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PYROCONVECTIVE INTERACTIONS AND SPOT FIRE DYNAMICS

ABOUT THIS PROJECT

This research is part of the project *Fire coalescence and mass spot fire dynamics*, which began in 2014. The project has two primary aims: to improve the understanding of pyroconvective interactions across fire lines of general geometric configuration; and to increase knowledge about how intrinsic fire dynamics, including drivers such as pyroconvection and radiation, affect the spread of fires across a landscape. The project combines mathematical modelling, numerical simulation and fire experimentation at laboratory and landscape scales.

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Above: AN EXPERIMENTAL SEPARATED V-SHAPED FIRE CONDUCTED IN THE CSIRO PYROTRON. PHOTO: ANDREW SULLIVAN, CSIRO

SUMMARY

This pioneering project is developing the first, two-dimensional fire simulation model that can operate in faster than real time, while incorporating intrinsic, fire line dynamics. Fires that burn in close proximity can influence each other due to pyroconvective interactions between individual fires. The same processes can apply to different parts of a single fire line. A typical example is when intense spotting causes many fires to form and coalesce. Interactions between individual spot fires and other parts of the main fire perimeter can increase local rates of spread, in unexpected directions, potentially producing broad, flaming zones that can entrap firefighters, and increase the likelihood of extreme bushfires.

By combining advanced mathematical modelling with laboratory and numerical experimentation, this research is providing insights into the physical drivers of these interactions. In particular, it elevates the critical role of pyroconvective interactions in many aspects of fire propagation. These findings are the basis of computationally efficient modelling techniques that enable pyroconvective effects and dynamic fire behaviours to be included in two-dimensional, fire spread simulators. More cost-effective than current simulators, they could ultimately help protect firefighters, communities at risk and property.

CONTEXT

Current operational fire simulation methodologies cannot account for dynamic modes of fire propagation (see definitions, page two) that are driven by complex interactions between the fire and the local atmosphere. Nor can they explain basic fire spread patterns, such as the observed parabolic rounding at the head of a wind-driven fire line. This project is developing modelling techniques that address these shortcomings.

BACKGROUND

Fire behaviour in dry eucalypt forests in Australia is characterised by spot fires – new fires ignited by the transport of burning debris, such as bark, ahead of an existing fire. This also applies to many other vegetation types, but to a lesser extent. Under most burning conditions, spot fires have little influence on the overall spread of a fire, except where spot fires can overcome hurdles, such as topography or breaks in fuel (vegetation). However, in severe bushfires, spot fires can become the dominant propagation mechanism – the fire spreads as a cascade of spot fires that forms a 'pseudo' front, way ahead of the main fire front.

It is well known that multiple, individual fires can affect the behaviour and spread of all fires present. Similarly, different parts of a single fire line can influence each other, particularly when the fire line develops certain geometric configurations. In such instances, fire spread is driven by the combination of extrinsic influences, such as wind and terrain, and intrinsic effects that arise when different fires or different parts of a fire interact through pyroconvective (and other) processes (see definitions). In some cases, intrinsic effects can become significant and result in distinctly dynamic modes of fire propagation, such as occur in junction fires, for example, where fires meet and merge.

These dynamic modes violate an assumption behind all existing operational fire behaviour models – that fires spread at a quasi-steady rate. These operational models also assume that different fires, or different parts of a single fire line, essentially burn independently; this neglects any potential influence of intrinsic effects. These models cannot account for potential dynamic interactions, which may significantly influence the spread of a fire. The inability to accurately predict fire behaviours can place firefighters at risk and hinder effective warnings to the general public.

Some aspects of dynamic fire behaviour can be modelled using coupled fire-atmosphere models, but these models are too expensive for operational use. To meet this operational need, this research is developing computationally efficient, two-dimensional, fire-simulation methods, an innovation which, for the first time, can account for key, intrinsic dynamics of fire propagation.

BUSHFIRE AND NATURAL HAZARDS CRC RESEARCH

This project treats a spreading fire as an evolving interface between burnt and unburnt ground. Previous research has also investigated this, but the methods used often encountered difficulties when fire lines merge or when isolated pockets of unburnt vegetation remain, which typically occur when spot fires coalesce (see Figure 1, above right). A methodology that can successfully deal with these complexities is crucial – which is why researchers chose to use the level set methodology.

The level set method forms the basis for the development of efficient propagation models that use physically simplified proxies to account for complicated dynamic effects. To develop the model, the research team is conducting a series of experiments using the CSIRO Pyrotron facility.

These experiments target specific fire line configurations, such as:

- Parallel fire lines
- V-shaped 'junction' fires
- Ring fires
- Multiple spot fires.

These laboratory experiments were also complemented by field experiments conducted in Portugal by international collaborators, under the auspices of the Portuguese Foundation for Science and Technology's *Project firewhirl: vorticity effects in forest fires*.

Numerical simulations using coupled fire-atmosphere models also provided detailed data on the physical mechanisms driving intrinsic fire dynamics, and a better understanding of their scale dependence. Numerical simulations also yielded insights into ember transport dynamics, including the effect of terminal velocity assumptions on ember fall distributions. Overall, these simulations inform development of an end-to-end model for spot fire development, which can account for dynamic fire propagation.

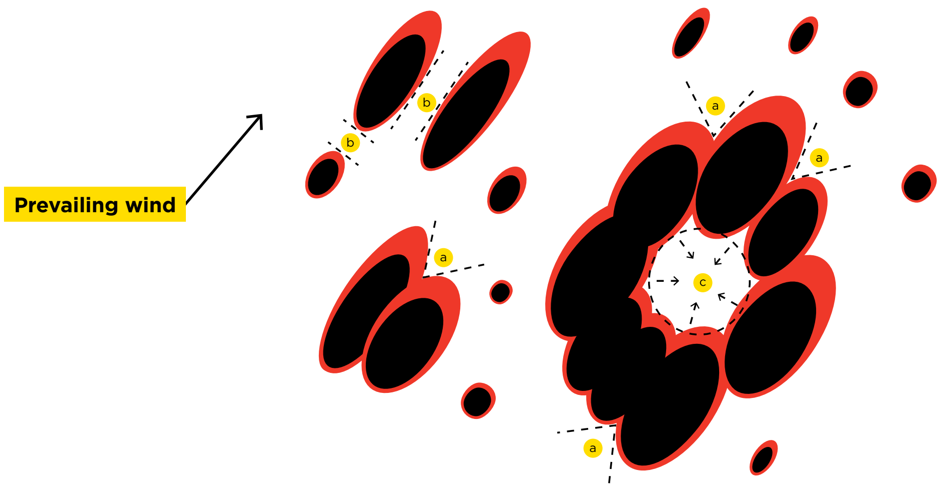


Figure 1: SCHEMATIC REPRESENTATION OF COALESCING SPOT FIRES AND THE DIFFERENT FORMS OF FIRE LINE INTERACTION BETWEEN INDIVIDUAL SPOTS. EXAMPLES OF FIRE LINE INTERACTIONS INCLUDE (a) INTERSECTING OBLIQUE LINES, (b) NON-INTERSECTING CONVERGING FIRE EDGES, AND (c) COLLAPSING OR CONSTRICTING PERIMETERS.

DEFINITIONS

Coalescence	The process of how nearby fires converge together.
Curvature	The degree to which a curve deviates from a straight line. In the case of fire, it is how curved the fire front is.
Dynamic fire propagation	Fire spread that abruptly changes its rate and intensity, without any significant changes in ambient environmental conditions.
Pyroconvection	The buoyant movement of fire-heated air, as distinct from normal atmospheric convection that mainly arises from solar heating and produces effects such as thermal winds, atmospheric instability and thunderstorms.
Quasi-steady rate of spread	A fire spreading from a point-source origin will increase its rate of forward spread until such time as an equilibrium state is reached, or in other words, until it reaches a more or less constant spread rate for the prevailing conditions.
Vorticity	The rotational component of the movement of a fluid such as air; for example, a fire whirl has a high degree of vorticity.
Vorticity-driven lateral spread (VLS)	A mode of dynamic fire behaviour – fire rapidly propagates across a steep, leeward slope in a direction nearly perpendicular to the wind direction.

RESEARCH FINDINGS

The research has highlighted the critical role that pyroconvective interactions play in many aspects of fire propagation. For example, it has discounted radiative heat transfer as the main driver of the local increase in rate of spread associated with junction fires — the observed effects were able to be accurately modelled using pyroconvective interactions alone. It has also highlighted the complex role that pyrogenic vorticity has in dynamic fire propagation.

Pyroconvective interactions can

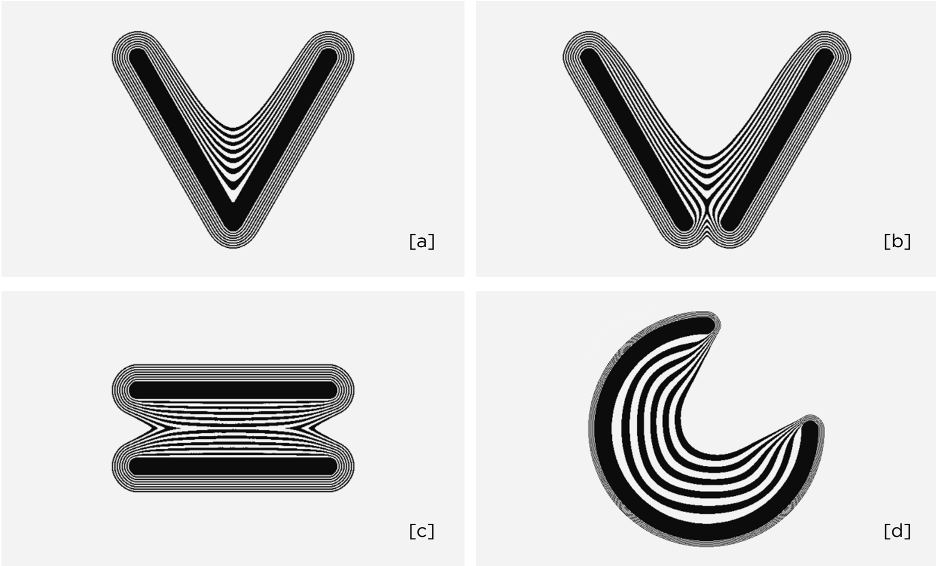
significantly affect fire behaviour — even in very basic patterns of fire spread, such as a line fire being driven by a uniform wind. The familiar 'parabolic head' shape that develops at the fire front is due to differences in the pyroconvective indraft along the fire line. Fire spread simulators now used operationally in Australia don't account for pyroconvective interactions, and cannot accurately model the development of a basic, straight-line fire.

To address these types of shortcomings, this research initially attempted to model pyroconvective interactions using fire line curvature. Fire line curvature served as a good predictor of dynamic fire spread in some, but not all, cases. The research then considered a very simple idea – to treat each point on the fire line as an independent 'sink point' for horizontal air flow.

This means that each point along a fire line creates its own radially symmetric indraft wind, the strength of which is determined by the intensity of the fire at that point. Considering the fire line as a whole, the indraft effects created by each of the individual points combine to produce an overall indraft wind, which is referred to as the 'pyrogenic flow'; that is, the flow of air created by the fire itself. This pyrogenic flow can then be added to the ambient wind flow to more accurately model the spread of the fire. This model is called the pyrogenic potential model, due to its similarity to models for determining the electrostatic potential of an array of electric point charges.

In effect, the pyrogenic potential model is a highly simplified, coupled fire-atmosphere model. The influence of the pyrogenic flow depends critically on the geometry of the fire line (for example, see Figure 2, above right). For certain configurations, the pyrogenic flow locally increases the rate of spread of certain parts of the fire line. For example, in a junction fire it produces the rapid advance of the point of intersection, as has been observed in experiments and numerical simulations (Figures 2a and 2b, above right). The pyrogenic flow causes two straight parallel fire lines to 'draw in' towards each other (Figure 2c, above right) and accounts for the higher rates of spread encountered as a closed arc of fire collapses upon itself (Figure 2d, above right).

Ongoing research will continue to develop the pyrogenic potential model. For example, the model was recently extended to account for other near-field effects, such as localised sources of vertical vorticity (see definitions). This has provided a way to model complex modes of dynamic fire propagation, such as



▲ Figure 2: EXAMPLES OF OUTPUT FROM THE PYROGENIC POTENTIAL MODEL FOR DIFFERENT INITIAL FIRE LINE GEOMETRIES: (a) JUNCTION FIRE (V-SHAPED FIRE); (b) SEPARATED V-SHAPED FIRE; (c) TWO PARALLEL FIRE LINES; (d) A CLOSED (270°) ARC. THE BLACK AND WHITE BANDING INDICATES THE SPREAD OF THE FIRES OVER EQUALLY SPACED POINTS IN TIME, SO THICKER BANDS CORRESPOND TO RELATIVELY HIGHER RATES OF SPREAD.

vorticity-driven lateral spread (see definitions). VLS is highly efficient at triggering zones of deep and widespread flaming, consisting of many coalescing spot fires. This can increase the likelihood of pyrocumulonimbus (fire-thunderstorm) development.

These state-of-the-art, near-field models are easily applied in fire simulation models such as Spark. As such, this research offers fire managers and fire behaviour analysts a world-first ability to model landscape-scale, fire spread, incorporating dynamic fire behaviours, using a faster than real-time simulator.

HOW IS THE RESEARCH BEING USED?

The recognition that fires can mutually influence each other's spread has been used in various contexts, such as prescribed burning and back burning. This research provides a theoretical basis for such practises, enabling a more quantitative understanding of their effects.

By accounting for pyroconvective interactions between different fires or different parts of a fire line, this research improves the estimation of the overall power of a fire. When combined with research into the atmosphere's role, it can alert forecasters to a fire's likelihood of transitioning into a more extreme event, such as a pyrocumulonimbus storm. This could better inform burning operations and help to avoid unexpected fire blow-ups. It could also prevent repeating past mistakes, where backburns have been started with good intentions, but unfortunate outcomes.

This research has improved the understanding of the dynamics of how fires spread, including insights into the relative importance of convective heat transfer compared to radiative heat transfer. This knowledge is critical for fully understanding fire spread and to further development in areas such as building codes for bushfire-prone areas.

Ultimately, the research enables the modelling of key aspects of fire behaviour that was previously only possible using computationally expensive, coupled models. The near-field techniques that

END-USER STATEMENT

"Using a multi-streamed approach, including laboratory experiments, coupled fire-atmosphere physical modelling and simplified analogue modelling, this project has demonstrated the feasibility of using computationally efficient approaches as a proxy for more costly approaches to modelling dynamic fire behaviours, such as the effect of mass-spotting upon peak fire power and rates of spread. Investigation toward incorporating this work into trial operational models and training is both progressing and very promising. This exciting work is directly relevant to strongly enhancing our understanding and predictive capacity in terms of dynamic fire behaviours."

– Brad Davies, Fire Behaviour Analyst, NSW Rural Fire Service

form the pyrogenic potential model allow complex modes of fire propagation to be simulated within operational time frames.

The research team is discussing the potential uses of the research with end-users. These potential applications include:

- The capacity to more accurately predict dynamic fire behaviours
- Better training materials that give firefighters a more complete understanding of fire behaviour potential
- Equipping fire behaviour analysts with technological tools to help them assess the likely progression of bushfires and the potential for their escalation.

CASE STUDY: FIREPOWER

The pyrogenic potential model has been used to investigate the effect of dynamic fire line interactions on the peak power generated by many, coalescing, spot fires. Figure 3 shows 25 simulated spot fires that have been allowed to spread. Interaction between spot fires creates localised regions of intense fire spread, which accumulate to produce higher peak fire power, with stronger coupling between separate fires producing higher intensities.

These results indicate that during mass spotting, fire line interactions can increase the power output of a fire complex. This increases the likelihood of violent pyroconvection and pyrocumulonimbus development.

FUTURE DIRECTIONS

The most compelling challenges ahead include:

- Using targeted experimentation and numerical simulation to investigate how the parameters defining the pyrogenic potential model scale across different fire sizes.
- Developing techniques for near-field modelling of modes of fire propagation driven by pyrogenic vorticity, such as VLS. This will combine research jointly funded by the Bushfire and Natural Hazards CRC and the Australian Research Council.
- Developing an end-to-end model for spot fire formation and coalescence.

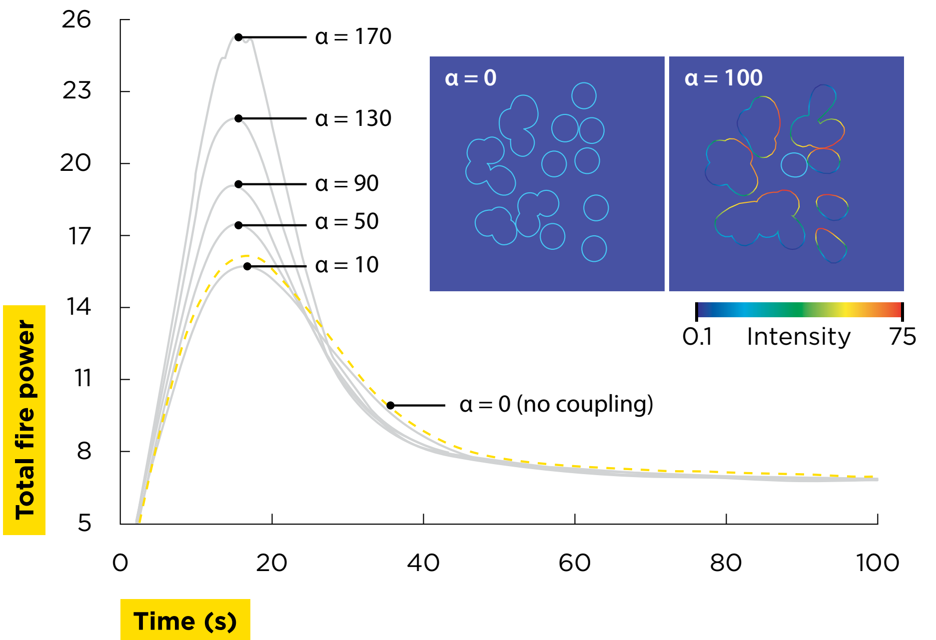


Figure 3: TOTAL (NON-DIMENSIONAL) FIRE POWER EMANATING FROM 25 COALESCING SPOT FIRES, MODELLED USING THE PYROGENIC POTENTIAL MODEL WITH DIFFERENT DEGREES OF COUPLING, PLOTTED AGAINST TIME SINCE IGNITION. NOTE THAT HIGHER VALUES OF THE PARAMETER α CORRESPONDS TO STRONGER COUPLING BETWEEN ADJACENT FIRES. THE DASHED LINE (α=0) CORRESPONDS TO THE CASE WHERE THERE IS NO INTERACTION BETWEEN ADJACENT FIRES. THE COLOURED INSET SHOWS THE EVOLUTION OF THE SPOT FIRES 15 SECONDS AFTER IGNITION WITHOUT COUPLING (α=0) AND WITH COUPLING (α =100). IT CAN BE SEEN THAT PYROCONVECTIVE INTERACTIONS BETWEEN THE DIFFERENT FIRES RESULTS IN LOCAL ENHANCEMENT OF THE RATE OF SPREAD AND INTENSITY OF THE FIRE. THE FIGURE HAS BEEN ADAPTED FROM HILTON *ET AL*. (2017).

FURTHER READING

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The Bushfire and Natural Hazards CRC is a national research centre funded by the Australian Government Cooperative Research Centre Program. It was formed in 2013 for an eight-year program to undertake end-user focused research for Australia and New Zealand.