The research has progressed along three main lines of focus:

1. Experimental observations of dynamic fire propagation in the CSIRO Pyrotron;
2. Investigation of intrinsic fire dynamics using couple fire-atmosphere modelling;
3. Development and validation of two-dimensional models incorporating pyroconvective feedback.

Experimental program

In the first case, the main aim was to test the hypothesis that pyroconvective interaction between the arms of 'V' fires interact to induce dynamic fire propagation within the 'V'. A total of 96 experimental fires were conducted in Phase 1 of the experimental program, and were carried out in the CSIRO Pyrotron. A number of additional experiments were conducted when deemed necessary. The experimental parameters were as follows:

- Dry eucalypt litter 12 t/ha
- Fuel moisture content 4-6% representative of wildfire conditions
- Wind speed 0 m/s and1 m/s
- 4 replicates of each treatment and controls
- 800mm and 1500mm arms were used
- Angles of 15°, 30°, 45° and 60° were considered.

Figure 2 shows one of the experimental fires soon after ignition and highlights the dynamic enhancement of the fire in the vicinity of the point of intersection of the arms of the V fire.

Figure 2: Photograph of experimental V-fire in the CSIRO Pyrotron. It shows the 800mm arms at an angle of 45° with a 1 m/s wind. Pronounced fire activity is evident in the vicinity of the point of intersection of the arms of the V.

Taken as a whole the experiments conducted under no wind conditions indicated that the forward rate of progression of the point of intersection of the V lines 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 V fire.

However, the arms of the V exhibited asymmetrical propagation that did indicate 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, it was strong enough to halt spread outside the V. Figure 3 shows a sequence of photos from one of the no-wind experiments. The figure illustrates the lack of propagation of the fire outside the arms of the V.

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

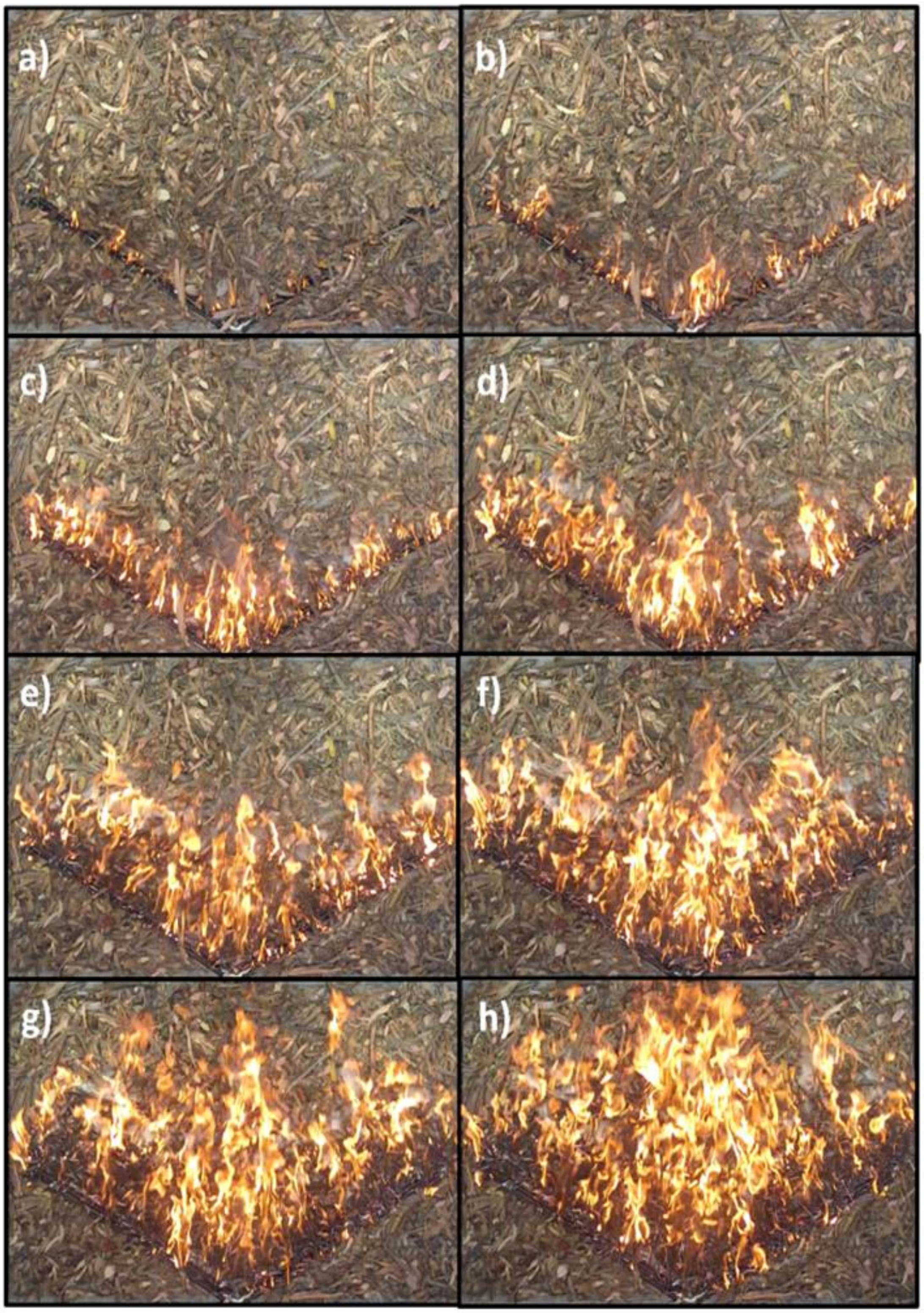

Figure 3: a-h) Series of rectified and corrected images taken from the planar video from one replication of the no-wind experiment using an 800 mm ignition line and 60° incidence angle. The images show the progression of the fire every 5 seconds after ignition (panel a). The flame front was defined as the leading edge of combustion at the fuel level as determined from multiple viewing angles, not to be confused with the presence of flame. The image was taken from Sullivan et al (2017).

For the experiments with a 1 m/s wind it was found that the forward rate of spread of the vertex was significantly higher that 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 Phase 1 of the experimental program are currently in the process of being published (Sullivan et al. 2017). The results were also used for calibration and validation on the two-dimensional simulations discussed below.

Coupled fire-atmosphere simulations

Research conducted on dynamic fire spread using the WRF-Fire coupled fire-atmosphere model has now been published. In particular, work on the pyroconvective dynamics of junction fires (V-fires) has been published in the International Journal of Wildland Fire (Thomas et al. 2017). This work considered the detailed wind and vorticity dynamics associated with the enhanced forward rate of propagation of the junction point of two intersecting fire lines, similar to this considered in Phase 1 of the experimental program. However, 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 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 illustrates the significant effect that pyroconvective interaction has on the progression of the fire. In this figure, the grey lines show the progression of the two separate fire lines – they are therefore indicative of the progression of the two fire lines in the absence of any pyroconvective interaction. The black lines, on the other hand, show the progression of the two fire lines when they are allowed to interact. As can be seen there is a considerable difference in the progression of the fire lines in these two separate scenarios. After 15 minutes (Figure 4c), pyroconvective interaction between the two fire lines has caused the fire to propagate forward an additional 500m compared to the case of non-interacting fire lines. This corresponds to an increase in rate of spread of 2 km/hr.

Thomas et al. (2017) also made a detailed examination of the physical processes driving the enhancement in forward rate of propagation. It was found that the enhancements in rate of spread occurred locally and intermittently along the fire lines, but always in connection with vertical vorticity couplets. The vertical vorticity couplets developed as follows:

- The concave geometry of the fire line results in the preferential formation of horizontal vorticity ahead of the fire line (inside the V).
- The vertical updraft emanating from the fire caused tilting and stretching of the horizontal vorticity into vertical vorticity
- The vertical vorticity manifested as counter-rotating vortex pairs – effectively small-scale fire whirls, which drove local enhancement in the forward propagation of the fire lines.
- Vortex pairs were more prevalent and stronger near high concavity.

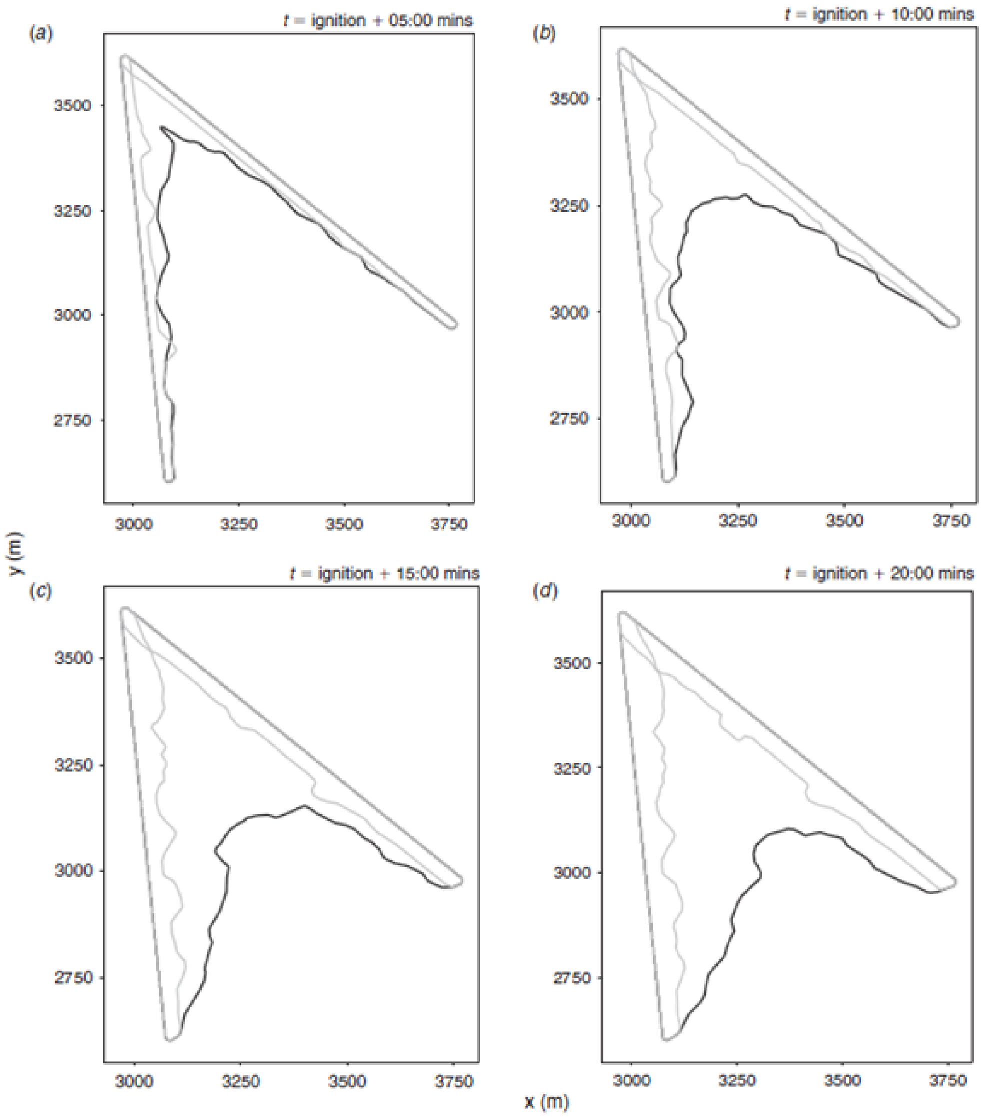

Figure 4: Composite plot of three model runs of the 45° configuration, shown (*a*) 5; (*b*) 10; (*c*) 15; and (*d*) 20 min after ignition. The grey lines show the evolution of the front when only one arm of the V is ignited; together, they show how the front would evolve without interaction between the two fire lines. The black line shows the evolution when both arms are ignited simultaneously. Figure taken from Thomas et al. (2017).

Figure 5 shows how the vortex pairs affect the local rate of progression of the fire line. The vortex pairs can be seen as blue/red couplets: red indicates counter-clockwise rotation, while blue indicates clockwise rotation. The depth of colour indicates the strength of the rotation. Note that enhanced forward propagation of the fire line occurs in connection between the blue/red couplets where the convergence of the counter rotating vortices "pulls" the fire line forward.

Interestingly, Thomas et al. (2017) also demonstrated that for straight fire lines the same dynamic does not occur. Indeed, for straight fire lines, coupled fire-atmosphere simulations indicated that while counter-rotating vortex couplets did form, they tended to be less intense, and more importantly, they formed *behind* the fire line.

The findings of Thomas et al. (2017) also provided fundamental insights into an unresolved question concerning the merging of two oblique fire lines: is the dynamic fire spread observed in such cases primarily driven by radiative or convective effects; or is it perhaps a combination of the two? The results of Thomas et al. (2017) strongly indicate that the answer to this fundamental question is that the dynamic fire behaviour is driven primarily by convection and in particular, by pyroconvective interaction between the two fire lines. This is a significant finding.

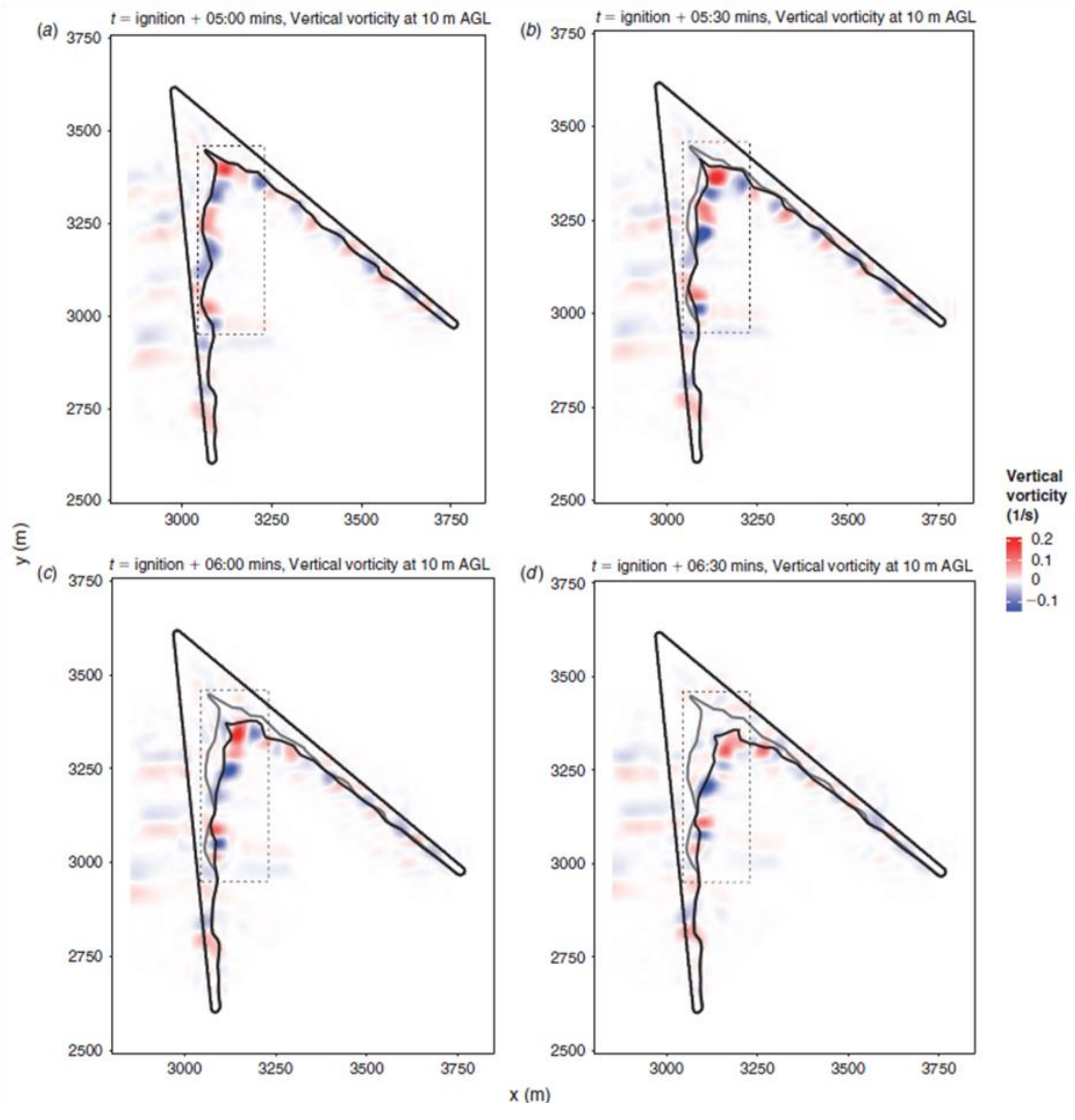

Figure 5: Advection and merging of counter-rotating vortex pairs. The time sequence shows the fire line location and vertical vorticity for one 45° ensemble member at 30s intervals, beginning 5 min after ignition. The (stationary) grey line shows the location of the fire line at the initial time of the sequence. Figure taken from Thomas et al. (2017).

The behaviour of circular arc fires have also been investigated using coupled fire-atmosphere simulations. These simulations provided significant insights into dynamic fire propagation and resulted in the project team altering the way dynamic fire model development was being addressed. In particular these coupled simulations provided resounding proof that fire line curvature was not the correct quantity to use for dynamic fire prediction in general. Indeed, it was found that circular arc fires with the *same* curvature, but with different extents, exhibited very different patterns of fire propagation. This fundamental observation caused the project team to focus consideration on the innovative use of potential flow based methods. This led to the development of the 'pyrogenic potential' model.

Fire simulation incorporating geometrical dependence

The project team has published a paper (Hilton et al. 2016) detailing the utility of the model defined by equations (1) and (2) and incorporating wind-dependence given by $\boldsymbol{u}(\gamma) \cdot \nabla\varphi$, with $\boldsymbol{u}(\gamma)$ defined by equation (4). The model was found to provide far more accurate prediction of the fire line geometry when compared with models that did not incorporate curvature dependence. An example of the model performance can be seen in Figure 6, which show how the model performed in predicting the perimeter of an experimental wind-driven grass fire.

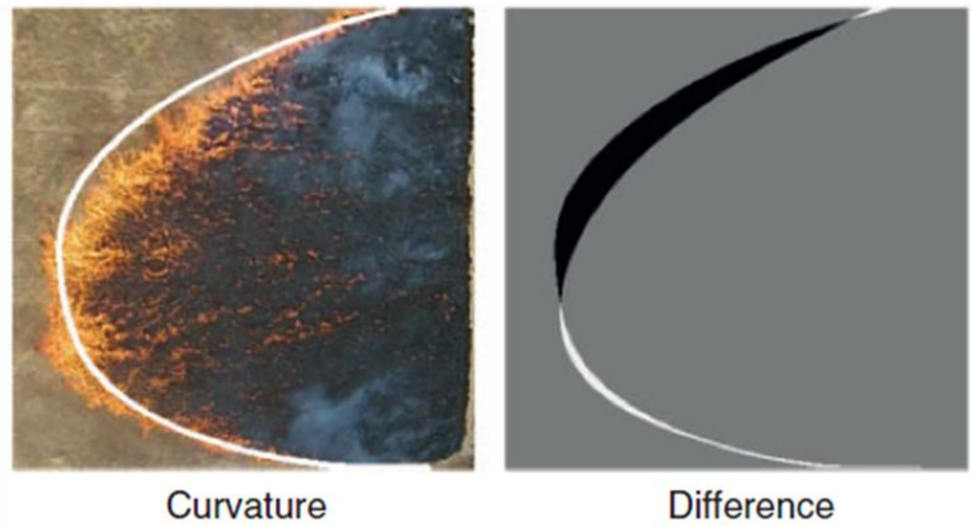

Figure 6: Left: Image of experimental grassfire 25 seconds after ignition. The white line is the model prediction. Right: difference between stencils from experimental and simulated perimeters with curvature effects. Figure taken from HIlton et al. (2016).

The model was also used to model the experimental junction fires of Viegas et al. (2012). This work is currently under review for inclusion in the Proceedings of the 2017 International Congress on Modelling and Simulation (Sharples and Hilton, 2017).

However, as mentioned above, the insights gained from the coupled fire-atmosphere model prompted the development of a new modelling approach using a 'pyrogenic potential'. The idea is that the pyroconvective interactions between different parts of the fire line (or fire lines) arise ultimately due to pyrogenic indraft. This indraft is modeled as a two-dimensional surface flow with a sink everywhere along the fireline. This is shown schematically in Figure 7. The figure shows that the air flowing horizontally into a fire's plume can be treated as an two-dimensional incompressible 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).

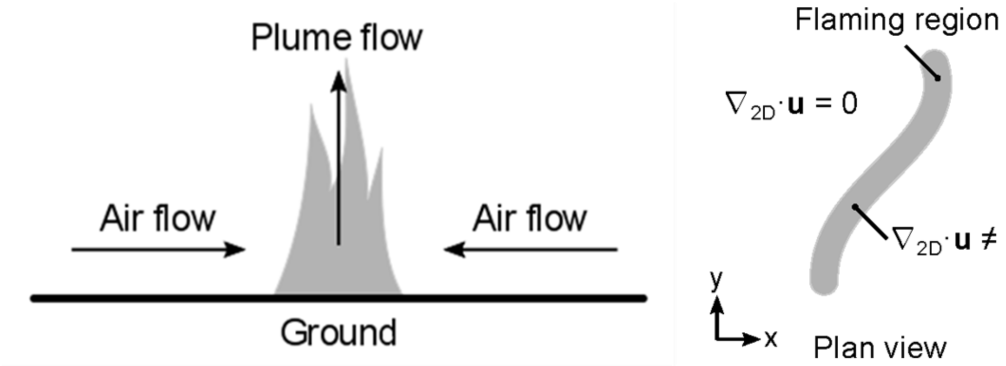

Figure 7: Left: Schematic view of the indraft into a fire plume. Right: Schematic view of a fire line as a sink for the horizontal indraft into the fire's plume.

Assuming that the horizontal flow into the base of the plume is irrotational, we can write it as the gradient of a pyrogenic potential function ψ. 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, in which fire line curvature has been removed, and instead the level-set equation is coupled with a Poisson equation for the pyrogenic potential:

$$\frac{\partial \varphi}{\partial t} = s\|\nabla\varphi\| + (\boldsymbol{u}(\gamma) + \nabla\psi) \cdot \nabla\varphi, \qquad \nabla^2\psi = \rho, \tag{3}$$

where $\rho = kf(R, \varphi, \nabla\varphi)$. Here k can be considered a tuning parameter, and f is a function of the local rate of spread R, and the level set function and it's derivative. Essentially this formulation means that the strength of the source term in the Poisson equation is proportional to the intensity of the fire line; that is, the pyrogenic indraft increases as the convective strength of the plume increases.

We refer to the model in equation (3) as the '*pyrogenic potential* model'.

Note also that the advective effect of the ambient wind on fire propagation is modeled as follows:

$$\boldsymbol{u}(\gamma) = \begin{cases} \gamma(\hat{w} \cdot \hat{n})\hat{w} & \text{if } \hat{w} \cdot \hat{n} > 0, \\ 0 & \text{if } \hat{w} \cdot \hat{n} \leq 0. \end{cases} \tag{4}$$

Here $\hat{w}$ and $\hat{n}$ are the unit vectors pointing in the direction of the wind and normal to the interface, respectively. The model defined by (3) and (4) has been applied to the same fires that the curvature-based models ahd previously been applied to. It was found that the pyrogenic potential model gave almost identical results to the curvature-based models. As such the pyrogenic potential model provides a physical rationale for why the curvature-based models were so effective at accurate predicting fire propagation in the case it was shown to be effective.

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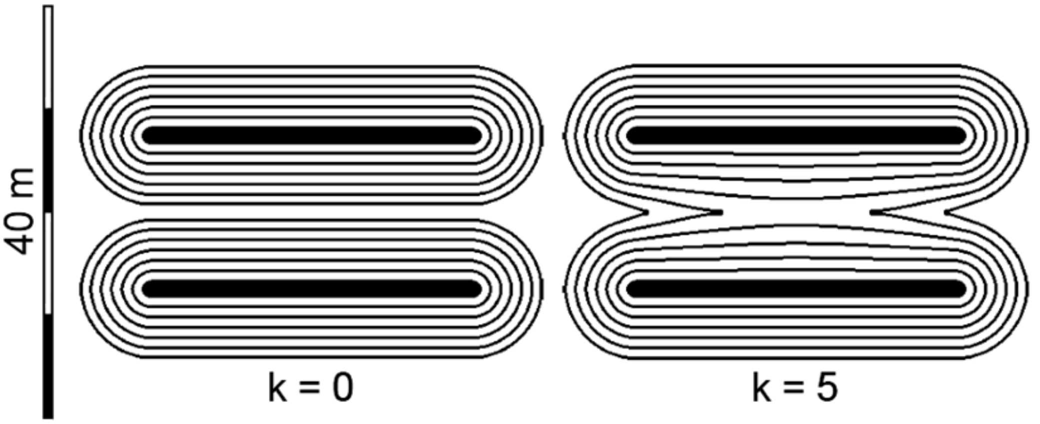

Figure 8: Parallel fire lines with simulated without pyrogenic potential (left) and with pyrogenic potential (right).

We note that such behaviour could not have been predicted using a curvature-based model, since the initial line fires were straight. This shows the promise of the pyrogenic potential in modelling dynamic fire propagation.

Furthermore, the pyrogenic potential model can better predict fundamental patterns of fire propagation, such as that of a wind-driven line fire. Figure 9 shows and example of one of the control experiments conducted in the CSIRO Pyrotron as part of Phase 1 of the experimental program. The fire line naturally develops in to a parabolic perimeter under the influence of the wind. This behaviour is also predicted by the pyrogenic potential model. In fact, it is worth noting that this sort of behaviour has only ever been predicted using fully coupled fire-atmosphere models, which are far, far more computationally intensive than the pyrogenic potential model. The pyrogenic potential model runs faster than real time, compared to fully coupled fire-atmosphere model runs which can take several hours to run. This is a remarkable development in fire propagation; indeed, it raises the question of whether fully coupled fire-atmosphere models are necessary to model dynamic fire spread.

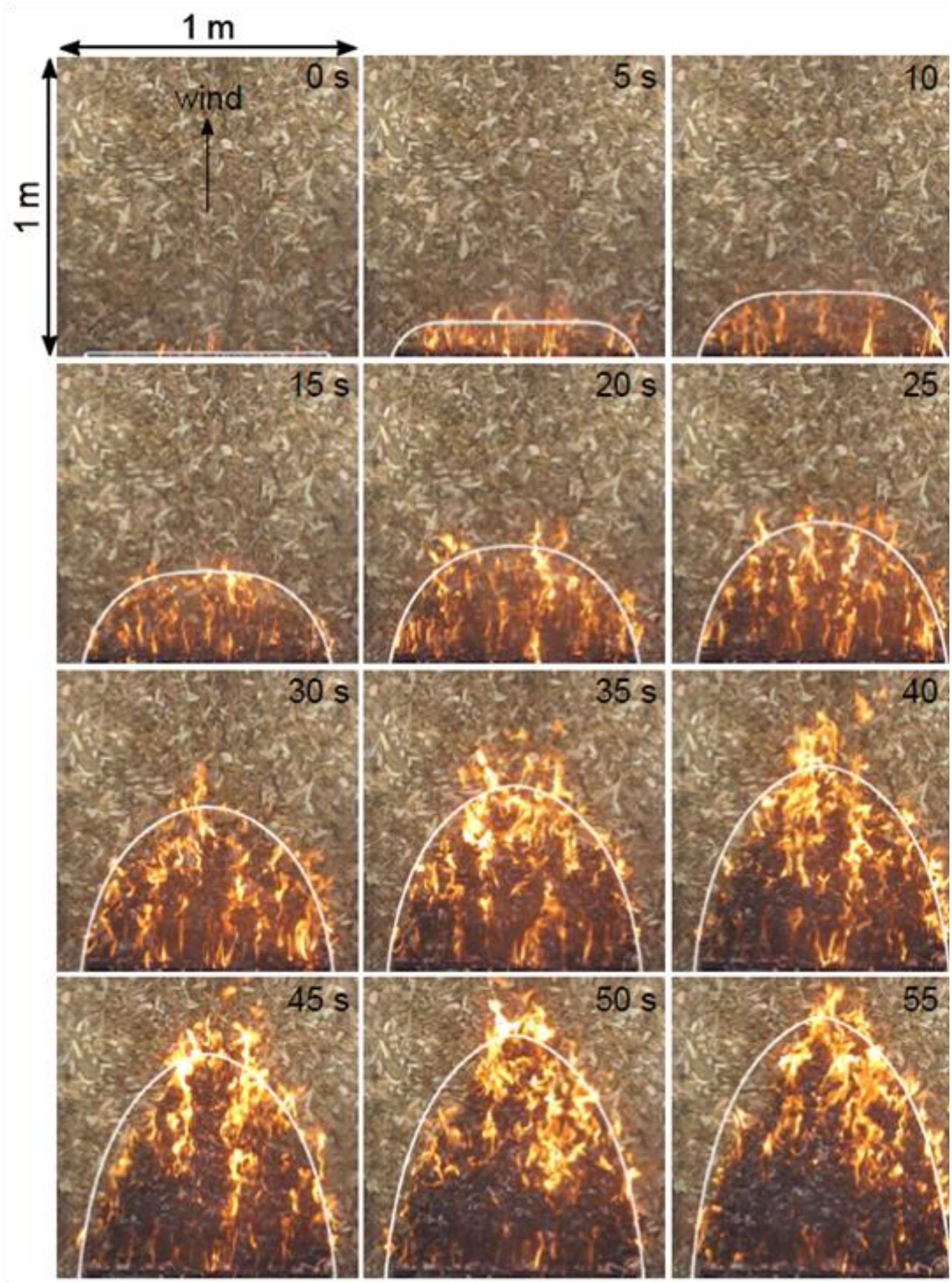

Figure 9: Comparison of laboratory experimental line fire to a basic propagation model incorporating a pyrogenic potential term, where the white line is the simulated fire perimeter, at 5 s intervals. Wind speed is 1 m/s in the direction indicated by the arrow in the first image.

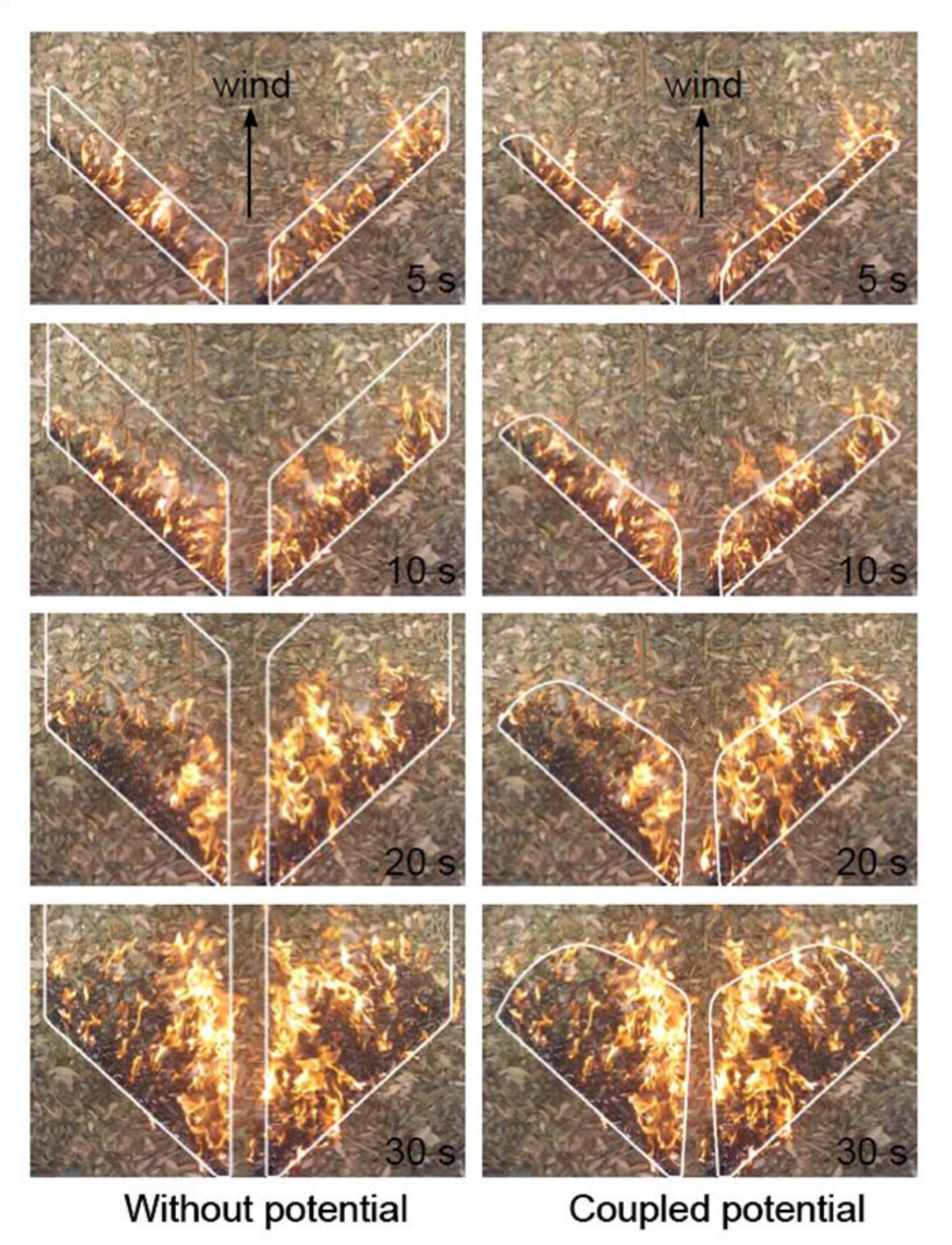

Figure 10: Comparison of experimental `V' line fire with a small gap at the apex to simulations without pyrogenic potential (left column) and with pyrogenic potential (right column), where the white line is the predicted fire perimeter.

The pyrogenic potential model has also been successfully applied to some of the other mode complicated experimental configurations considered in the Pyrotron experiments. Figure 10 shows the behaviour of a 'separated V' fire. In this fire two fire lines in a V formation are lit simultaneously, but with a small gap at their apex. The figure compares the performance of the model with and without pyrogenic potential. As can be seen, the model is able to emulate the observed fire propagation far more accurately with pyrogenic potential than without. This research is currently being written up for publication in a scientific journal. The research has also been used as parts of other studies, currently in the process of being published – see the list of publications.

PRESENTATIONS

The project has delivered the following presentations and posters:

1. **DYNAMIC MODELLING OF FIRE COALESCENCE: Spot fire project.** Bushfire and Natural Hazards CRC Research Advisory Forum, QUT Brisbane, November 2015. Delivered by J. Sharples.
2. **PYROCONVECTIVE INTERACTION OF TWO MERGED FIRE LINES: Curvature effects and dynamic fire spread.** 21st International Congress on Modelling and Simulation, Gold Coast, December 2015. Delivered by C. Thomas
3. **EXTREME AND DYNAMIC FIRE BEHAVIOUR.** Victorian Country Fire Authority - Fire Behaviour Analyst Pre-season Workshop, December 2015. Delivered by J. Sharples.
4. **AN OVERVIEW OF EXTREME FIRE BEHAVIOUR.** Laharum Brigade Information Day, July 2015. Delivered by J. Sharples.
5. **UNDERSTANDING EXTREME FIRE BEHAVIOUR.** ACT Rural Fire Service Advanced Firefighter Principle Course, July 2015. Delivered by J. Sharples.
6. **EXTREME AND DYNAMIC FIRE BEHAVIOUR: Strange things that can happen in and around the high-country and rugged terrain.** ACT Rural Fire Service Crew Leaders Development Workshop, August 2015. Delivered by J. Sharples.
7. **EXTREME AND DYNAMIC FIRE BEHAVIOUR.** NSW Rural Fire Service Southern Districts Information Day, October 2015. Delivered by J. Sharples.
8. **DYNAMIC FIRE BEHAVIOUR AND FIRE LINE GEOMETRY**. Australia and New Zealand Industrial and Applied Mathematics (ANZIAM) Conference 2016, Canberra, February 2016. Delivered by C. Thomas.
9. **UNDERSTANDING EXTREME BUSHFIRE DEVELOPMENT.** Joint University of New South Wales and New South Wales Rural Fire Service Workshop, Homebush NSW, February 2016. Delivered by J. Sharples.
10. **UNDERSTANDING FIRE LINE DYNAMICS USING A COUPLED FIRE-ATMOSPHERE MODEL**. Joint University of New South Wales and New South Wales Rural Fire Service Workshop, Homebush NSW, February 2016. Delivered by C. Thomas.
11. **DYNAMIC FIRE SPREAD AND FIRE LINE GEOMETRY**. 5th International Fire Behaviour and Fuels Conference, Melbourne, April 2016. Delivered by J. Sharples.
12. **NATURE ABHORS CURVATURE – FIRES INCLUDED: Modelling spot fire coalescence.** Poster presentation at the 2015 AFAC and Bushfire and Natural Hazards Conference, Adelaide, September 2015. Presented by J. Sharples.
13. **DYNAMIC FIRE BEHAVIOUR AND FIRE LINE GEOMETRY.** Poster presentation at the 5th International Fire Behaviour and Fuels Conference, Melbourne, April 2016. Presented by C. Thomas.
14. **FIRE COALESCENCE AND MASS SPOT FIRE DYNAMICS: Experimentation, modelling and simulation.** Bushfire and Natural Hazards CRC Research Advisory Forum, ANU Canberra, November 2016. Delivered by J. Sharples.

15. **MATHEMATICAL MODELLING OF THE DYNAMIC EVOLUTION OF WILDFIRES**. 2017 Mathematics Across the Disciplines meeting, ANU Canberra, May 2017. Delivered by J. Sharples.
16. **EXTREME AND DYNAMIC FIRE BEHAVIOUR** XFireNZ – Preparing New Zealand for Extreme Fire Behaviour project meeting, University of Cantebury, February 2017. Delivered by J. Sharples.
17. **UNDERSTANDING THE DYNAMIC DRIVERS OF EXTREME BUSHFIRE BEHAVIOUR.** The 2016 G.S. Watson Lecture, La Trobe University, September 2016. Delivered by J. Sharples.
18. **FIRE COALESCENCE AND MASS SPOT FIRE DYNAMICS** Bushfire and Natural Hazards CRC Research Showcase, Adelaide, July 2017. Delivered by J. Sharples.
19. **INCORPORATION OF SPOTTING AND FIRE DYNAMICS IN A COUPLED ATMOSPHERE-FIRE MODELLING FRAMEWORK** Poster presentation, Bushfire and Natural Hazards CRC Research Showcase, Adelaide, July 2017. Delivered by C. Thomas.
20. **EXPERIMENTAL INVESTIGATION OF JUNCTION FIRE DYNAMICS, WITH AND WITHOUT WIND** Poster presentation, Bushfire and Natural Hazards CRC Research Showcase, Adelaide, July 2017. Delivered by J.Sharples.

END USER ENGAGEMENT

Members of the project team engaged with various end users a number of times throughout the year. The main user engagement activities are included in the list of presentations provided above. Specifically these activities included:

- The 2016 AFAC/Bushfire and Natural Hazards CRC conference
- The 2016 Bushfire and Natural Hazards CRC Research Advisory Forum
- The ACT Rural Fire Service Advanced Firefighter Principles Course and the Crew Leader Development Course.
- Tasmanian Fire Service Fire Behaviour Analyst Workshop

PROGRESS OF THE PHD SCHOLAR

The PhD scholar (Chris Thomas) has been making steady progress and his research has produced a number of significant insights, particularly via his innovative use of WRF-Fire to investigate idealized dynamic fire spread scenarios. So far Chris has published one journal article, one peer-reviewed conference paper and a conference poster. He currently has two journal papers and two peer-reviewed conference papers paper in preparation. He also delivered a research seminar at UNSW Canberra. Chris is well on-track to successfully complete his PhD research and submit his thesis within scheduled timeframes.

PUBLICATIONS LIST

1. Thomas, C., Sharples, J.J., Evans, J.P. (2015) Pyroconvective interaction of two merged fire lines: Curvature effects and dynamic fire spread. In Weber, T., McPhee, M.J. and Anderssen, R.S. (eds) MODSIM2015, 21st International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2015.
2. Sharples, J.J., Hilton, J.E., Sullivan, A.L., Miller, C., Thomas, C.M. (2016) Using fire line geometry to model dynamic fire spread. In: Proceedings of the 5th International Fire Behaviour and Fuels Conference April 11-15, 2016, Melbourne, Australia. Published by the International Association of Wildland Fire, Missoula, Montana, USA
3. Raposo, J.R., Viegas, D.X., Xie, X., Almeida, M., Figueiredo, A.R., Porto, L., Sharples, J.J. (2016) Analysis of the physical processes associated to junction fires at laboratory and field scales. *International Journal of Wildland Fire* (under review).
4. Hilton, J.E., Miller, C. Sharples, J.J., Sullivan, A.L. (2016) Curvature effects in the dynamic propagation of wildfires. *International Journal of Wildland Fire*, 25(12) 1238-1251.
5. Thomas, C., Sharples, J.J., Evans, J.P. (2017) Modelling the dynamic behaviour of junction fires with a coupled atmosphere-fire model. *International Journal of Wildland Fire*, 26(4) 331-344.
6. Thomas, C.M., Sharples, J.J., Evans, J.P. (2016) Modelling the dynamic behaviour of junction fires with a coupled atmosphere-fire model. Poster presentation at the 5th International Fire Behaviour and Fuels Conference April 11-15, 2016, Melbourne, Australia.
7. Sharples, J.J., Hilton, J.E., Miller, C., Sullivan, A.L. (2015) Nature abhors curvature – fires included! Poster presentation at AFAC/Bushfire and Natural Hazards CRC Conference.
8. Sullivan, A.L., Swedosh, W., Hurley, R.J., Sharples, J.J., Hilton, J.E. (2017) Experimental Investigation of junction fire dynamics, with and without wind. Poster presentation at the Bushfire and Natural Hazards Research Showcase, Adelaide.
9. Thomas, C.M., Sharples, J.J., Evans, J.P. (2017) Incorporation of spotting and fire dynamics in a coupled atmosphere-fire modelling framework**.** Poster presentation at the Bushfire and Natural Hazards Research Showcase, Adelaide.
10. Roberts, M.E., Sharples, J.J., Rawlinson, A.A. (2017) Incorporating ember attack in bushfire risk assessment: a case study of the Ginninderry region. Proceedings of MODSIM2017, 22nd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2017. (under review)
11. Thomas, C.M., Sharples, J.J., Evans, J.P. (2017) Modelling firebrand transport: comparison of two methodologies. Proceedings of MODSIM2017, 22nd International Congress on Modelling and Simulation. Modelling and

Simulation Society of Australia and New Zealand, December 2017. (under review)

12. Badlan, R.L., Sharples, J.J., Evans, J.P., McRae, R.H.D. (2017) The role of deep flaming in violent pyroconvection. Proceedings of MODSIM2017, 22nd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2017. (under review)
13. Hilton, J.E., Sharples, J.J., Sullivan, A.L., Swedosh, W. (2017) Spot fire coalescence with dynamic feedback. Proceedings of MODSIM2017, 22nd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2017. (under review),
14. Hilton, J.E., Sullivan, A.L., Swedosh, W., Sharples, J.J., Thomas, C.M. (2017) Incorporating convective feedback in wildfire simulations using pyrogenic potential. In preparation, to be submitted to Environmental Modelling and Software.
15. Sullivan, A.L., Swedosh, W., Hurley, R.J., Sharples, J.J., Hilton, J.E. (2017) Investigation of the effects of interactions of intersecting oblique fire lines, with and without wind. In preparation, to be submitted to the International Journal of Wildland Fire.
16. Sharples, J.J., Hilton, J.E. (2017) Modelling the dynamic behaviour of small scale junction fires. Proceedings of MODSIM2017, 22nd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2017. (under review)

CURRENT TEAM MEMBERS

The research team is currently made up as follows:

A/Prof. Jason Sharples, UNSW

Dr James Hilton, CSIRO Data61

Dr Andrew Sullivan, CSIRO Land and Water

End-user/Advisory Committee – lead by Brad Davies and Stuart Matthews, NSW Rural Fire Service.

ADDITIONAL TEAM MEMBERS

Mr Christopher Thomas, UNSW

Chris is a PhD scholar in Mathematics at UNSW under the supervision of A/Prof Sharples, and is the recipient of a BNHCRC top-up scholarship. Chris' project has been aligned with the spot-fire coalescence project and he is now an integral part of the project team.

Mr Richard Hurley, CSIRO

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 bee instrumental in analyzing the Pyrotron experimental data. He has also contributed significantly to publications.

Additional assistance for experimental work in Phase 1 was provided by Dr Matt Plucinski and Mr Vijay Koul.

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Sharples, J. J., I. N. Towers, G. Wheeler, V.-M. Wheeler, and J.A. McCoy (2013). Modelling fire line merging using plane curvature flow. *Proceedings: 20th International Congress on Modelling and Simulation*, pp. 297–303.

Sullivan, A.L. (2009) Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. *International Journal of Wildland Fire*, 18(4), pp.349-368.

Sullivan, A.L., Knight, I.K., Hurley, R.J., Webber, C. (2013) A contractionless, low-turbulence wind tunnel for the study of free-burning fires. *Experimental Thermal and Fluid Science* 44, 264–274.

Thomas, C., Sharples, J.J., Evans, J.P. (2017) Modelling the dynamic behaviour of junction fires with a coupled atmosphere-fire model. International Journal of Wildland Fire, 26(4) 331-344.

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