FIRE COALESCENCE AND MASS SPOT FIRE DYNAMICS:

Experimentation, modelling and simulation

Jason Sharples
Applied and Industrial Mathematics Research Group
School of Physical, Environmental and Mathematical Sciences, UNSW Canberra

James Hilton
CSIRO Data 61

Andrew Sullivan
CSIRO Land and Water

OUTLINE

- Project summary
- Research accomplishments
  1. Experimental program
  2. Coupled fire-atmosphere modelling
  3. Dynamic fire simulation
- Progress against milestones
- Pathway to utilisation

PROJECT SUMMARY
SPOT FIRES AND FIRE COALESCENCE

- Fire behaviour in Australian vegetation is often characterised by the occurrence of spot fires.
- Spotting can be the dominant process under extreme fire conditions, and adds a significant dynamic element to the overall propagation of fires.
- Multiple individual fires grow and merge into larger ones – this can result in ‘deep flaming’, increases in fire intensity and spread!
- Such effects are currently not accounted for in operational models.....!!!
- Implications for fire power and pyroconvective budget.

PROJECT SUMMARY
AIMS

- Investigate the potential of simple geometric approaches to model the complicated processes involved in fire coalescence
- Develop computationally efficient models for spot fire coalescence – effectively 2D models of 3D processes
- Examine the effects of dynamic enhancement of fire spread on the pyroconvective budget of mass spotting events; that is, the spatial integral of instantaneous energy release (SIIER).

1. RESEARCH ACCOMPLISHMENTS

EXPERIMENTAL PROGRAM

Lead by Andrew Sullivan, CSIRO Pyrotron

CSIRO PYROTRON EXPERIMENTS – PHASE 1
V-SHAPED FIRES

- To test hypothesis that pyroconvective interaction between the arms of ‘V’ fires interact to induce dynamic fire propagation within the ‘V’.

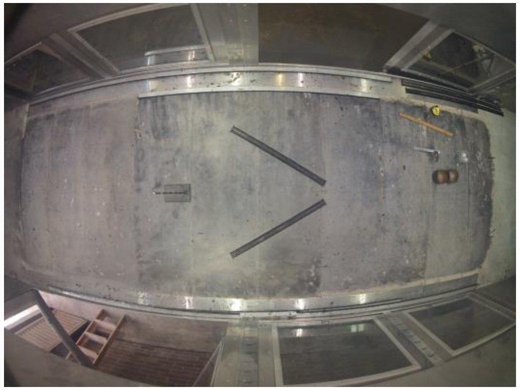
- Total of 96 experimental fires conducted in the CSIRO Pyrotron (plus extras).
  - Dry eucalypt litter12 t/ha
  - Fuel moisture content 4-6% representative of wildfire conditions
  - Wind speed 0 m/s and1 m/s
  - 4 replicates of each treatment and controls
  - Phase 1 April-May, 2016
  - Phase 1 extension, September 2016

CSIRO PYROTRON EXPERIMENTS – PHASE 1

V-SHAPED FIRES

Various angles between arms of the V

Arms of two different lengths

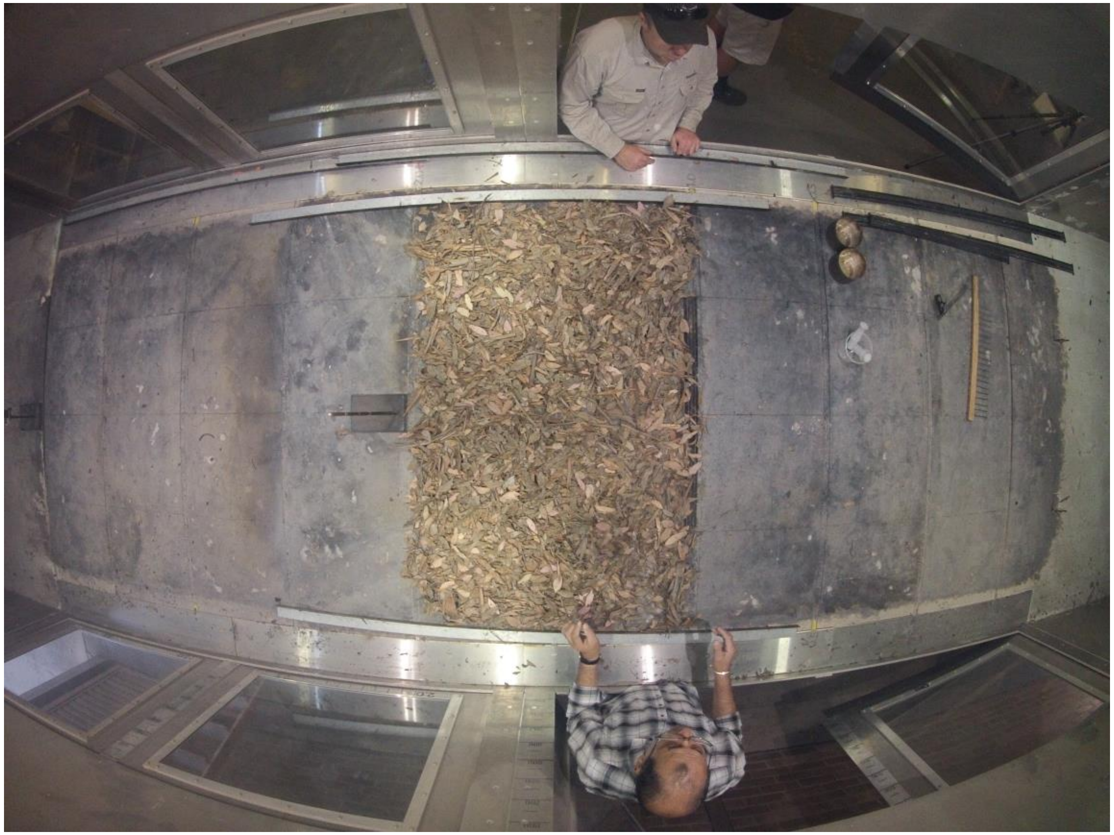


Separated V fires

- To investigate the effect of curvature (or not!)

CSIRO PYROTRON EXPERIMENTS – PHASE 1

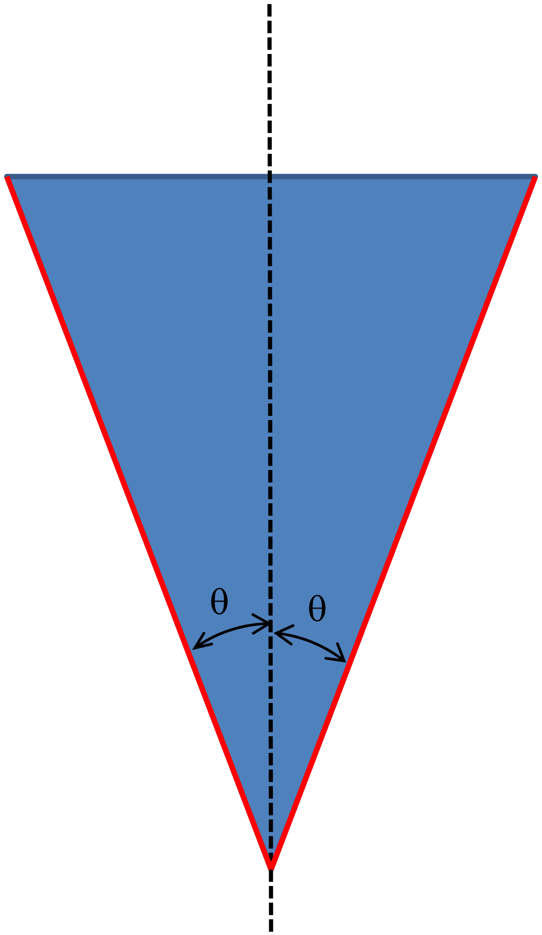
V-SHAPED FIRES



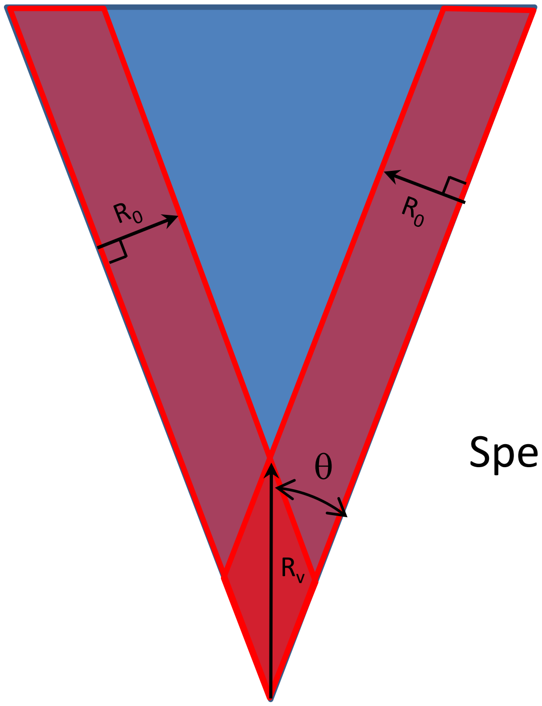
Setting up for the control experiment.

CSIRO PYROTRON EXPERIMENTS – PHASE 1

NULL HYPOTHESIS



No interaction of two arms of V



Speed of vertex:

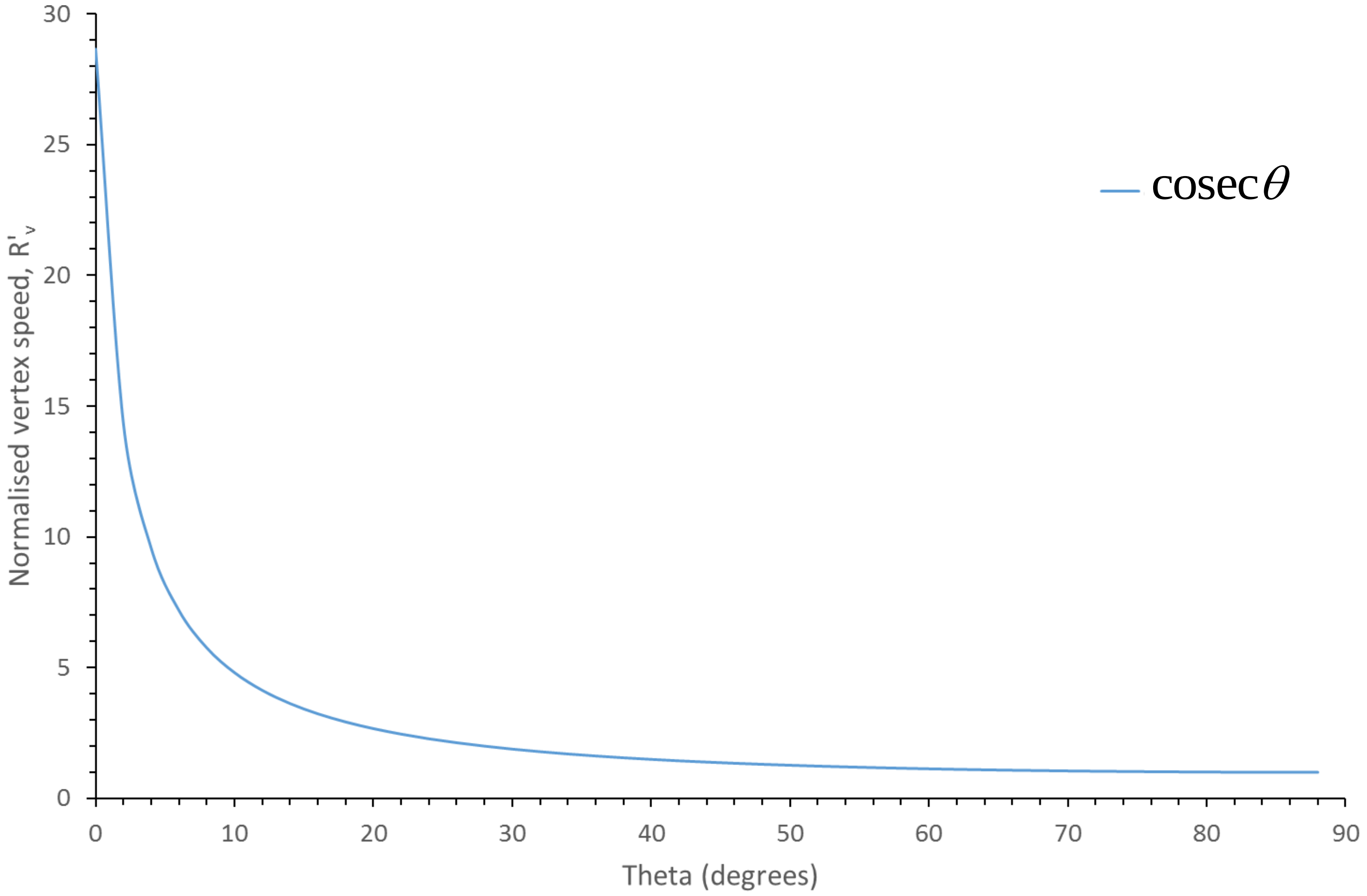
$$R_v = \frac{R_0}{\sin\theta} = R_0 \operatorname{cosec}\theta$$

Speed of vertex, normalised by R_0

$$R_v' = \frac{R_v}{R_0} = \operatorname{cosec}\theta$$

CSIRO PYROTRON EXPERIMENTS – PHASE 1

NULL HYPOTHESIS



CSIRO PYROTRON EXPERIMENTS – PHASE 1

45° NO WIND

CSIRO PYROTRON EXPERIMENTS – 5 SEC

45° NO WIND

CSIRO PYROTRON EXPERIMENTS – 10 SEC

45° NO WIND

CSIRO PYROTRON EXPERIMENTS – 15 SEC

45° NO WIND

CSIRO PYROTRON EXPERIMENTS – 30 SEC

45° NO WIND

CSIRO PYROTRON EXPERIMENTS 1MIN

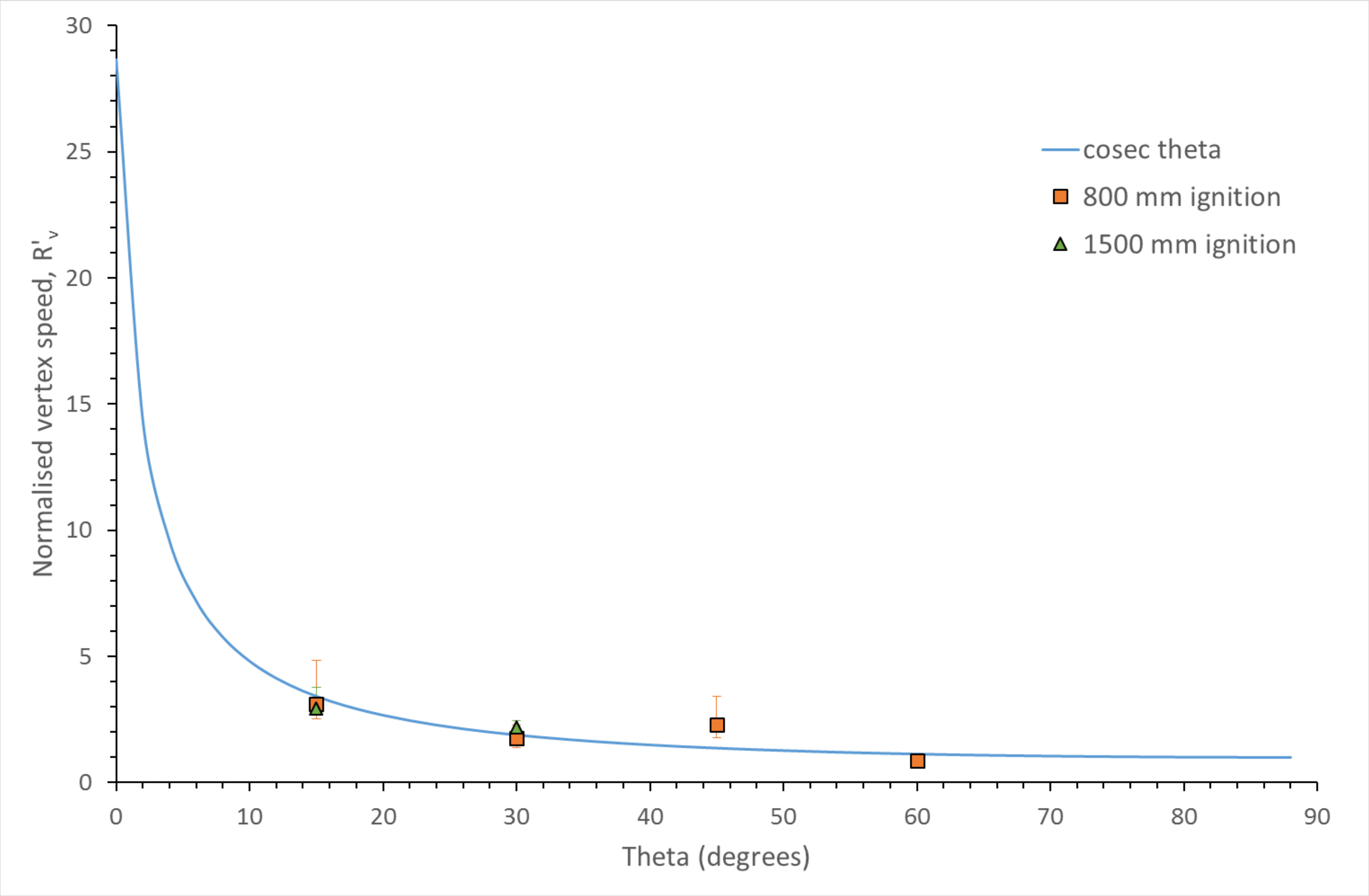
45° NO WIND

CSIRO PYROTRON EXPERIMENTS

FULL SET OF EXPERIMENTS

- 64 ‘V’ shaped fires:
  - 20 x 800 mm ignitions without wind
    - 15, 30, 45 and 60 degree ‘V’ plus control (no ‘V’)
  - 20 x 800 mm ignitions with wind
    - 15, 30, 45 and 60 degree ‘V’ plus control (no ‘V’)
  - 12 x 1500 mm ignitions without wind
    - 15, 30 degree ‘V’ plus control (no ‘V’)
  - 12 x 1500 mm ignitions with wind
    - 15, 30 degree ‘V’ plus control (no ‘V’)
- 24 separated ‘V’ shaped fires (150 mm separation of vertex)
  - 30 and 45 degree, with and without wind
- 8 half ‘V’ shaped fires
  - 15, 30, 45 and 60 degree, with and without wind (no reps)

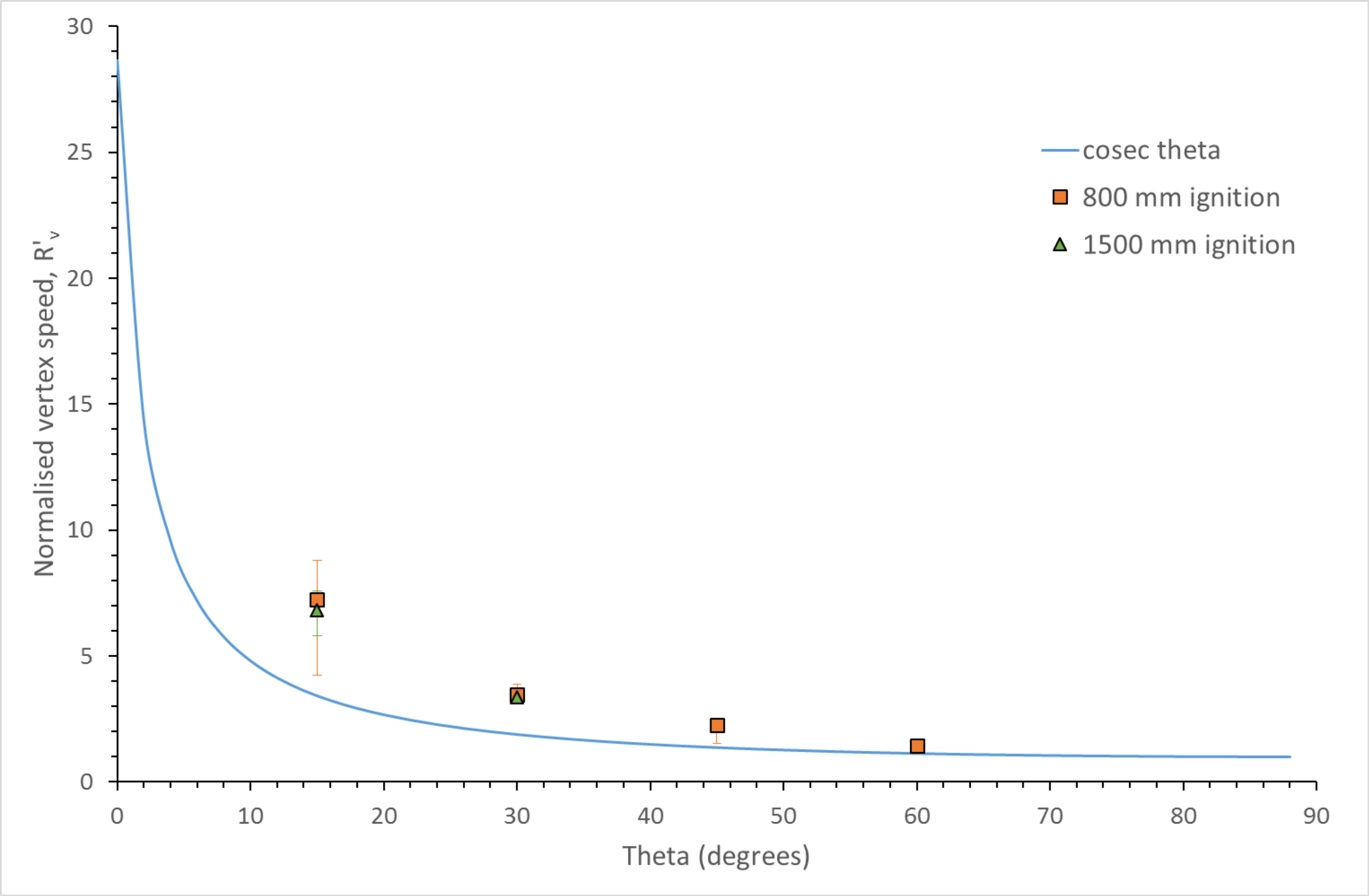
RESULTS: NO WIND CASES



CSIRO PYROTRON EXPERIMENTS – 5 SEC

45° NO WIND

RESULTS: NO WIND CASES

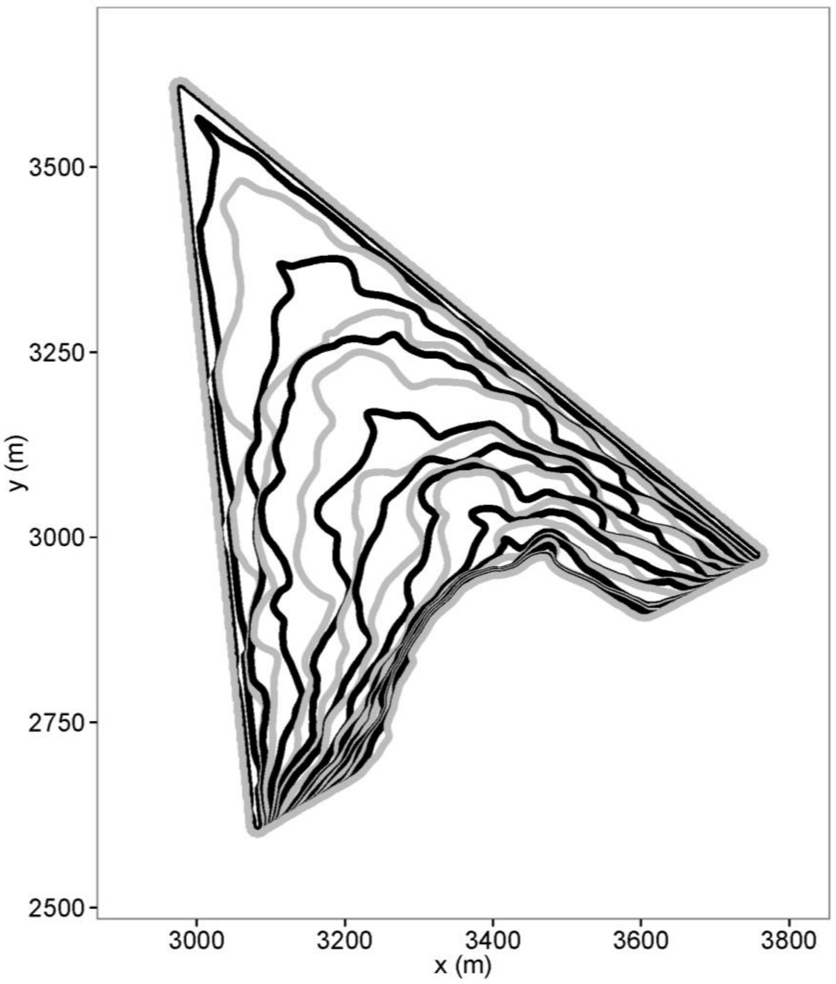


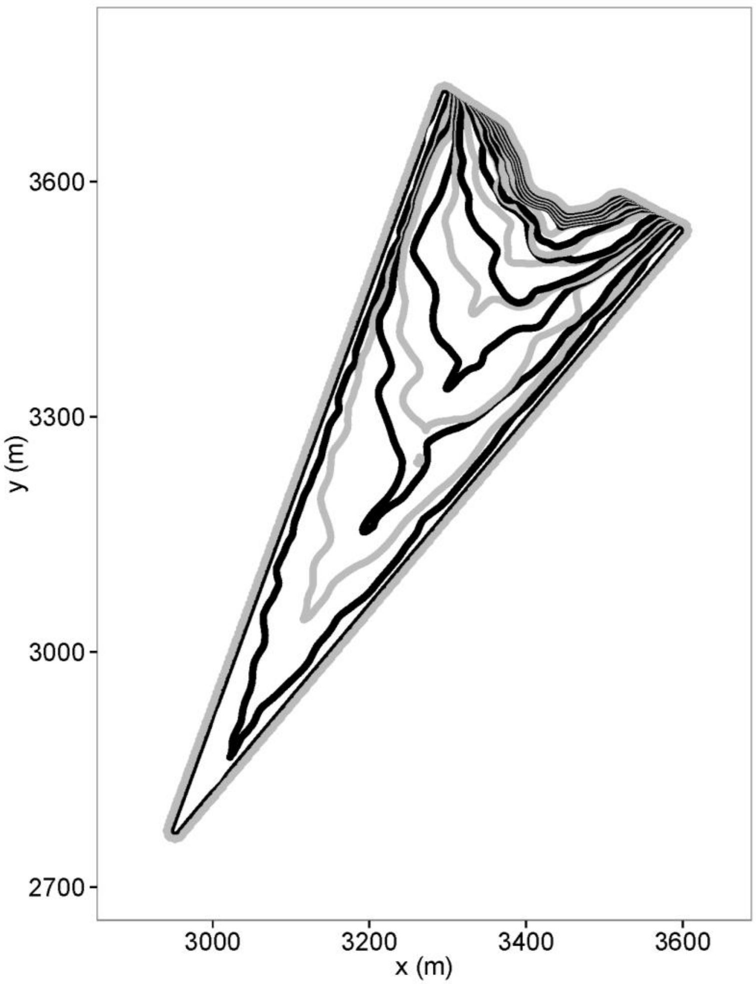
2. RESEARCH ACCOMPLISHMENTS

COUPLED FIRE-ATMOSPHERE MODELLING

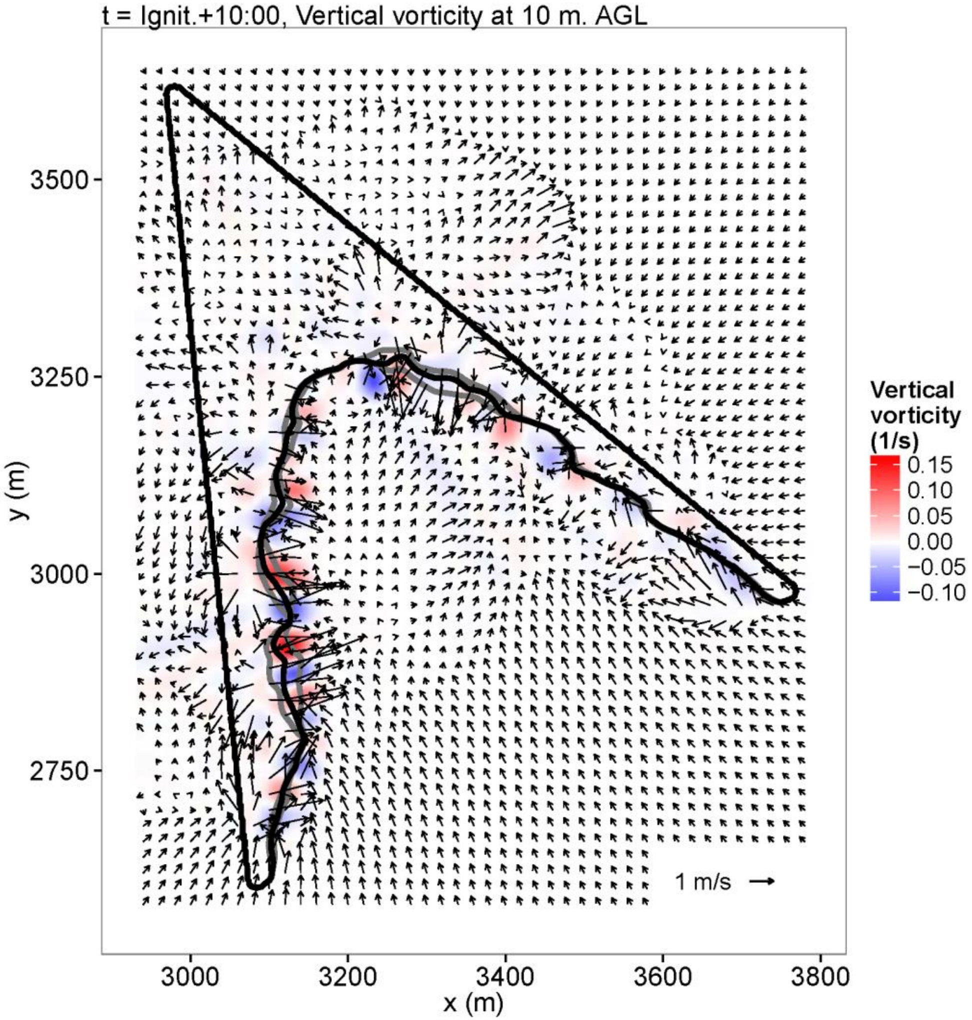
- Coupled simulations using WRF-Fire
- Work conducted by Chris Thomas, PhD Scholar
- V fires, circular arc fires
  – examining curvature effects
- Work in progress – dynamic ember transport

EXAMINING THE EFFECTS OF FIRE LINE GEOMETRY

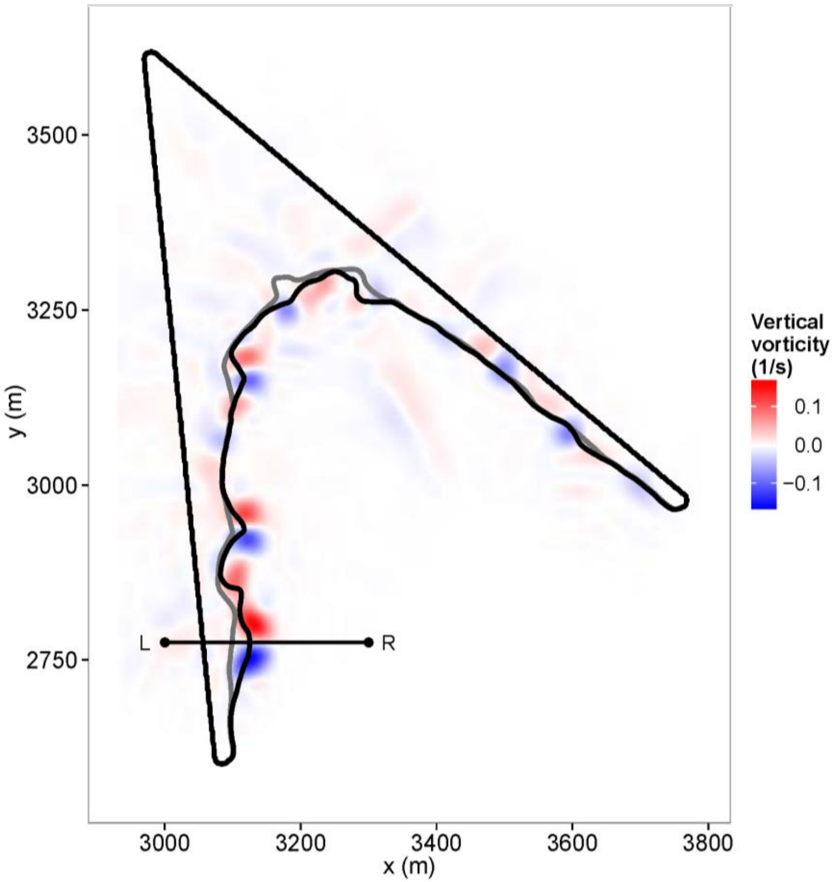


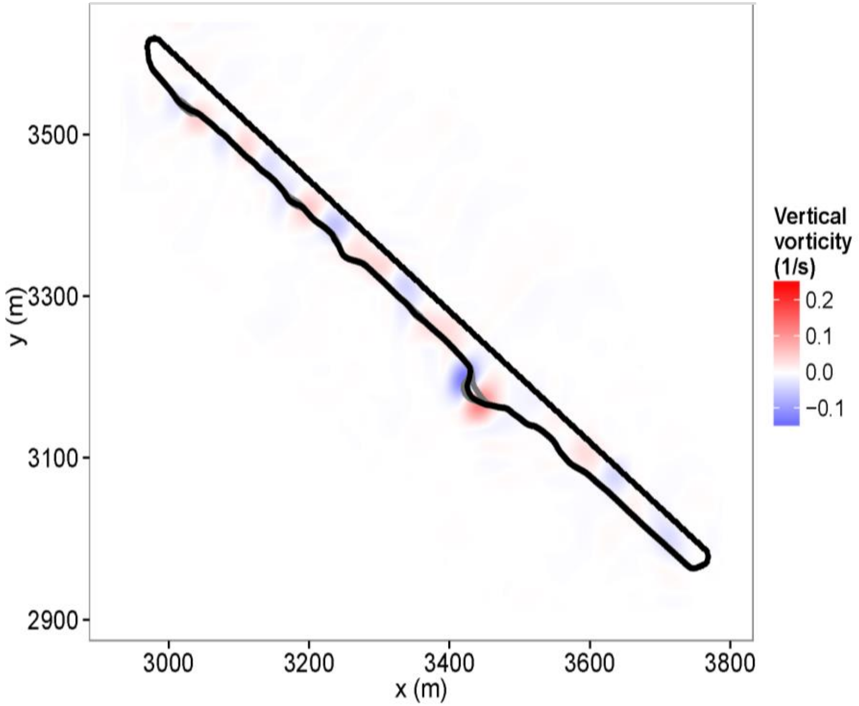


EXAMINING THE EFFECTS OF FIRE LINE GEOMETRY

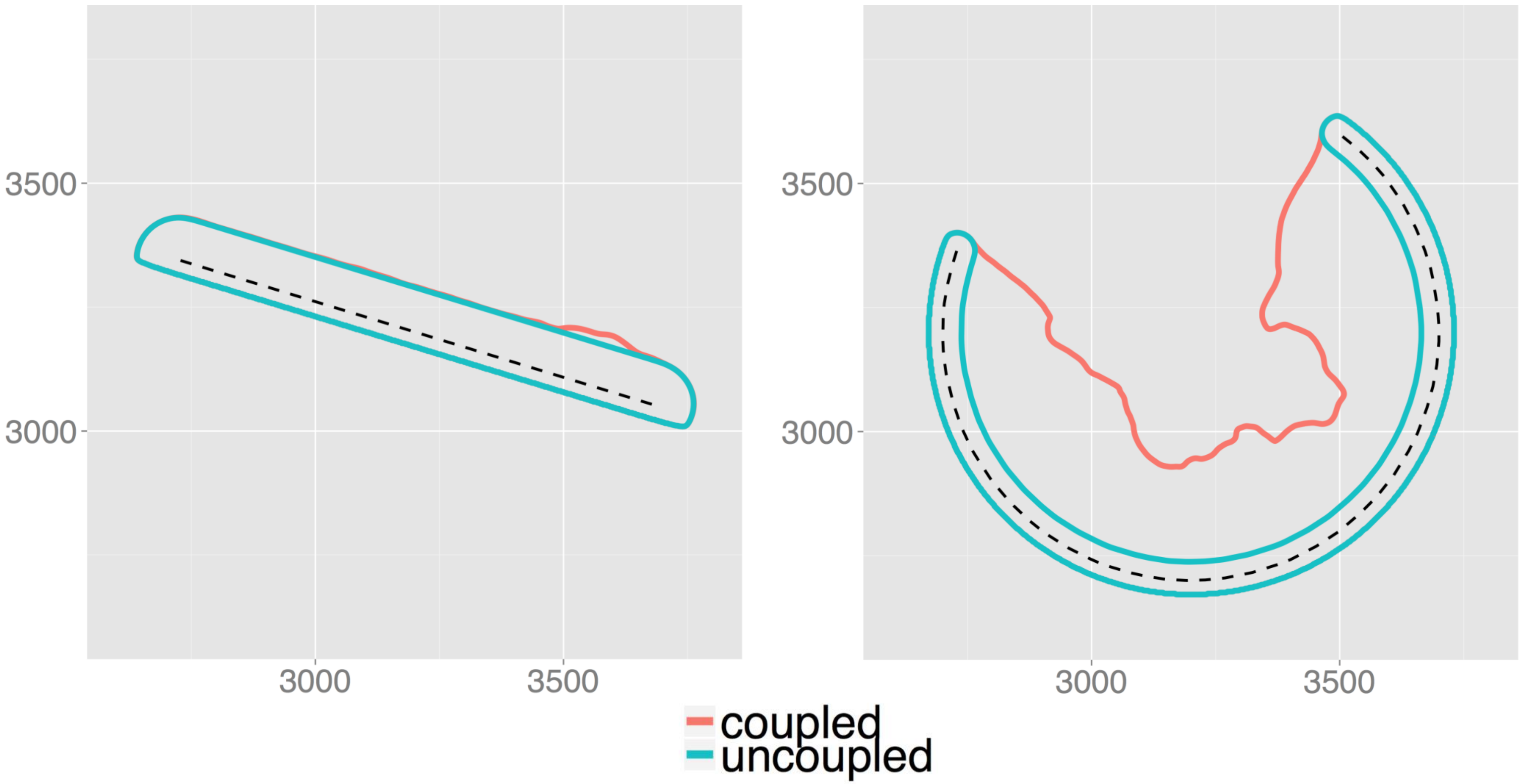


EXAMINING THE EFFECTS OF FIRE LINE GEOMETRY



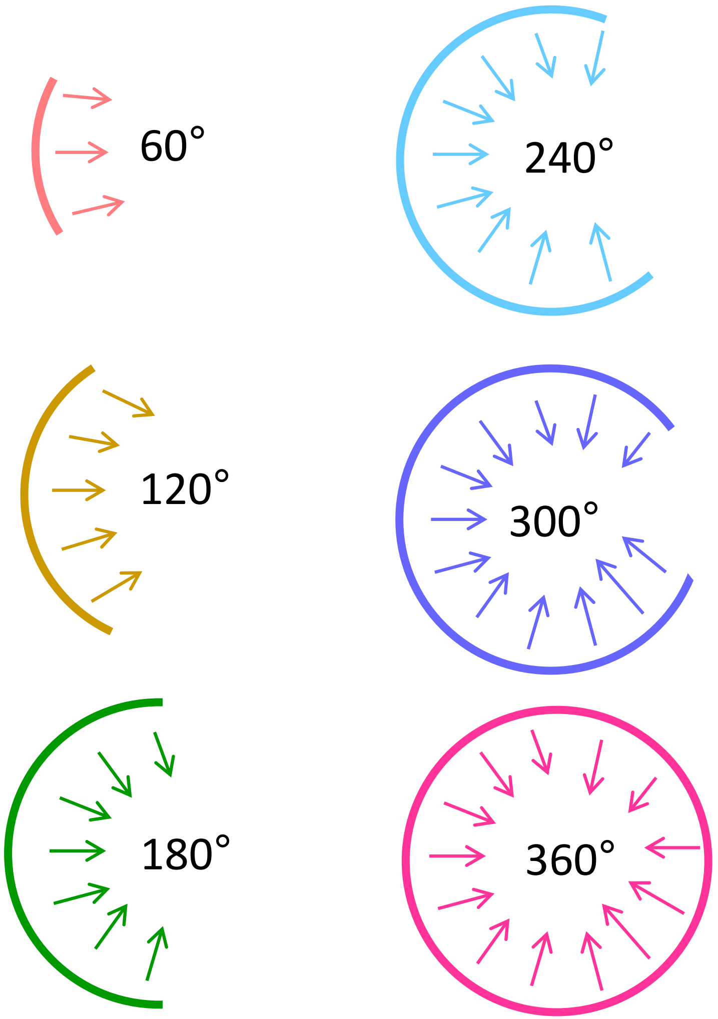


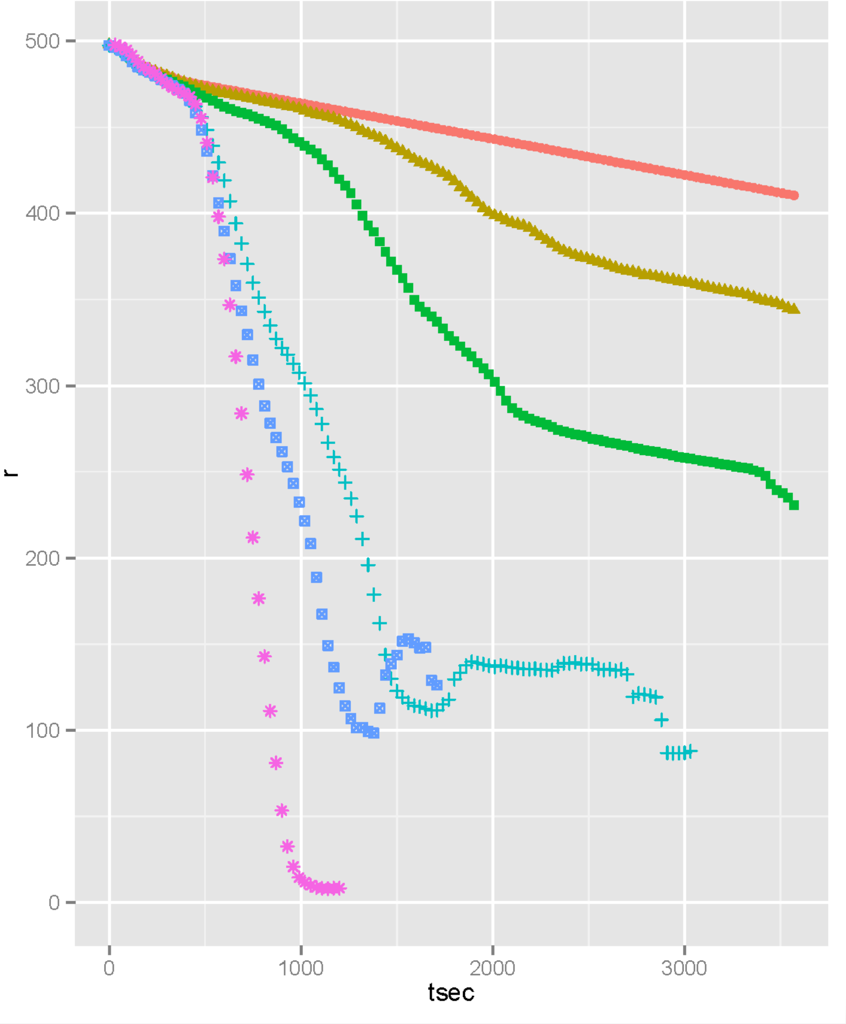
EXAMINING THE EFFECTS OF FIRE LINE GEOMETRY



CIRCULAR ARC FIRES

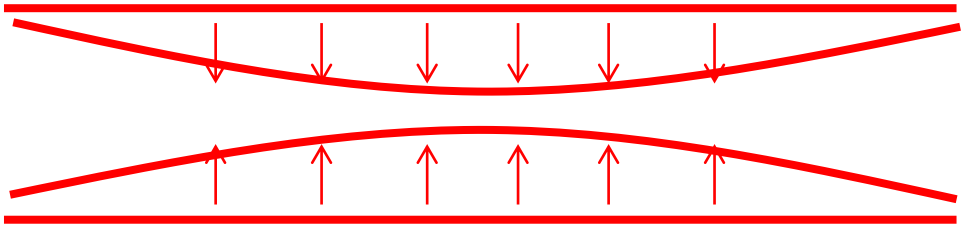
DIFFERENT GEOMETRIES WITH EQUAL CURVATURE

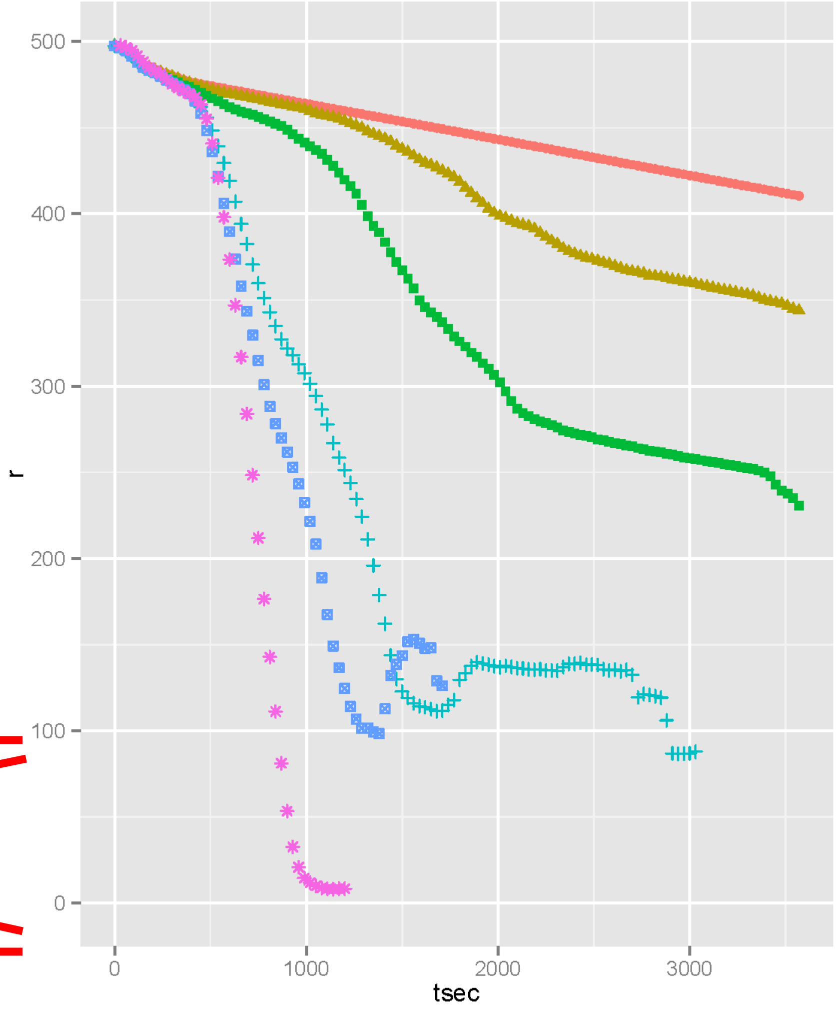




CIRCULAR ARC FIRES – EQUAL CURVATURE

These results effectively tell us that while curvature is a useful quantity to predict fire spread in some circumstances, it does not reflect the actual processes driving the dynamic fire propagation.



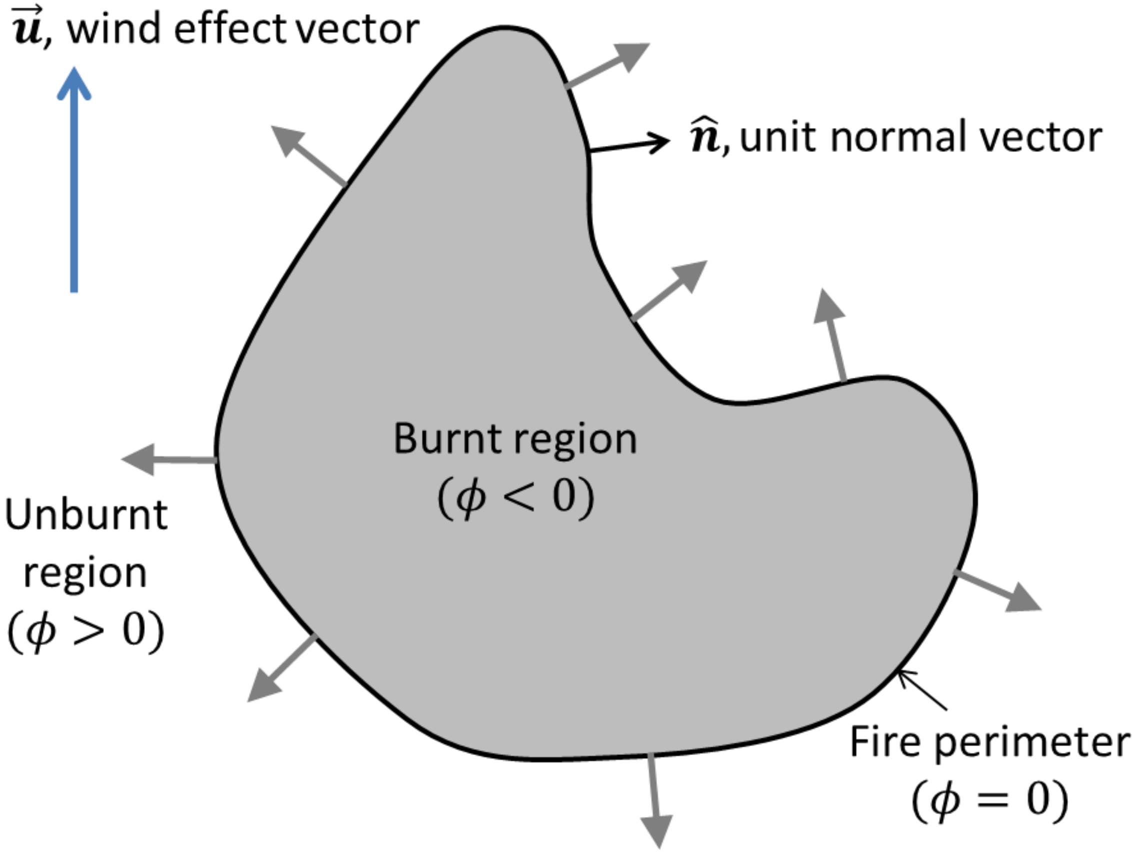


3. RESEARCH ACCOMPLISHMENTS

DYNAMIC FIRE SIMULATION

- Level set formulation of fire spread simulator
- Incorporating fire line curvature as a predictor of rate of spread
- Built into CSIRO Spark framework
    - Well-suited for incorporating dynamic effects (VLS, eruptive fire behaviour, mass spotting with dynamic coalescence)
- Moving beyond curvature dependent models

LEVEL SET METHOD WITH FIRE LINE CURVATURE

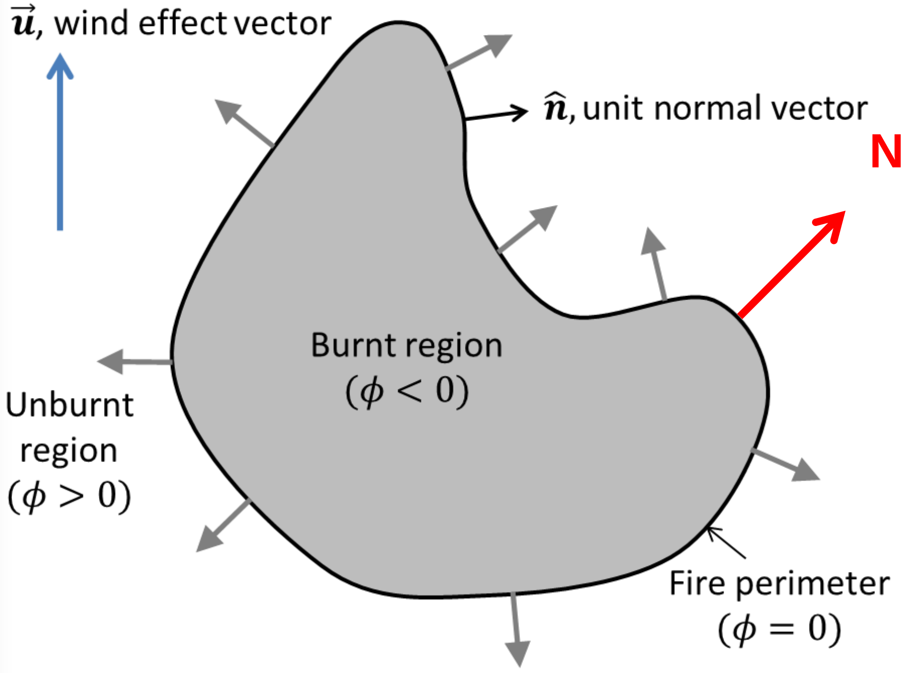


Curvature is defined as the divergence of the unit normal vector field:

$$\kappa = \nabla \cdot \mathbf{n}$$

LEVEL SET METHOD WITH FIRE LINE CURVATURE

Defined in terms of the level set function ϕ, which measures the distance from the interface (fire front).

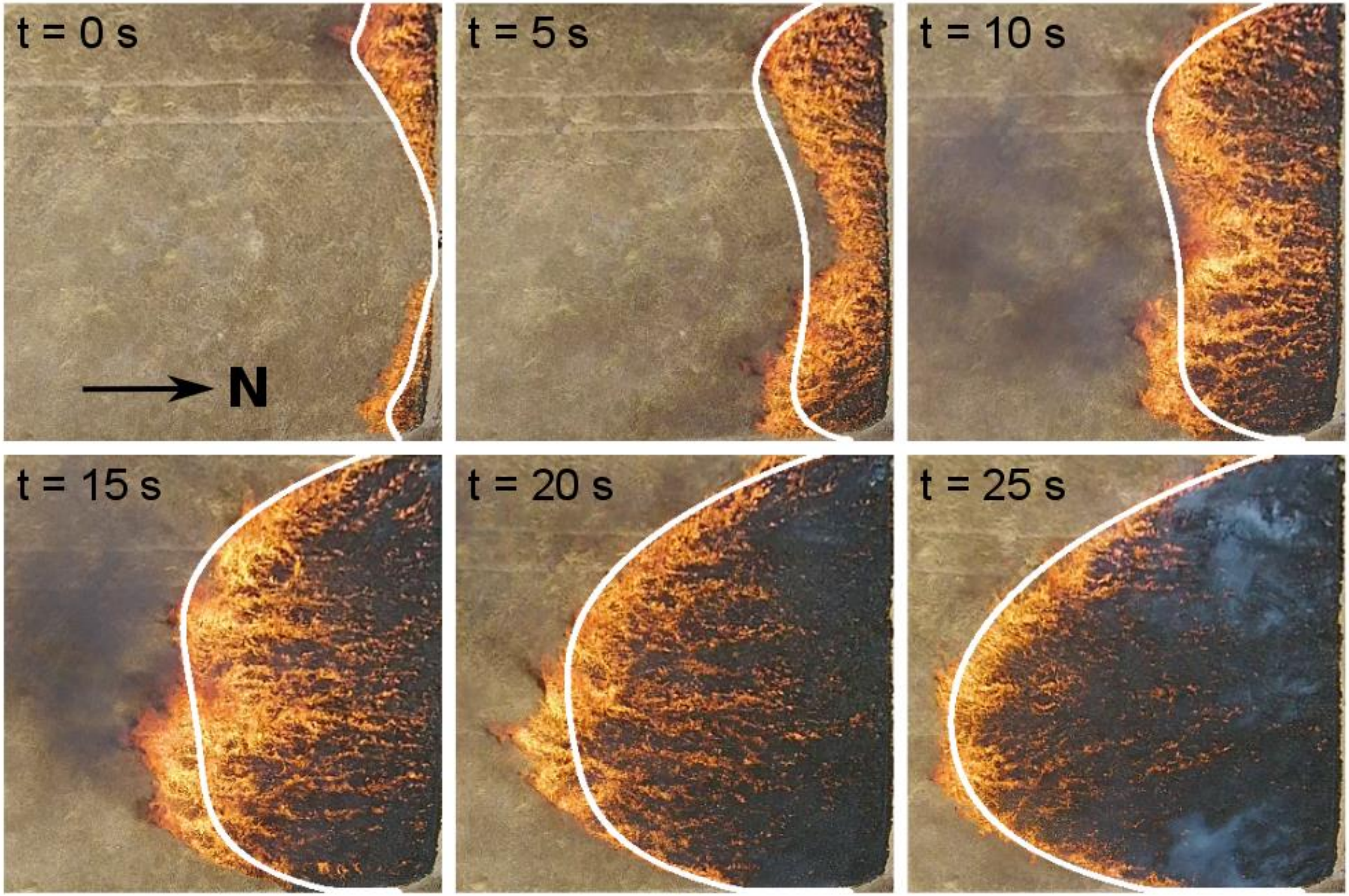


Normal speed

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

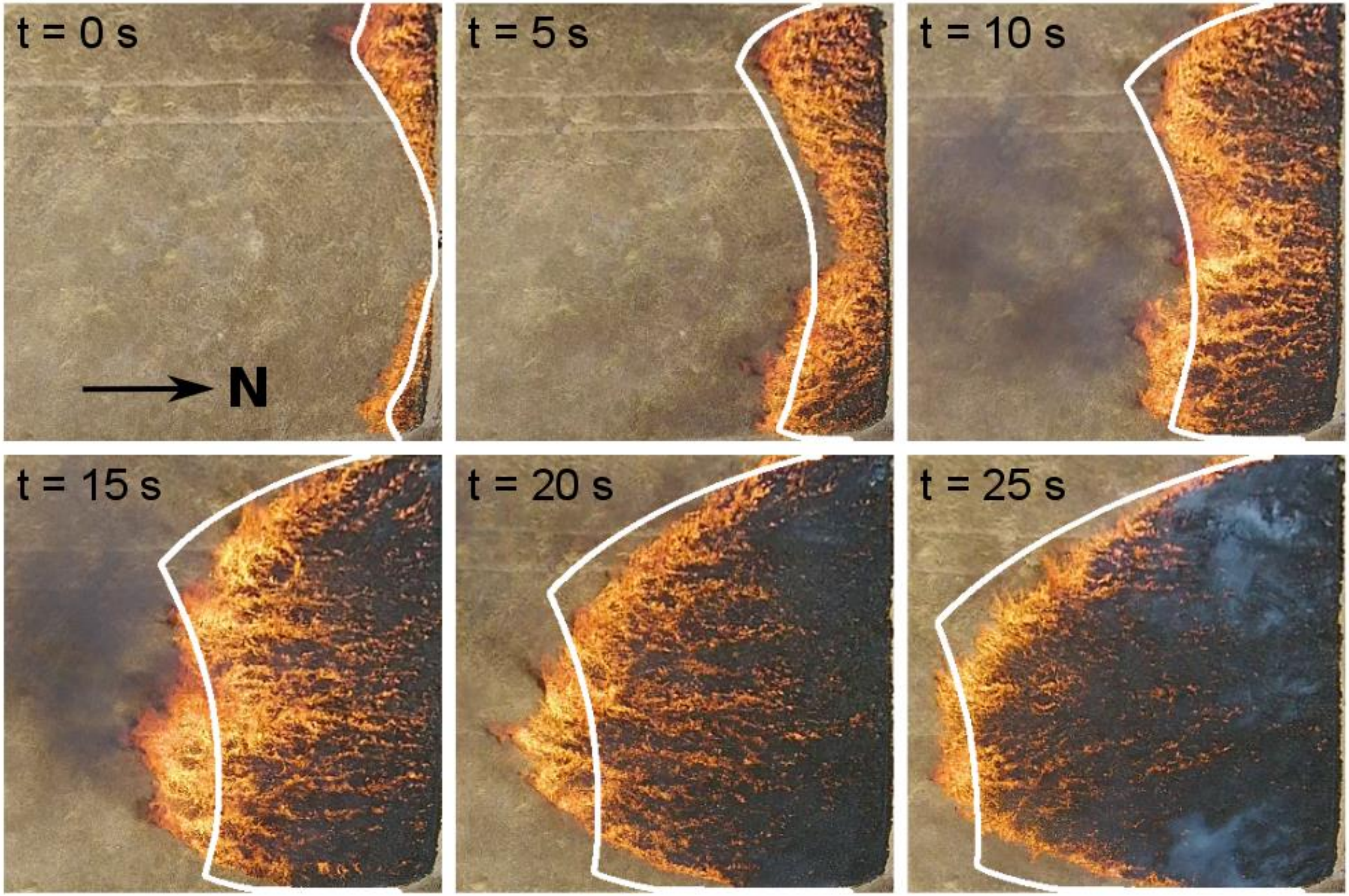
$$s(\alpha) = \alpha\kappa$$

WIND-DRIVEN FIRE SPREAD



Curvature dependence

WIND-DRIVEN FIRE SPREAD

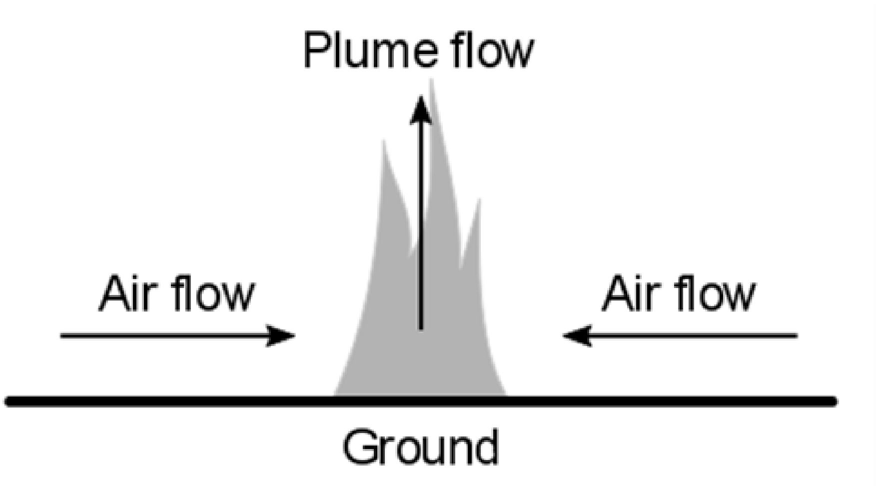


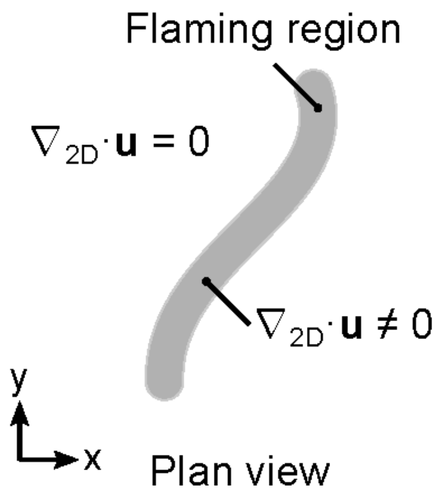
No curvature dependence

POTENTIAL FLOW

WHAT DO WE DO WHEN CURVATURE DOESN’T WORK?

BORROW AN IDEA FROM ELECTROSTATICS...!





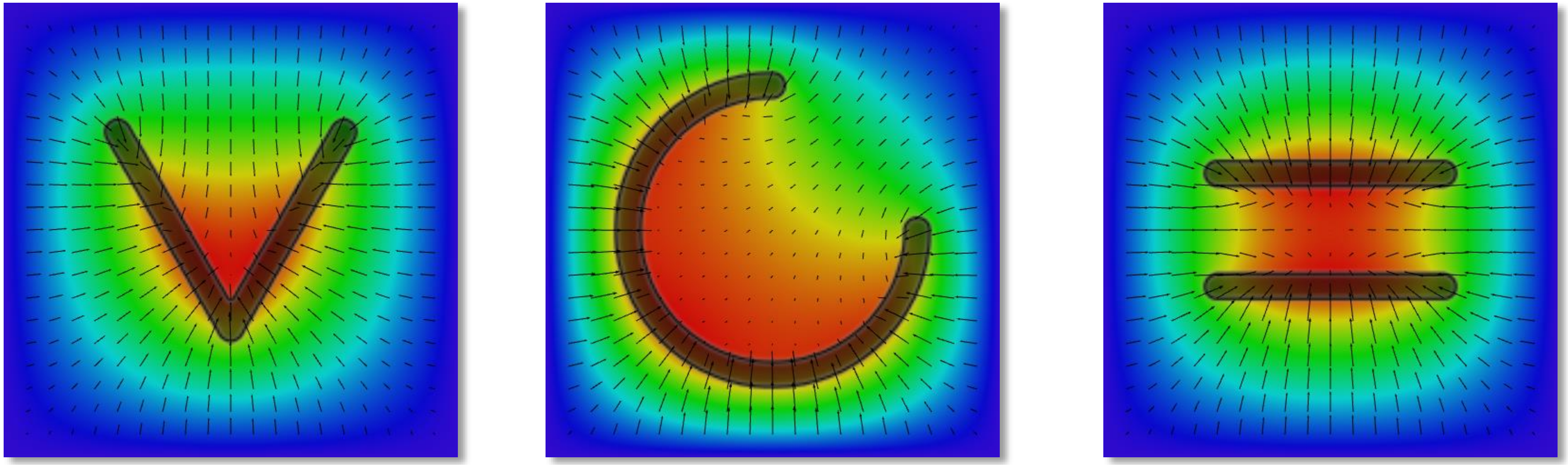
- Consider flow in 2D plane near ground
- Assume plume acts like a sink term

The strength of the inflow can be modelled as a kind of ‘**pyrogenic potential**’.

POTENTIAL FLOW

BEYOND FIRE LINE CURVATURE…

- Potential given by Poisson equation, $\Delta\Psi = \rho$, air flow is $\nabla\Psi$
- Poisson equation is much nicer to work with than curvature!
- Analytic solution for any 2D geometry can be found.

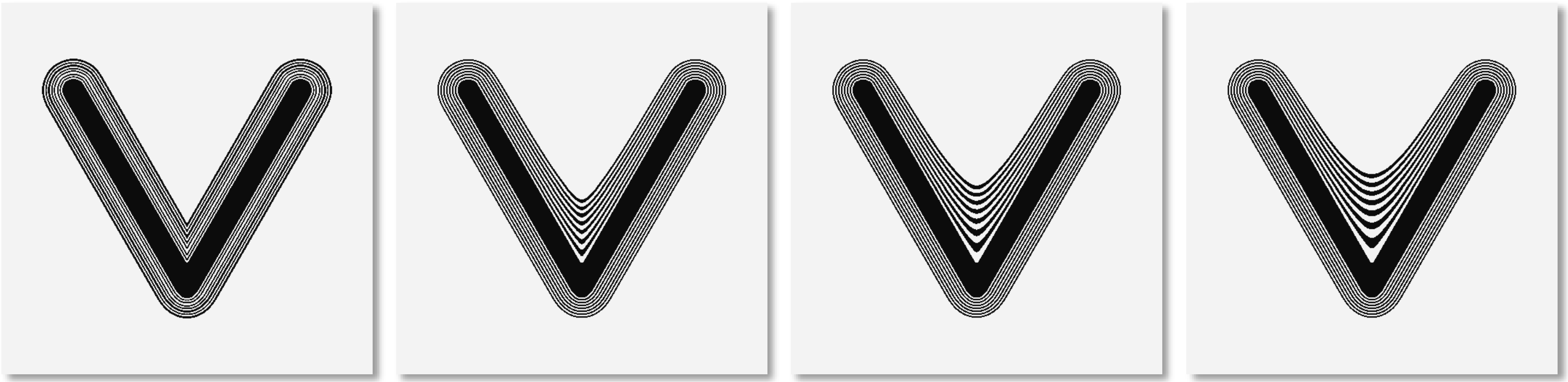


$$\frac{\partial\phi}{\partial t} + s\left\|\nabla\phi\right\| + \left(\mathbf{u}(\gamma) + \nabla\Psi\right)\cdot\nabla\phi = 0, \quad \Delta\Psi = \rho$$

POTENTIAL FLOW

RESULTS

- Isochrones from V fires



No potential

Pyrowind = $\nabla\psi$

Pyrowind = $2\nabla\psi$

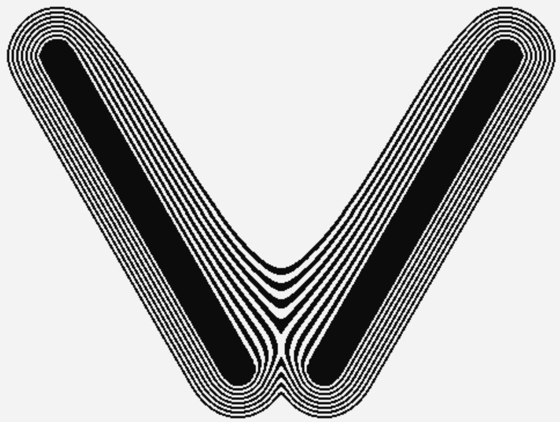
Pyrowind = $3\nabla\psi$

- The pyrogenic potential manifests as a ‘curvature effect’

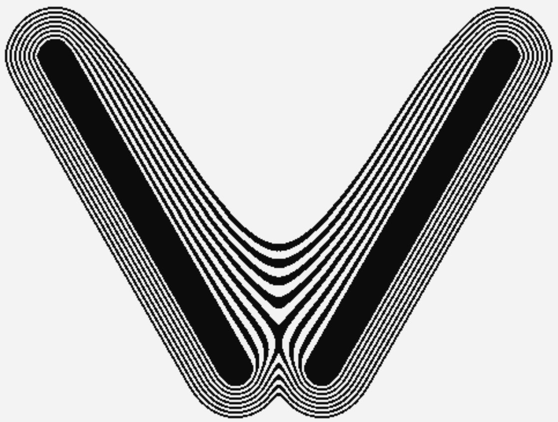
POTENTIAL FLOW

RESULTS

- ➢ Isochrones from separated V fires



Pyrowind = $2\nabla\psi$



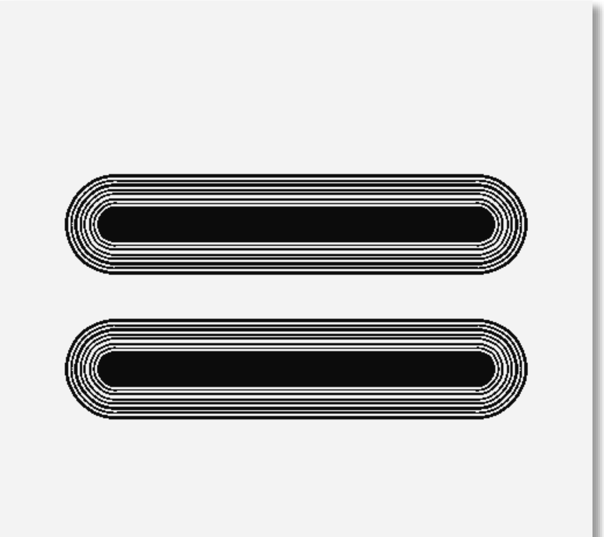
Pyrowind = $3\nabla\psi$

- ➢ The pyrogenic potential produces a ‘curvature effect’ even when there is no curvature…!

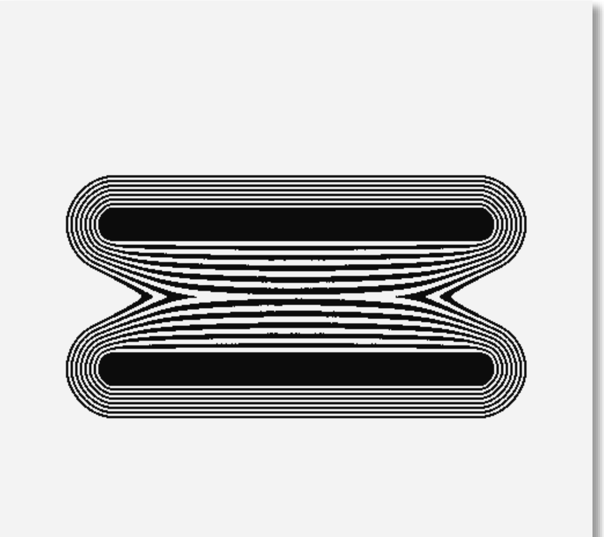
POTENTIAL FLOW

RESULTS

- Isochrones from parallel lines



No potential



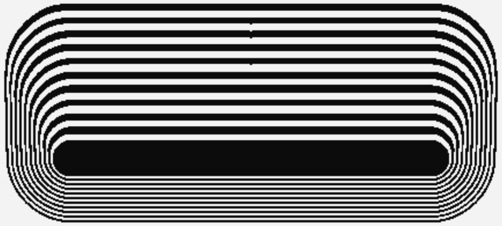
Pyrowind = $\nabla\psi$

- Fire lines ‘attract’ and merge

POTENTIAL FLOW

RESULTS

- Isochrones from single line



No potential, wind only

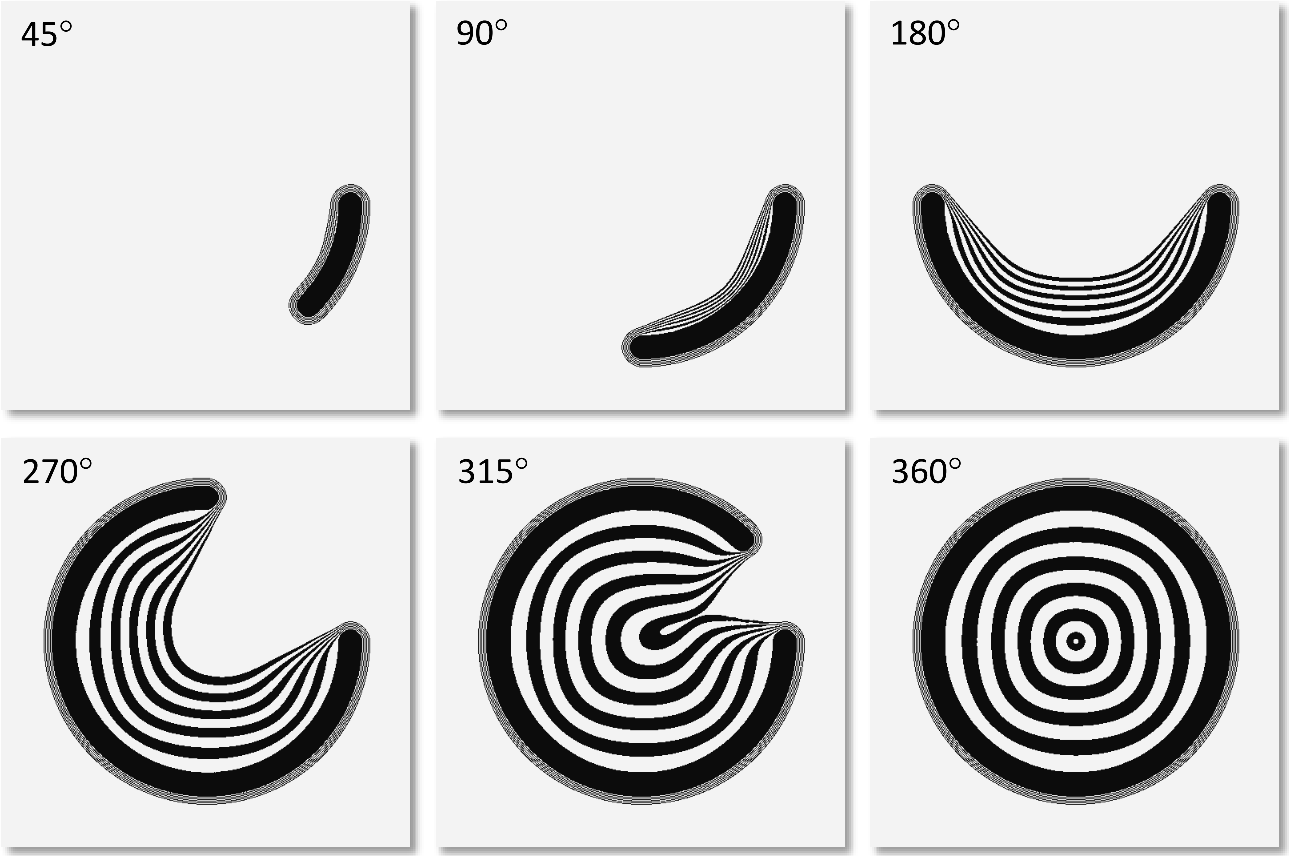
Wind = const + $\nabla\psi$

- Natural rounding of fire front
- Previously demonstrated only in fully coupled fire-atmosphere models....

POTENTIAL FLOW

RESULTS

- Isochrones from initial arcs



- Results seem very close to fully coupled simulations.

PROGRESS AGAINST MILESTONES

1. **Journal article published**

   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*. In press, accepted 22 August 2016.

2. **Journal article under review**

   Thomas, C.M., Sharples, J.J., Evans, J.P. (2016) Modelling the dynamic behaviour of junction fires with a coupled atmosphere-fire model. *International Journal of Wildland Fire* (under review).

3. **Journal article under review**

   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).

PROGRESS AGAINST MILESTONES

4. **Journal article in preparation**

   Sullivan, A.L., Swedosh, W., Sharples, J.J., Hilton, J.E. (2016) Experimental analyses of fire line interactions in junction fires. To be submitted to *Combustion and Flame*.

5. **Journal article in preparation**

   Hilton, J.E., Swedosh, W., Sharples, J.J., Sullivan, A.L. (2016) Modelling dynamic fire propagation using pyrogenic potential flow. To be submitted to *International Journal of Wildland Fire*.

6. **Conference paper published**

   Thomas, C. M., Sharples, J. J., Evans, J. P. (2015). Pyroconvective interaction of two merged fire lines: curvature effects and dynamic fire spread. In T. Weber, M. J. McPhee, & R. S. Andersen (Eds.), MODSIM2015, 21st International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand. Gold Coast.

UTILISATION ROADMAP

CLUSTER NAME: NEXT GENERATION FIRE MODELLING

PROJECT NAME:

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

- **What need is being addressed?**

  Currently there is no scientific understanding of how spot fires coalesce. There is currently no capacity to model (or predict in any way) how spot fire coalescence contributes to large scale fire spread and extreme bushfire development.

- **What is the utilisation product?**

  Fundamental knowledge that can be readily incorporated into emerging fire spread modelling frameworks (i.e. Spark). A better (scientific) basis for development of measures of relevance to the National Fire Danger Rating Project, e.g. Convective power, FireCAPE, etc.

- **What difference will this utilisation make?**

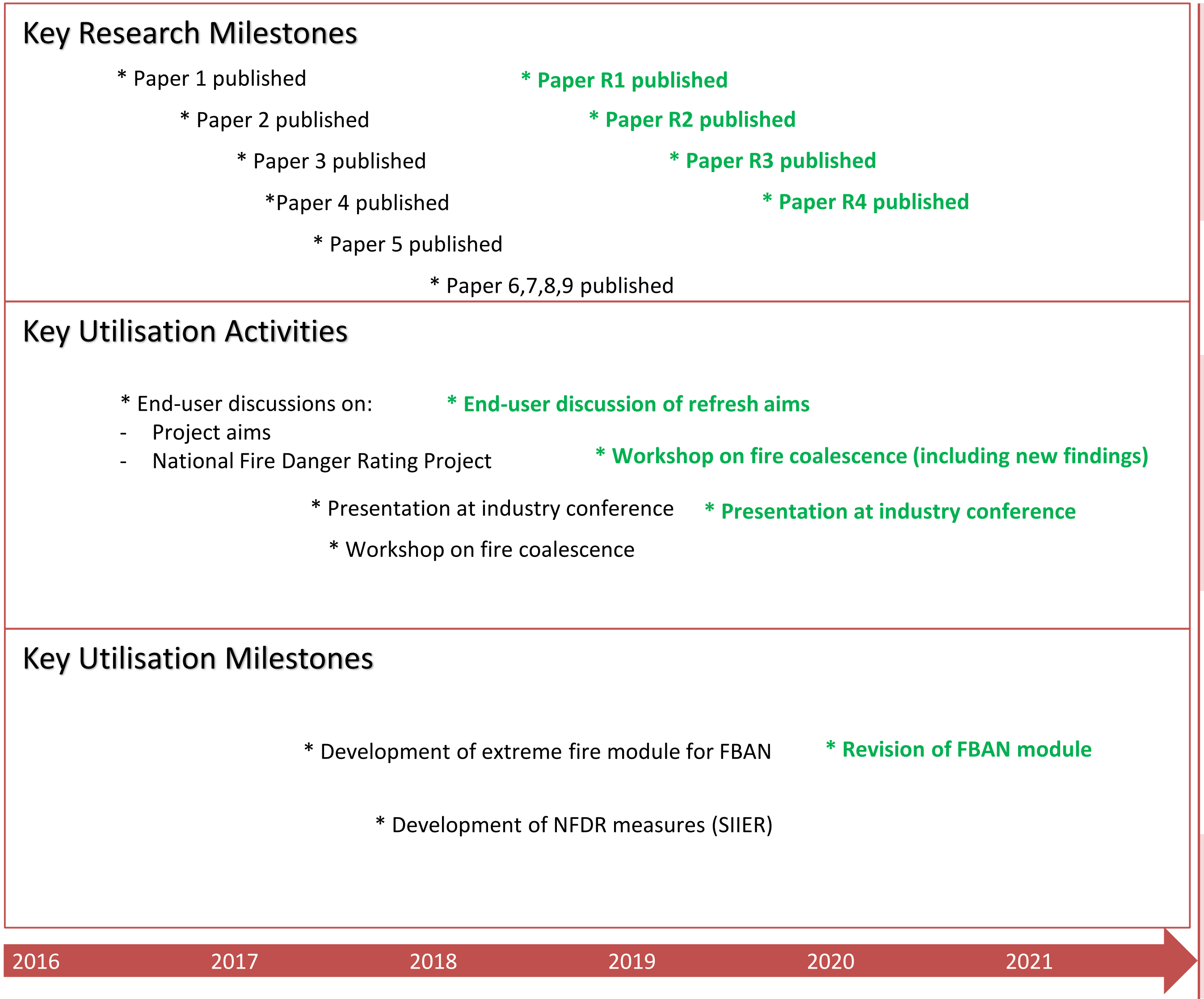
  Provide enhanced understanding of extreme bushfire development. Provide fire agencies with better guidance for response planning.

- **Who wants it?**

  Fire agencies for improved operational response. AFAC/fire agencies for improved training.

UTILISATION TITLE: FIRE COALESCENCE (DRAFT OCT 2016)

How will it be done?



Key Research Milestones

* Paper 1 published

* Paper 2 published

* Paper 3 published

*Paper 4 published

* Paper 5 published

* Paper 6,7,8,9 published

*** Paper R1 published**

*** Paper R2 published**

*** Paper R3 published**

*** Paper R4 published**

Key Utilisation Activities

* End-user discussions on:
- Project aims
- National Fire Danger Rating Project

* Presentation at industry conference

* Workshop on fire coalescence

*** End-user discussion of refresh aims**

*** Workshop on fire coalescence (including new findings)**

*** Presentation at industry conference**

Key Utilisation Milestones

* Development of extreme fire module for FBAN

* Development of NFDR measures (SIIER)

*** Revision of FBAN module**

Who is doing it?
- *UNSW*
- *CSIRO*
- *NSW RFS*
- *BoM*
- *Others…?*

Who needs to be involved?
- *Fire and emergency service agencies*
- *AFAC Predictive Services Group*

What are the key challenges?
- *Communicating highly technical content*
- *Provision of a compatible modelling platform (including development and maintenance)*

What are the key opportunities?
- *Incorporation of dynamic influences in fire spread models without the computational overheads*
- *State of the art education and training for extreme fire behaviours*

What will it cost?
- *Depends on the depth of utilisation and level of support for the process.*