An introduction to physics-based simulation of wildfires

- Dr Duncan Sutherland

Today’s talk

Introduction

- My place in wildfire science
- Simulation method

Physics-based fire simulations

- Validation study
- The effect of ignition protocol
- Junction and oblique line fires

Future (and other present) work

- Gravity currents
- Ember storms

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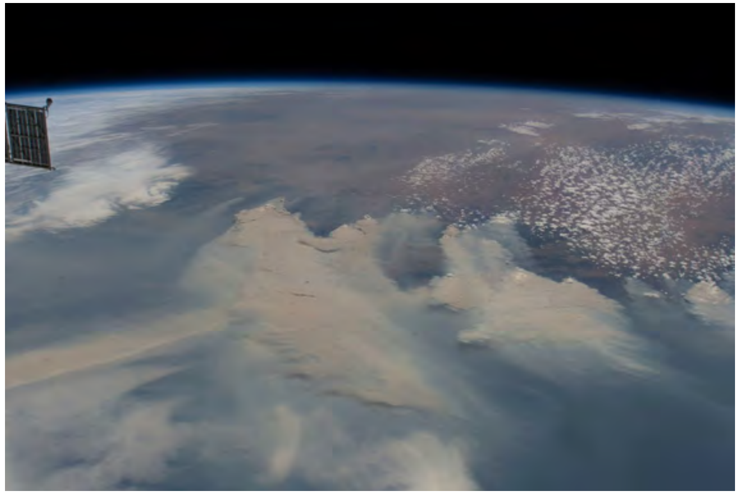
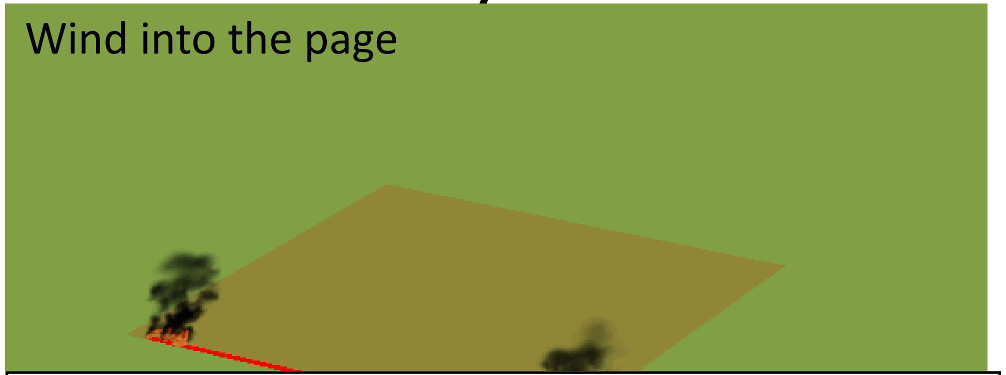
Wildfires (bushfires) are devastating



What is my research and why do I do it?



Physics-based fire simulation using (W)FDS

Capture reality as faithfully as possible

Discover the most relevant physics

Build better operational models

Provide the most realistic predictions

Research identity

- Applied mathematics PhD – numerical methods for 2D turbulence
- Postdoc in a fire safety engineering group Vic Uni
- Lecturer (maths), bushfire research group UNSW
- Primarily working on fluid dynamics problems motivated by wildfire
- Additional mathematical problems motivated by wildfire

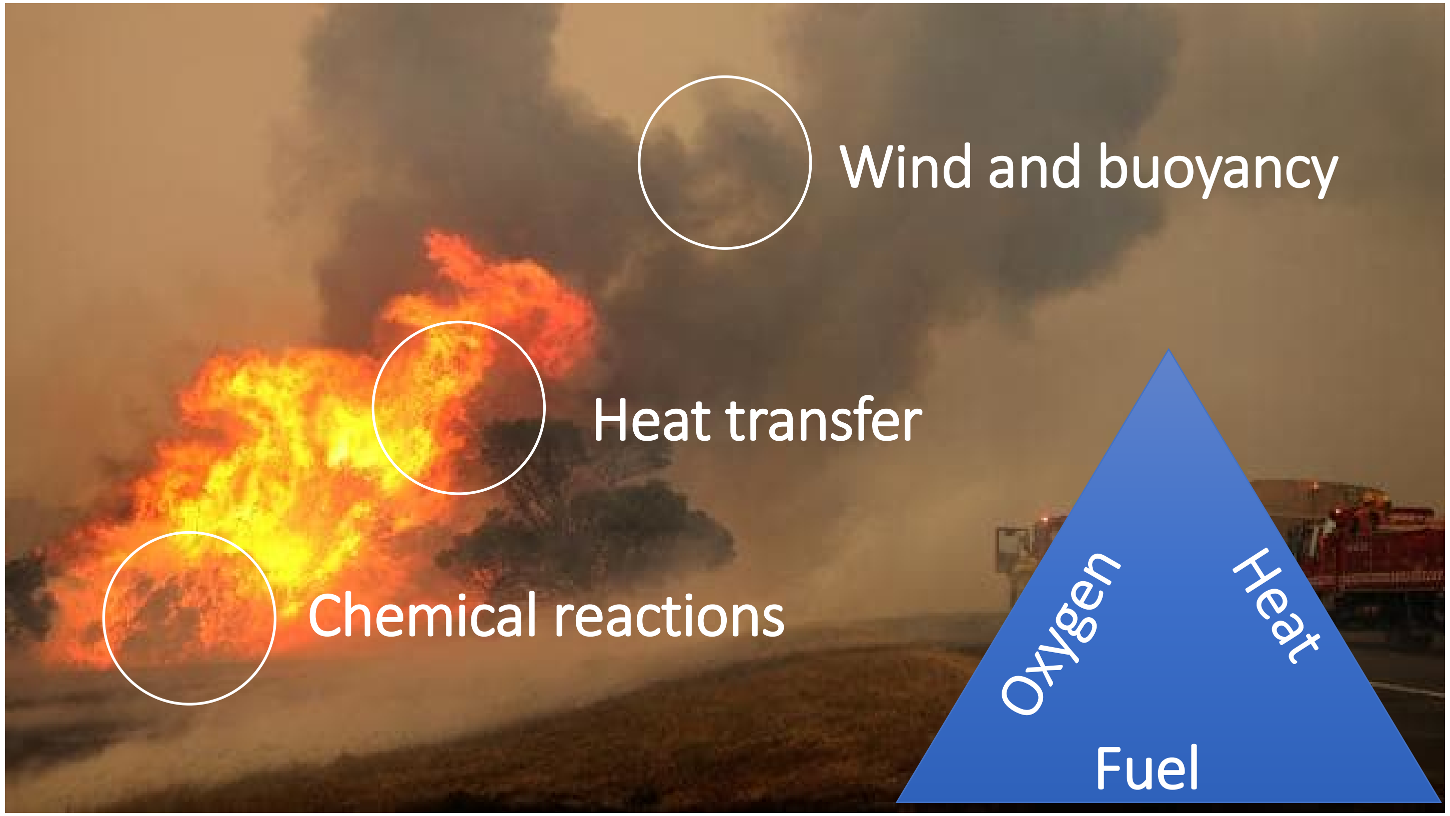
Research identity

Simulations inform:

- Classical applied mathematics modelling
- Stochastic PDE simulations
- Dynamical systems analysis
- Machine Learning models
- Experimental practice
- Sustainable development of the built environment
- Fire management practice

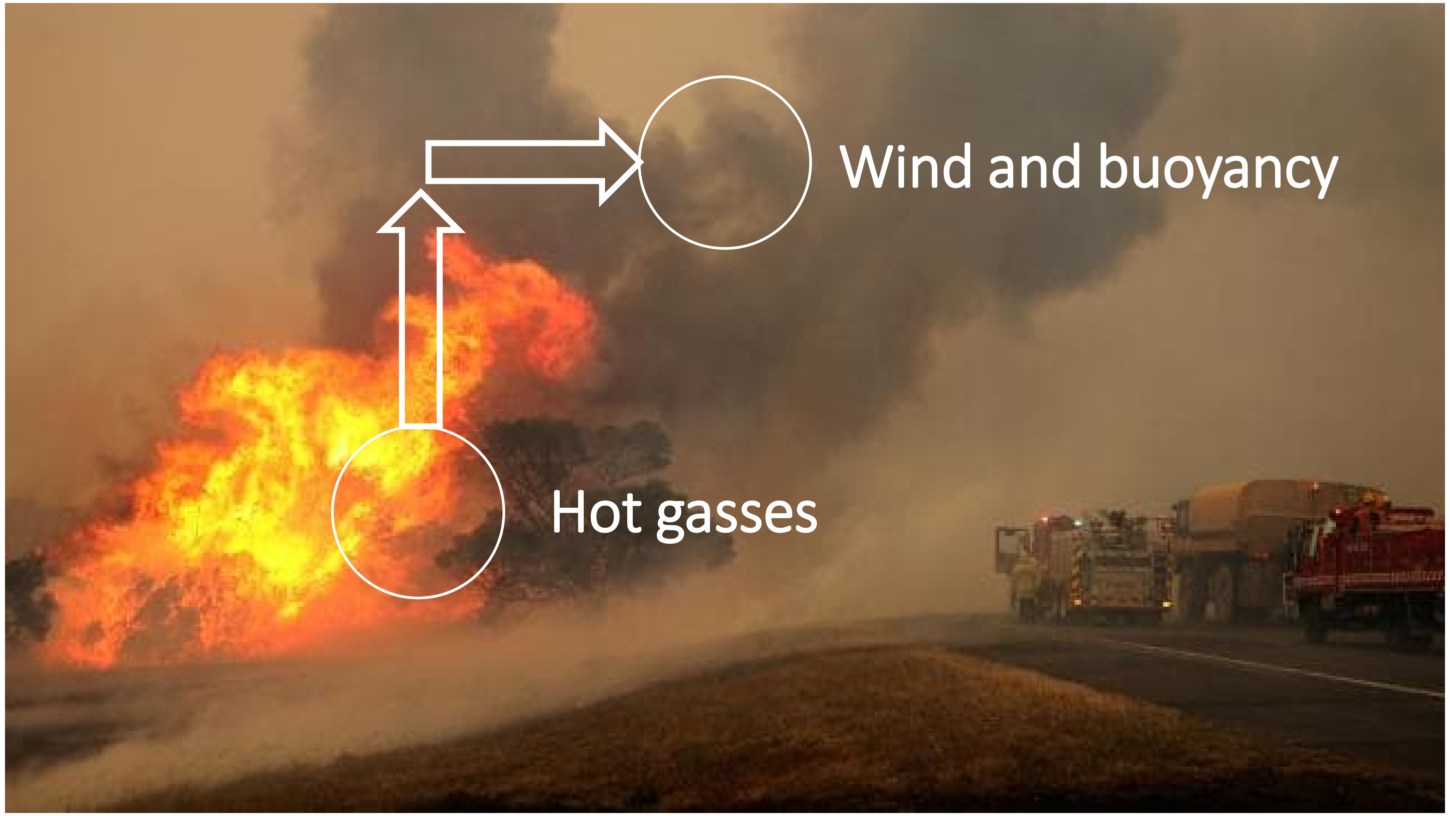
Network

Important factors in bushfires

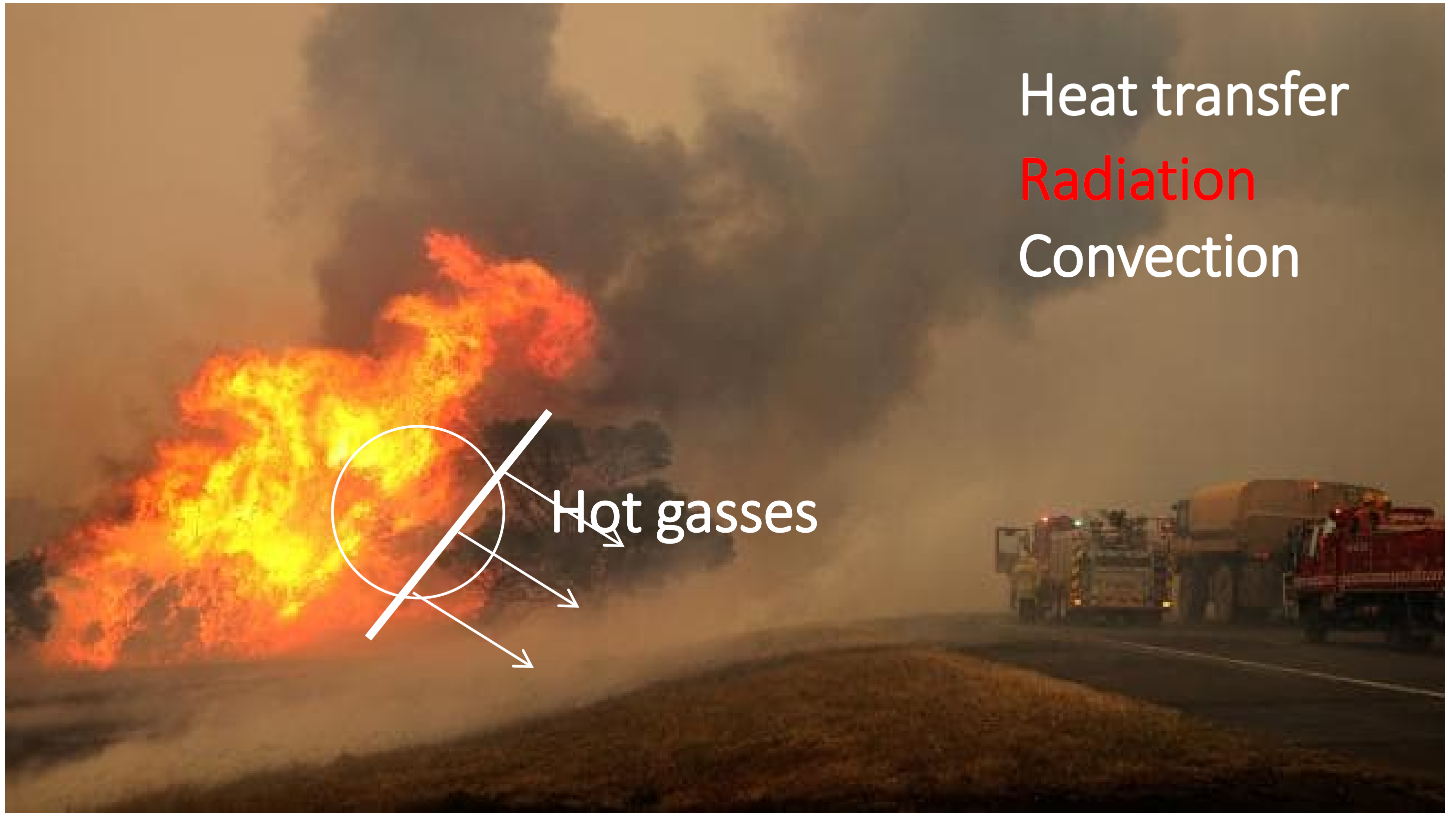


Important factors in bushfires

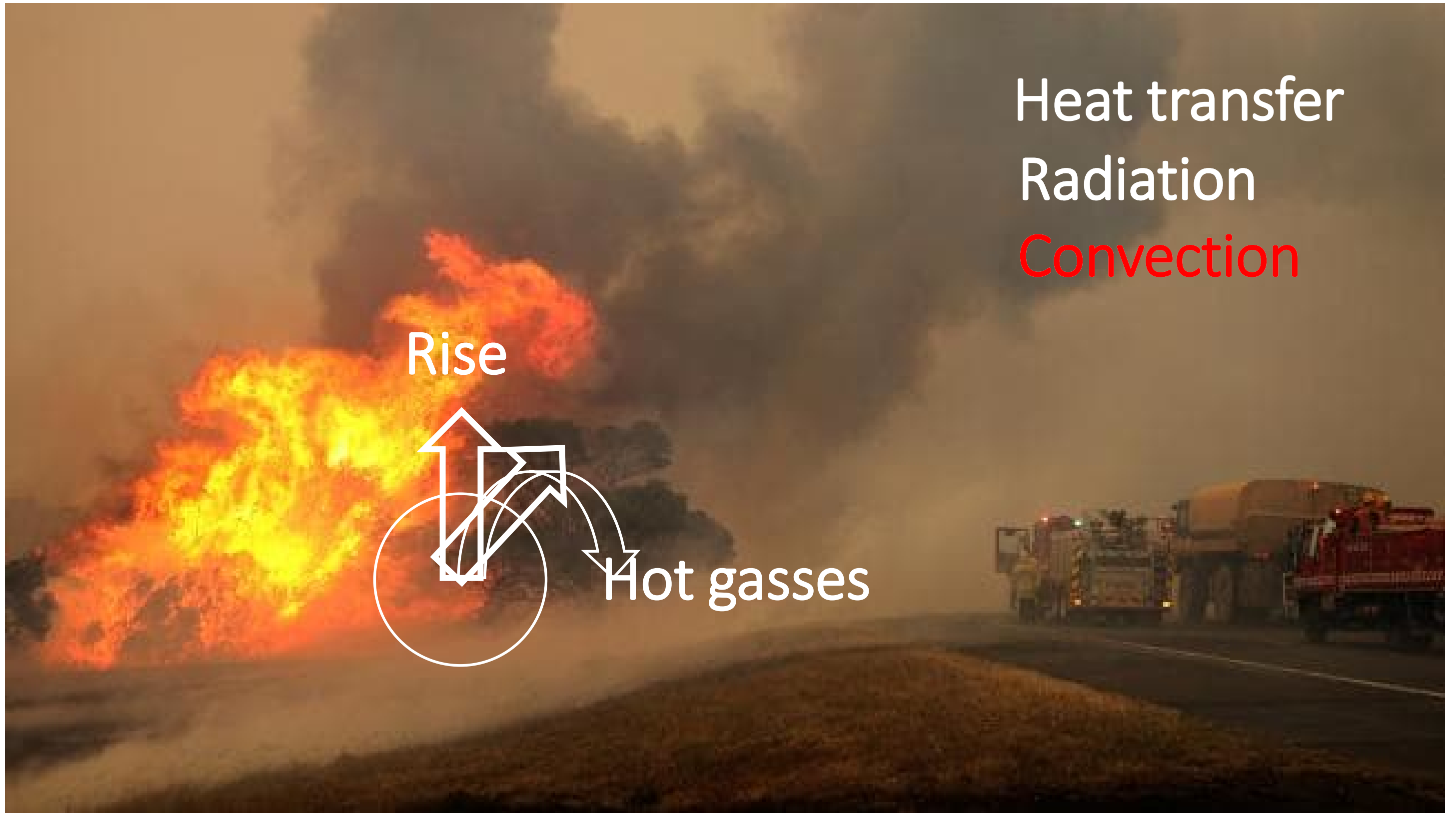
Wind and buoyancy



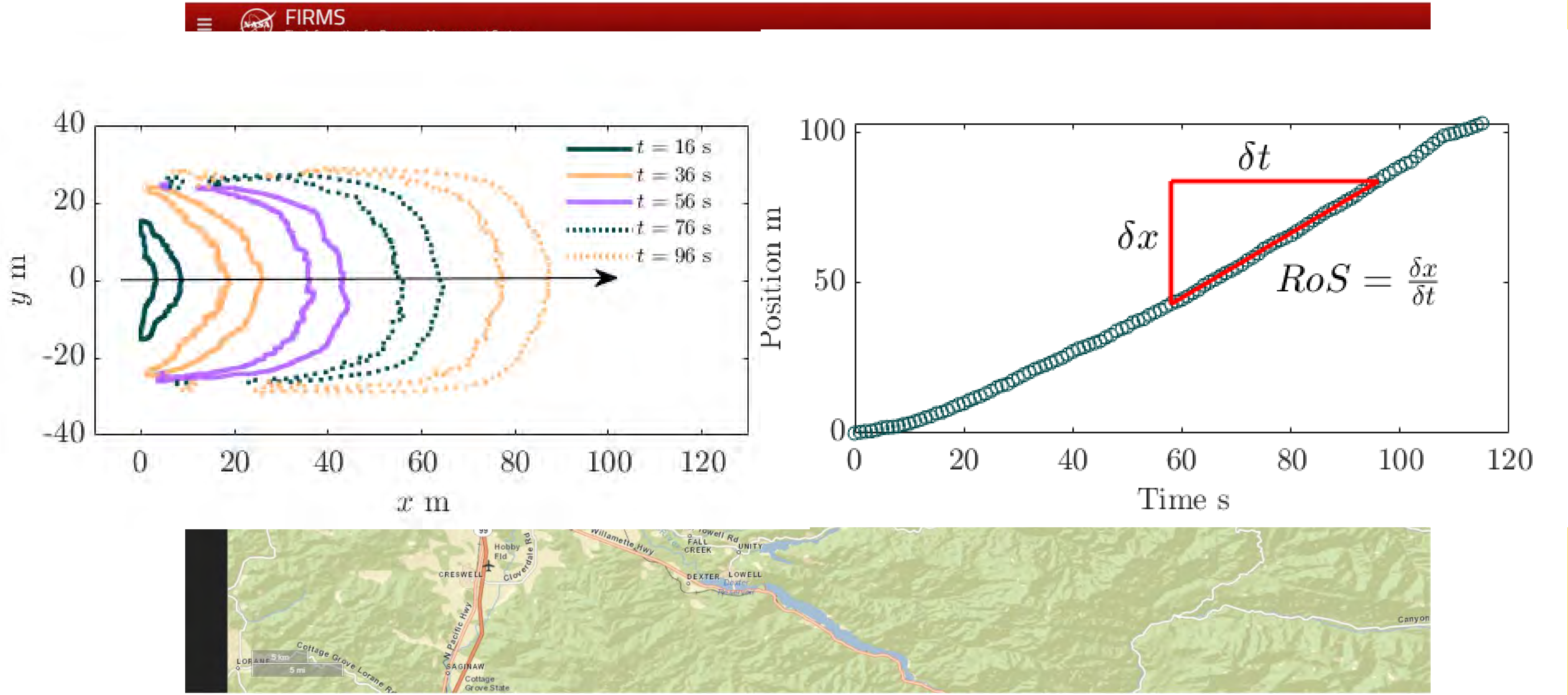
Heat transfer by radiation



Heat transfer by convection



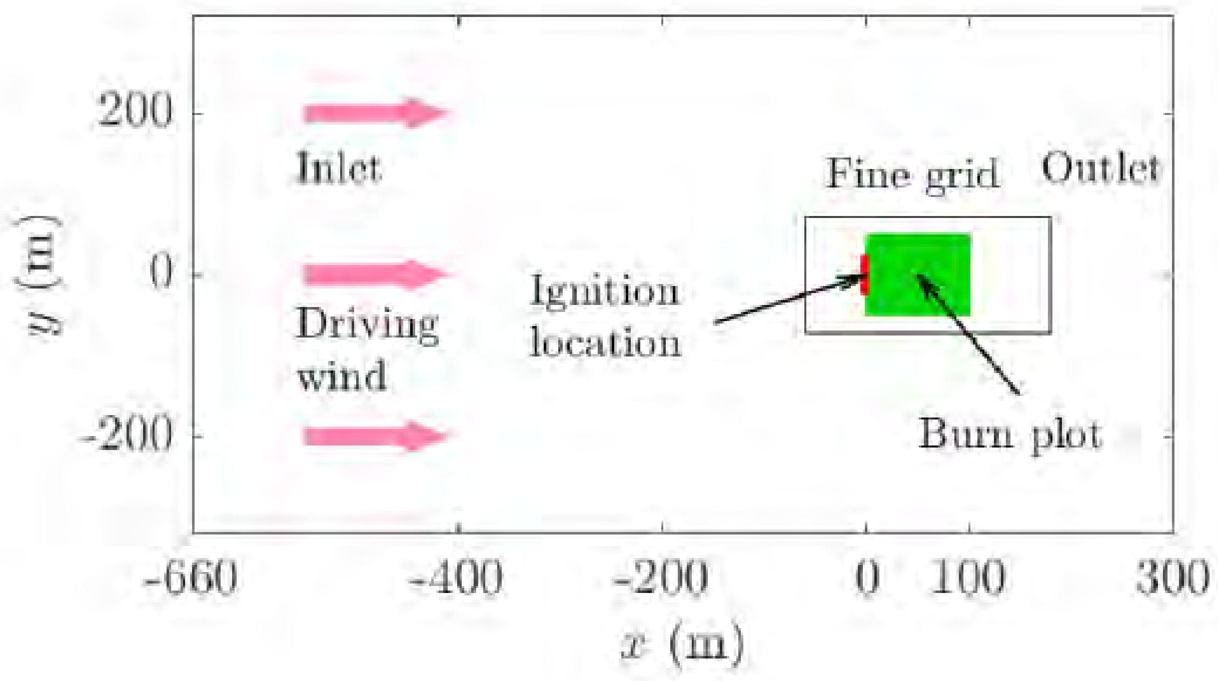
Prediction of rate of spread



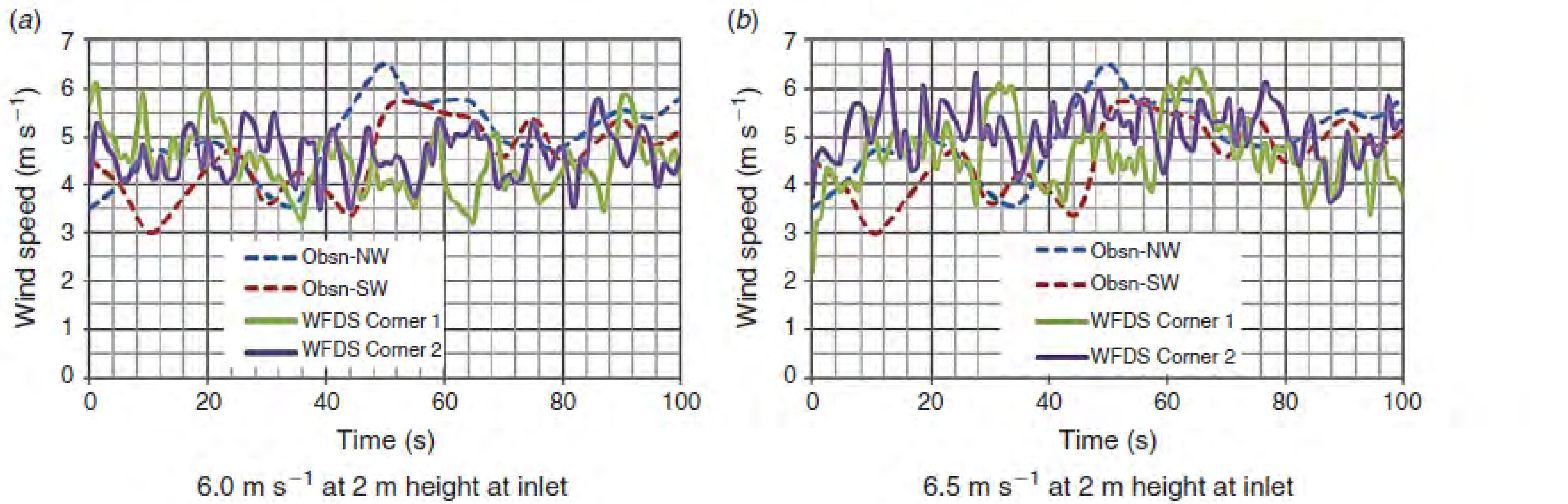
Validation

Cheney, N.P., Gould, J.S. and Catchpole, W.R., 1993. The influence of fuel, weather and fire shape variables on fire-spread in grasslands. *International Journal of Wildland Fire*, *3*(1), pp.31-44.

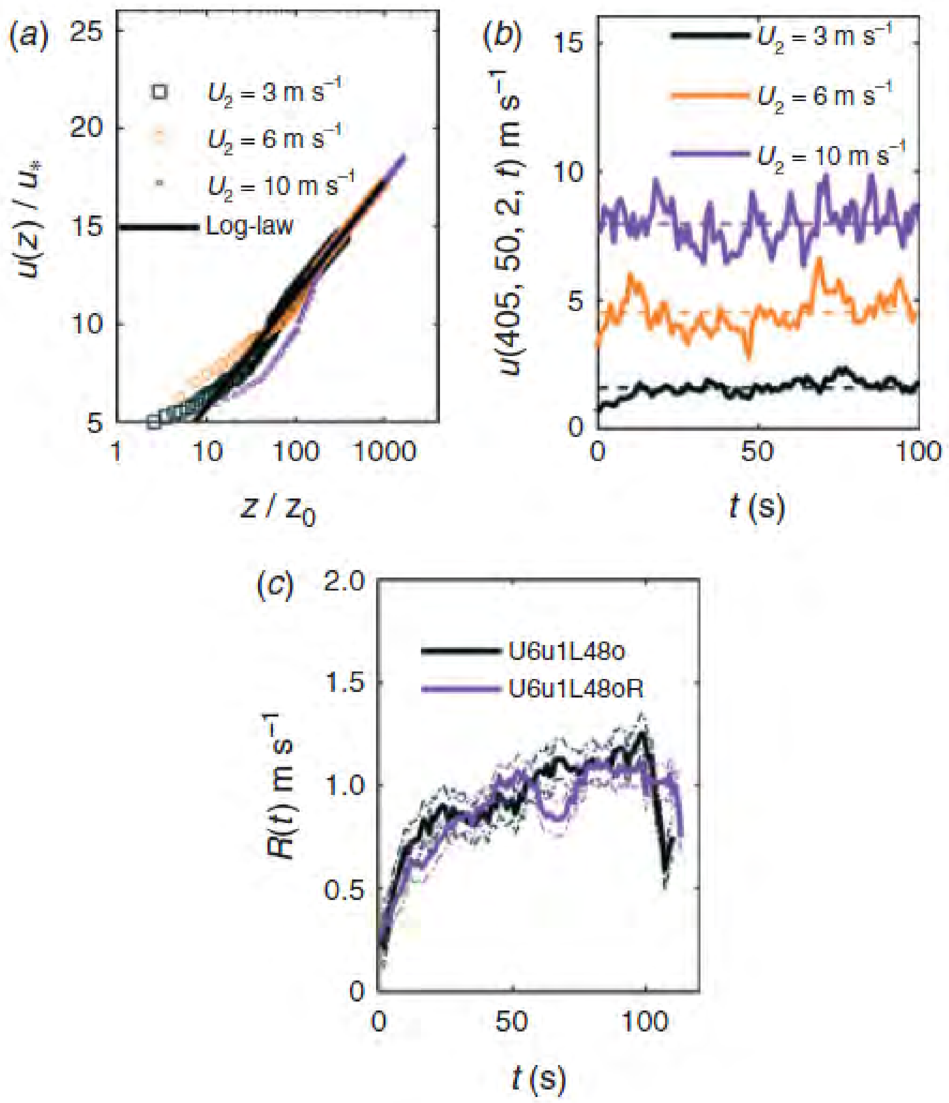
Moinuddin, K.A.M., Sutherland, D. and Mell, W., 2018. Simulation study of grass fire using a physics-based model: striving towards numerical rigour and the effect of grass height on the rate of spread. *International Journal of Wildland fire*, *27*(12), pp.800-814.



Validation

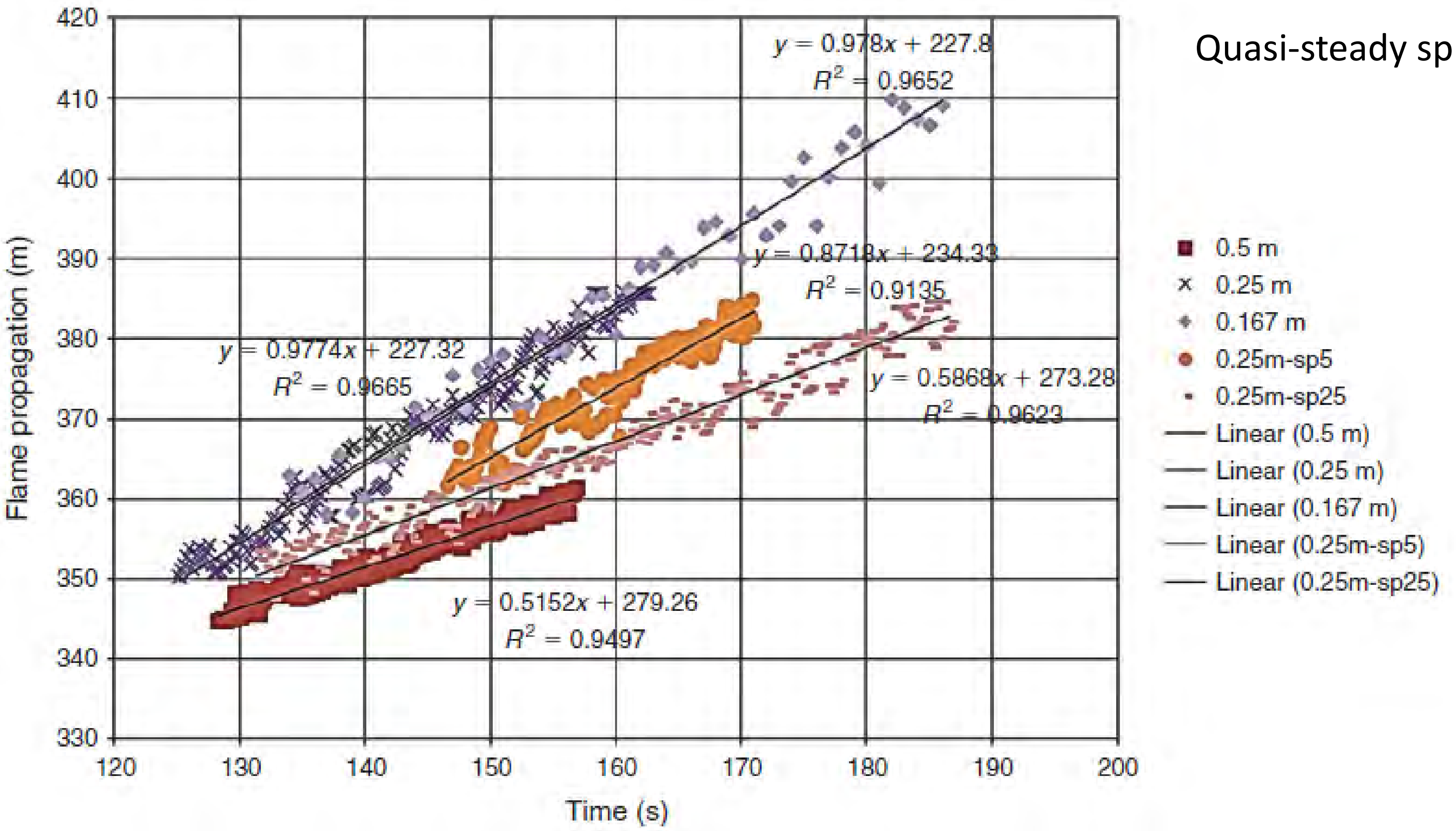

(a)
Wind speed (m s⁻¹)
Time (s)
Obsn-NW
Obsn-SW
WFDS Corner 1
WFDS Corner 2
6.0 m s^{-1} at 2 m height at inlet
(b)
Wind speed (m s⁻¹)
Time (s)
Obsn-NW
Obsn-SW
WFDS Corner 1
WFDS Corner 2
6.5 m s^{-1} at 2 m height at inlet

Validation



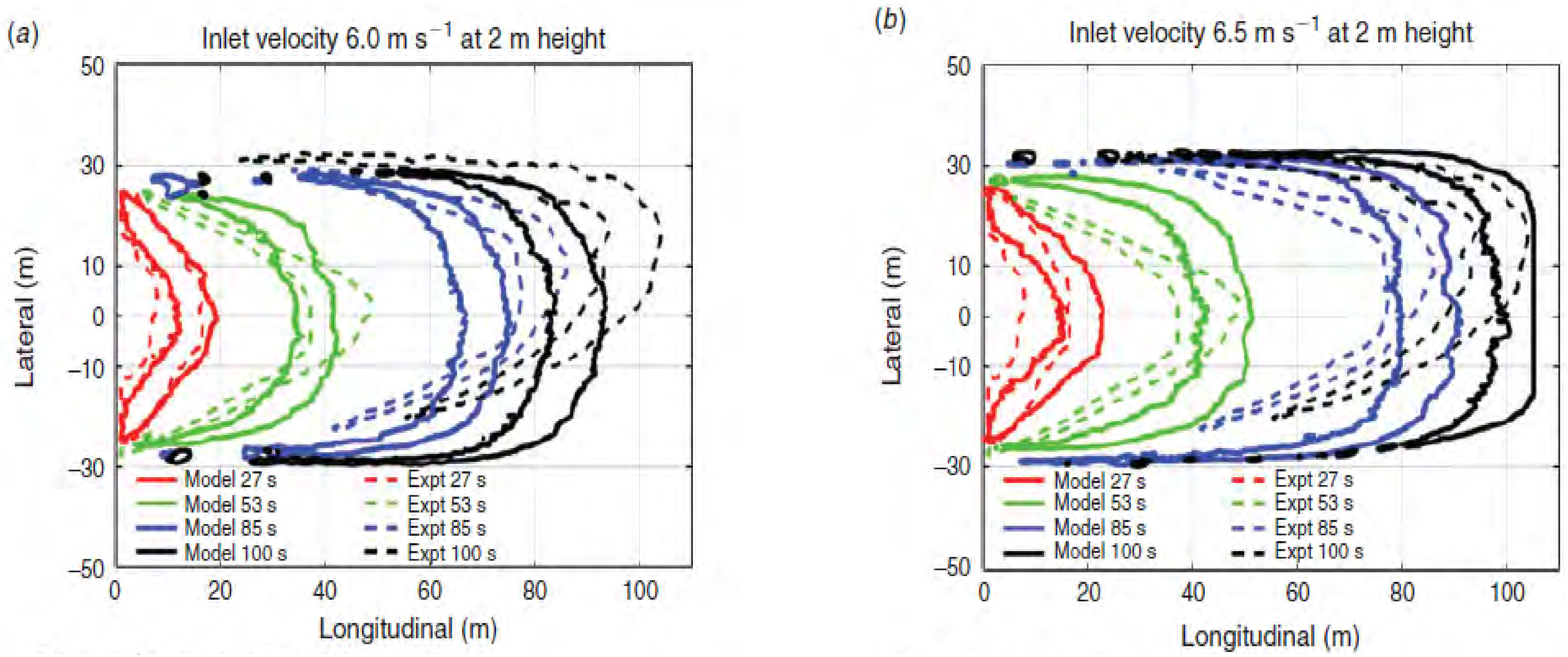
(a)
$U_2 = 3$ m s^{-1}
$U_2 = 6$ m s^{-1}
$U_2 = 10$ m s^{-1}
Log-law
$u(z) / u_*$
z / z_0
(b)
$U_2 = 3$ m s^{-1}
$U_2 = 6$ m s^{-1}
$U_2 = 10$ m s^{-1}
$u(405, 50, 2, t)$ m s^{-1}
t (s)
(c)
U6u1L48o
U6u1L48oR
$R(t)$ m s^{-1}
t (s)

Validation

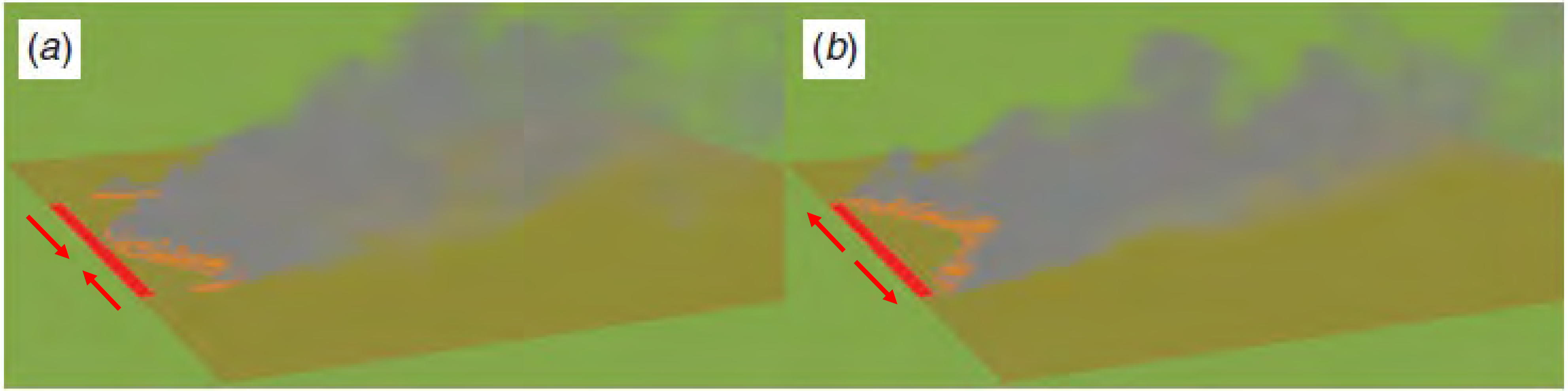


Quasi-steady spread rate

Validation

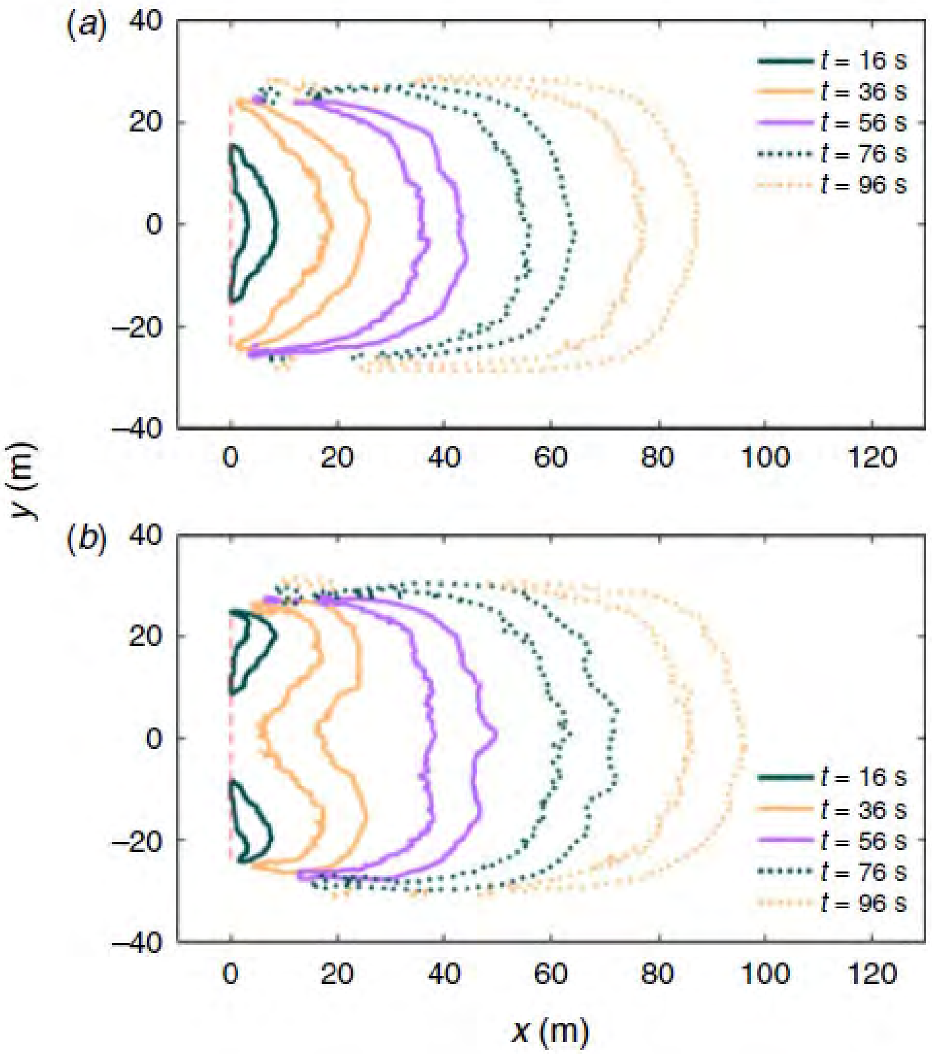

(a)
Inlet velocity 6.0 m s⁻¹ at 2 m height
Lateral (m)
Longitudinal (m)
50
30
10
0
–10
–30
–50
0
20
40
60
80
100
Model 27 s
Model 53 s
Model 85 s
Model 100 s
Expt 27 s
Expt 53 s
Expt 85 s
Expt 100 s
(b)
Inlet velocity 6.5 m s⁻¹ at 2 m height
Lateral (m)
Longitudinal (m)
50
30
10
0
–10
–30
–50
0
20
40
60
80
100
Model 27 s
Model 53 s
Model 85 s
Model 100 s
Expt 27 s
Expt 53 s
Expt 85 s
Expt 100 s

Effect of ignition protocol



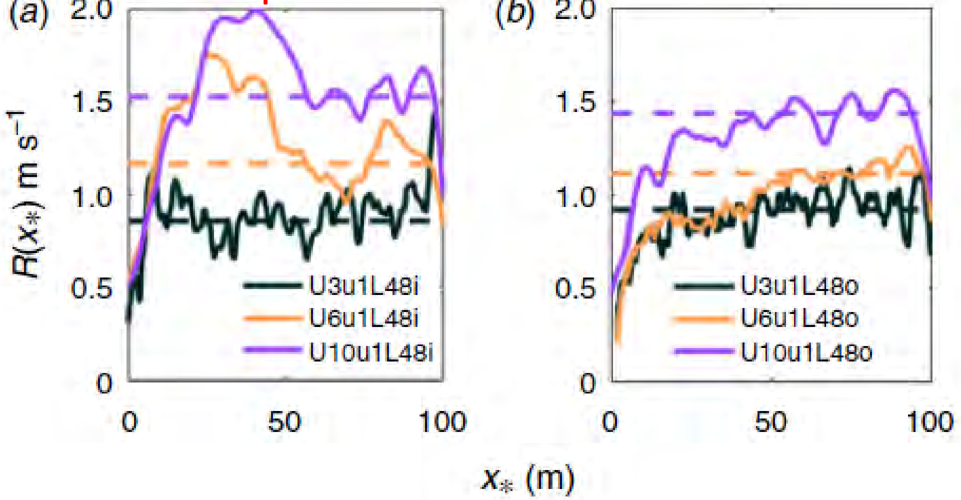
Sutherland, D., Sharples, J.J. and Moinuddin, K.A., 2020. The effect of ignition protocol on grassfire development. *International journal of wildland fire*, *29*(1), pp.70-80.

Effect of ignition protocol

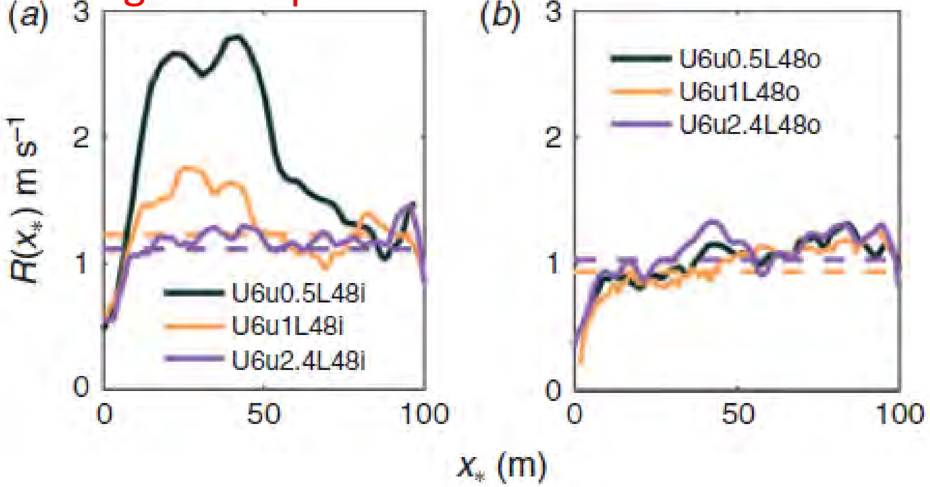


Effect of ignition protocol

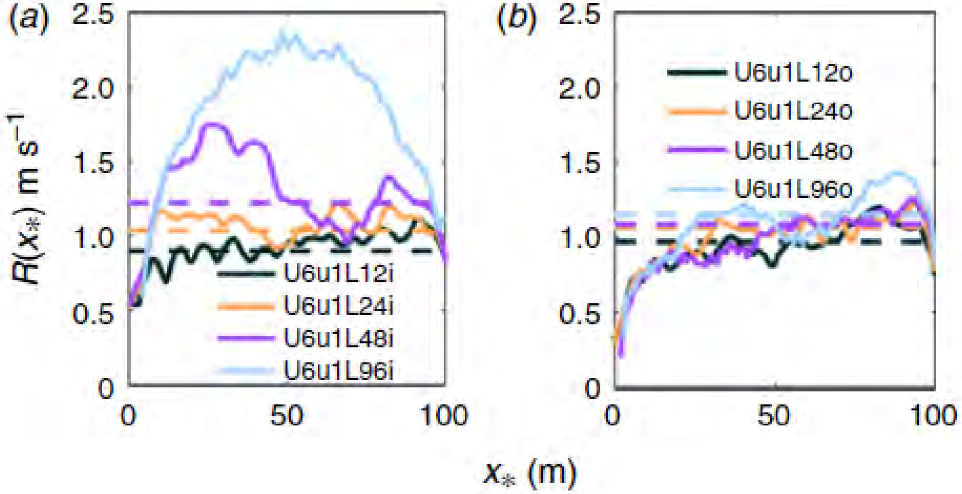
Wind speed varies



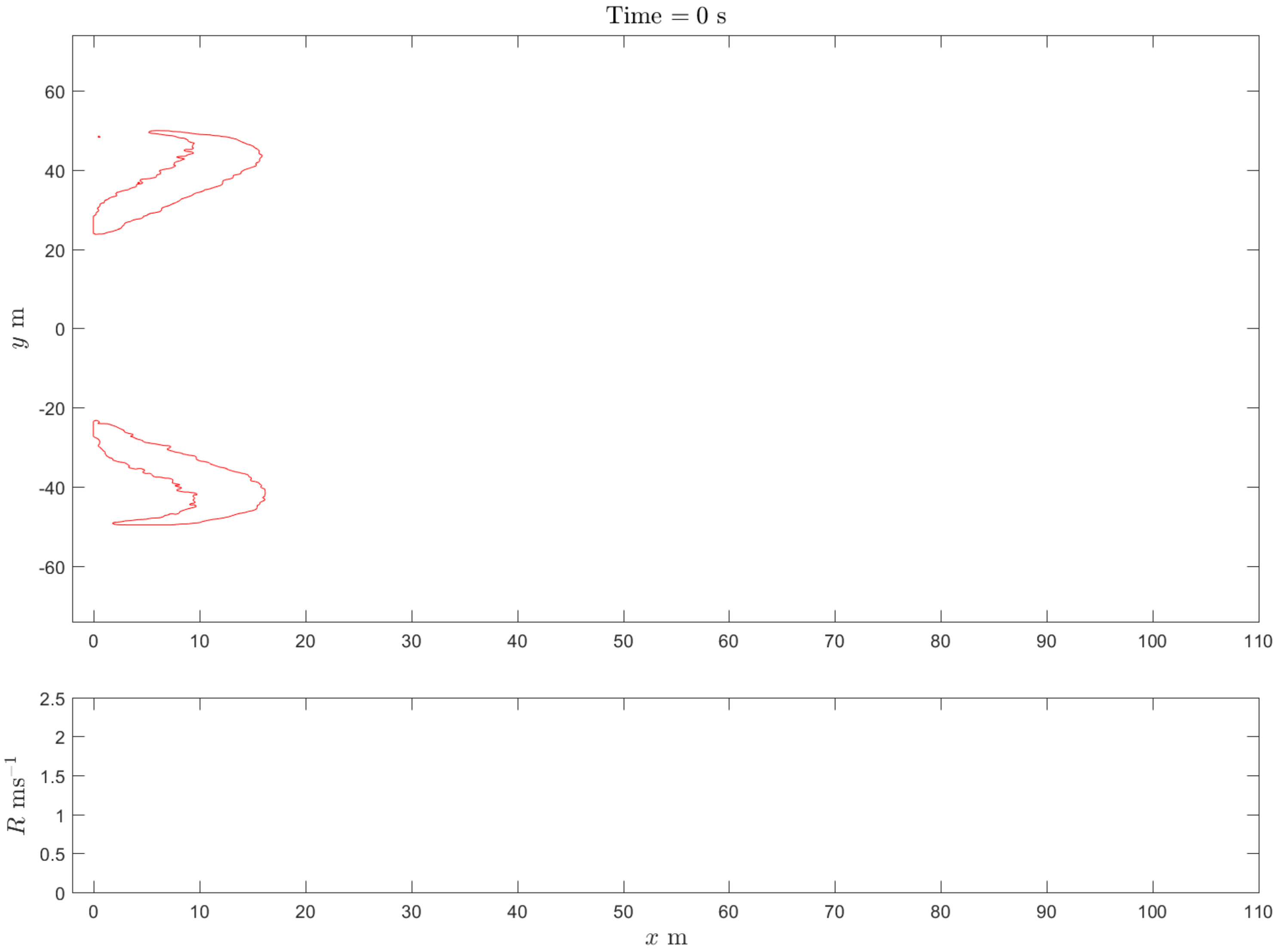
Ignition speed varies



Ignition length varies

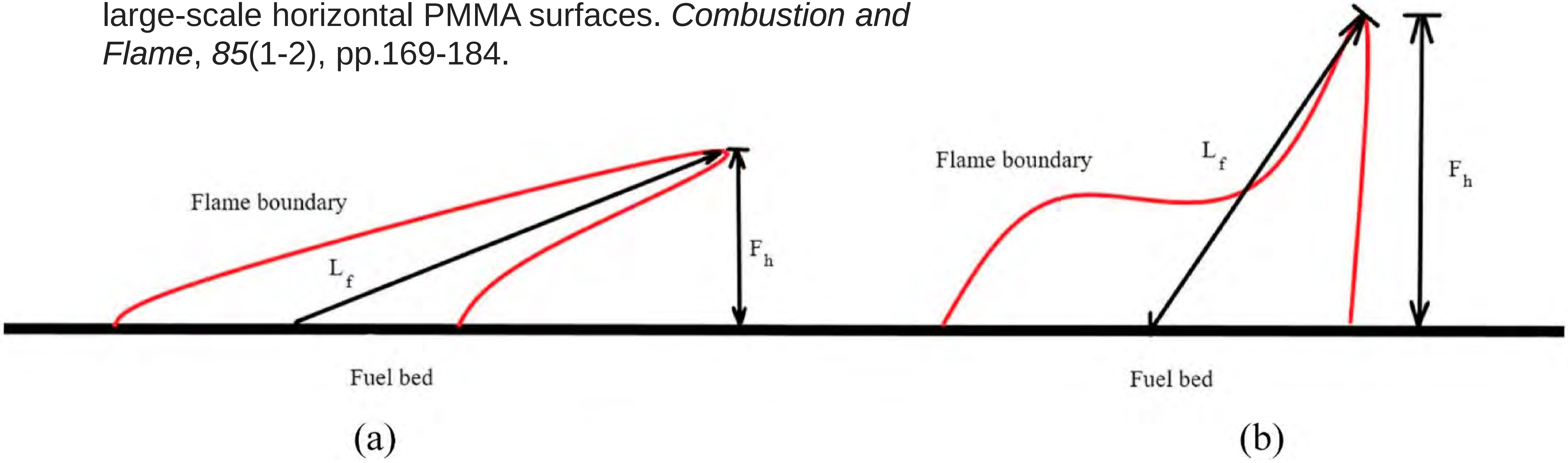


Animation of an extreme case



Multiple propagation modes

Apte, V.B., Bilger, R.W., Green, A.R. and Quintiere, J.G., 1991. Wind-aided turbulent flame spread and burning over large-scale horizontal PMMA surfaces. *Combustion and Flame*, *85*(1-2), pp.169-184.

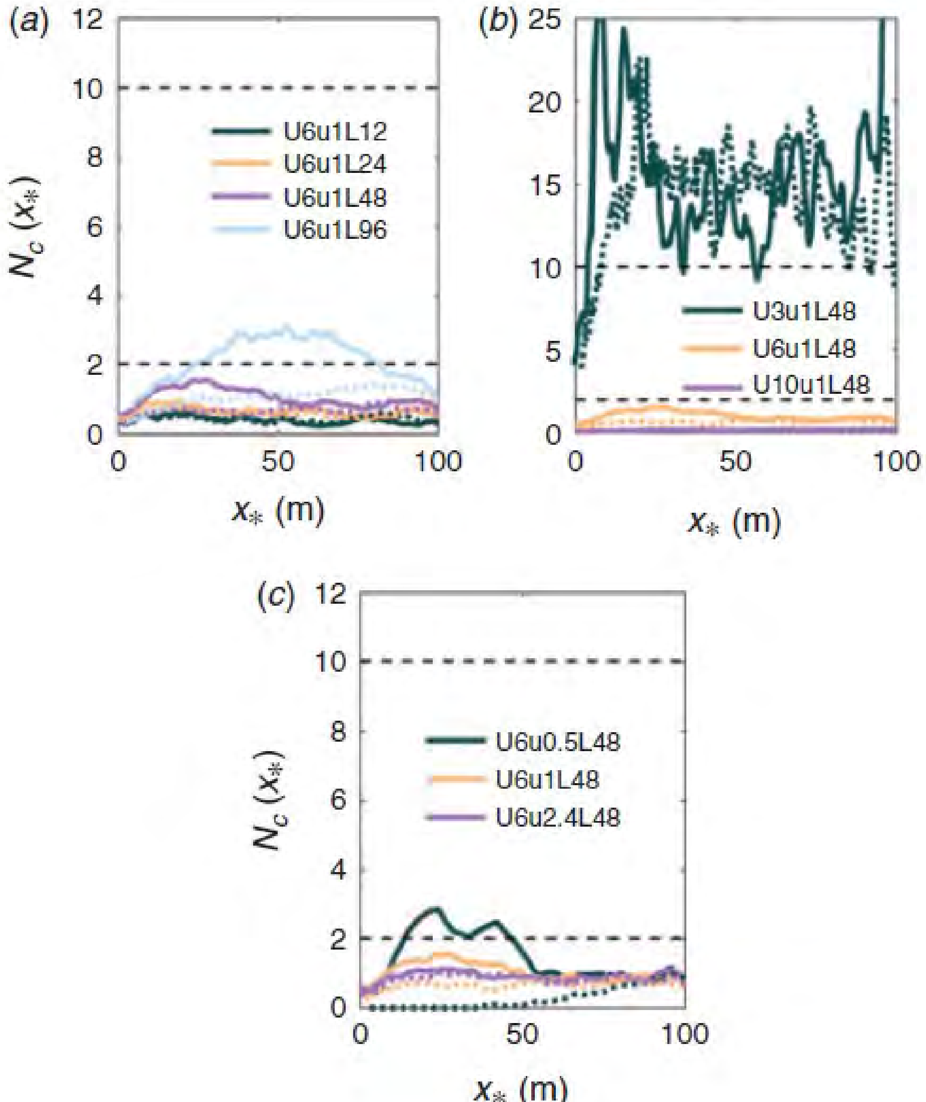


Wind-driven fire

Buoyancy-driven fire

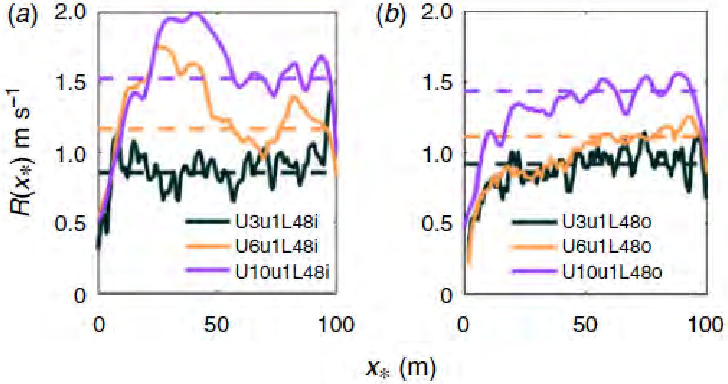
Dold, J., 2011, December. Fire spread near the attached and separated flow transition, including surge and stall behaviour. In *Proc. 19th Int. Congress on Modelling and Simulation* (pp. 200-206).

Merging fires

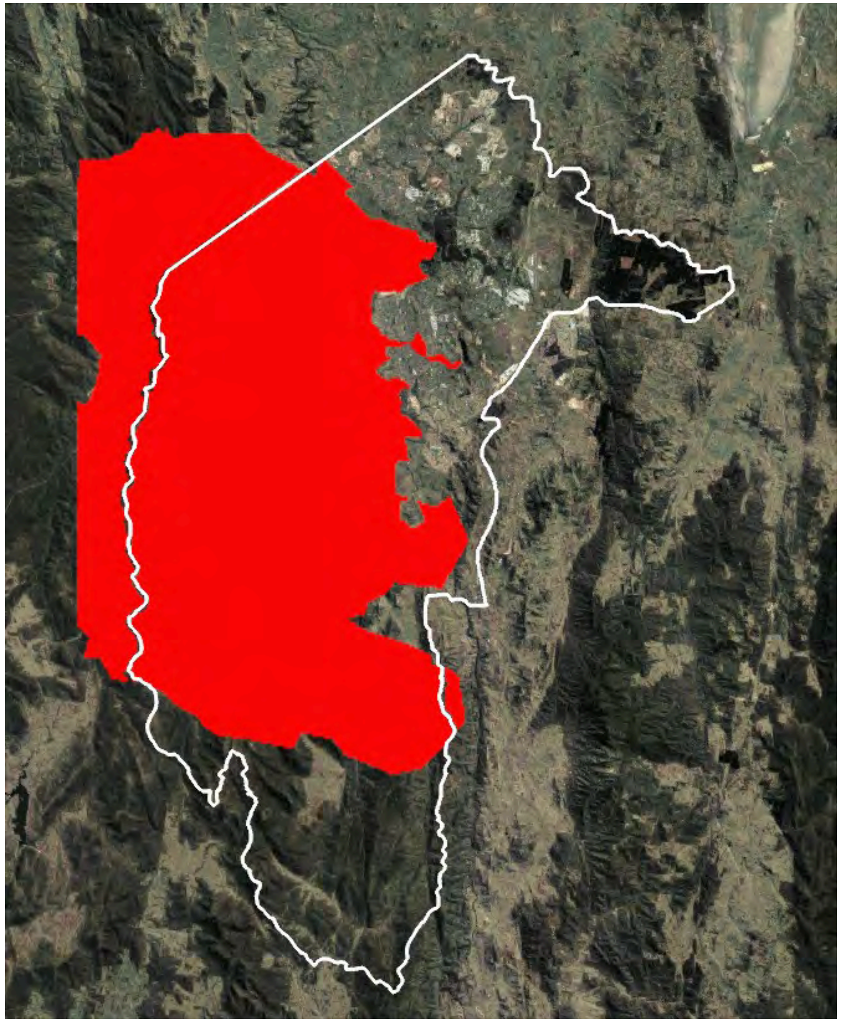


$$N_c = \frac{2gQ}{(U_{10} - R)^3 \rho c_p T_a}.$$

Recall:

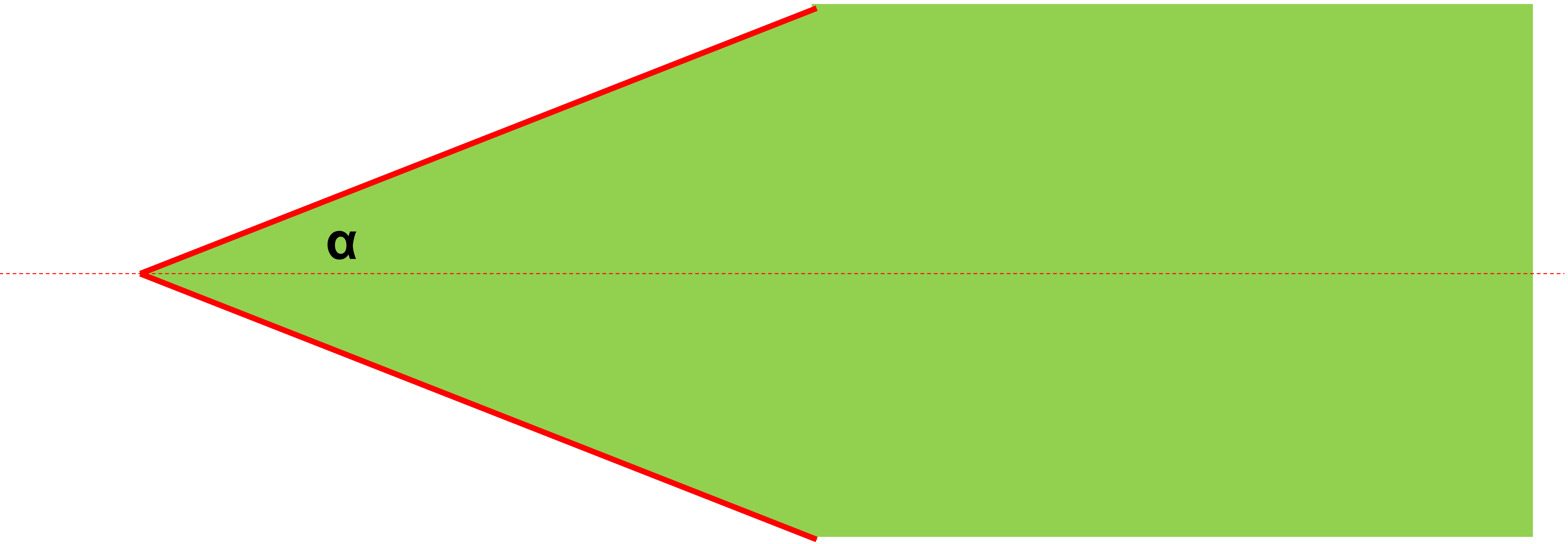


Understanding the Origin and Development of Extreme and Mega Bushfires

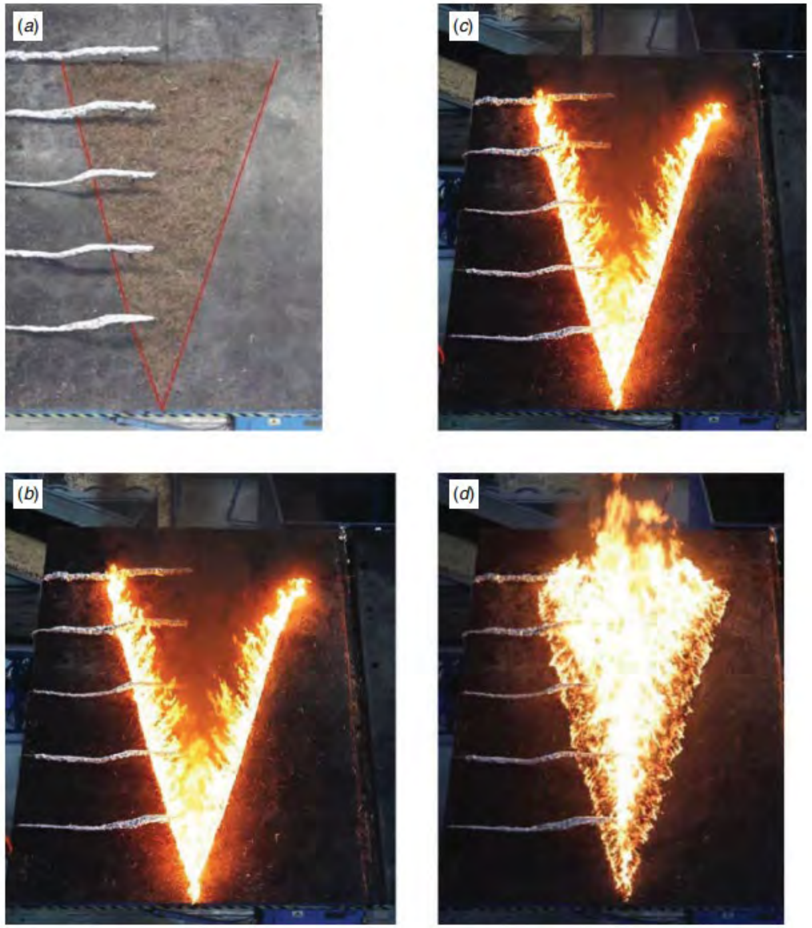


- All fires start small
- Small fires can merge to become large
- The dynamic merger process is not well understood
- Predict the rate of spread
- Better manage fire suppression and evacuations

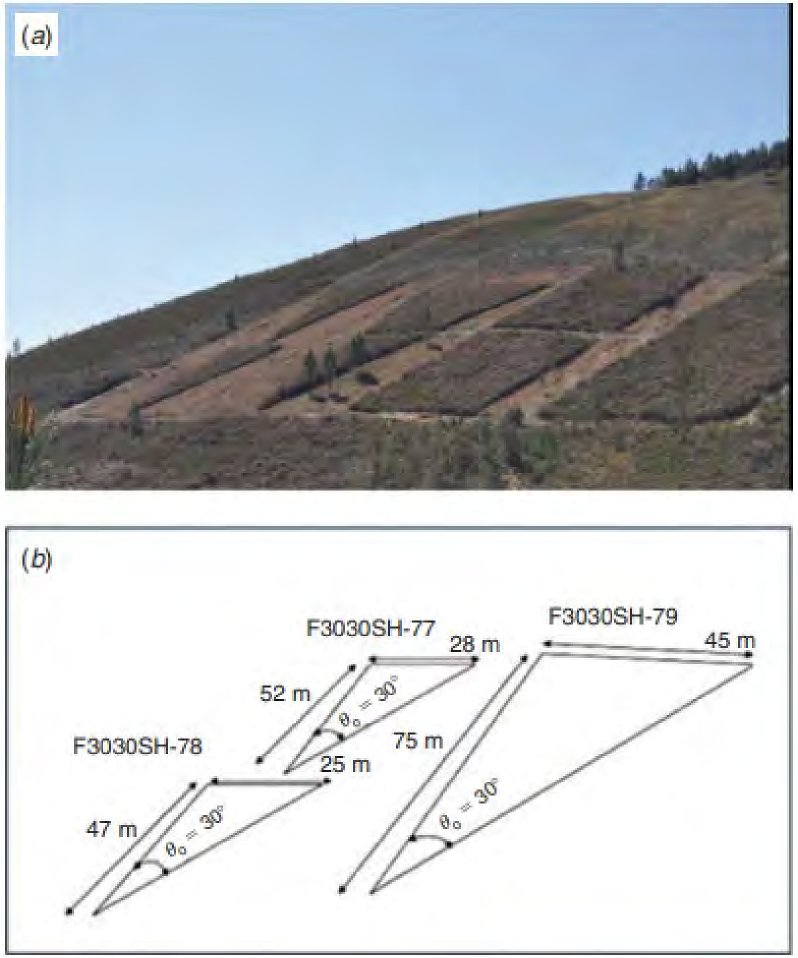
Junction fires are made of two ignition lines in v-configuration, with fuel in between



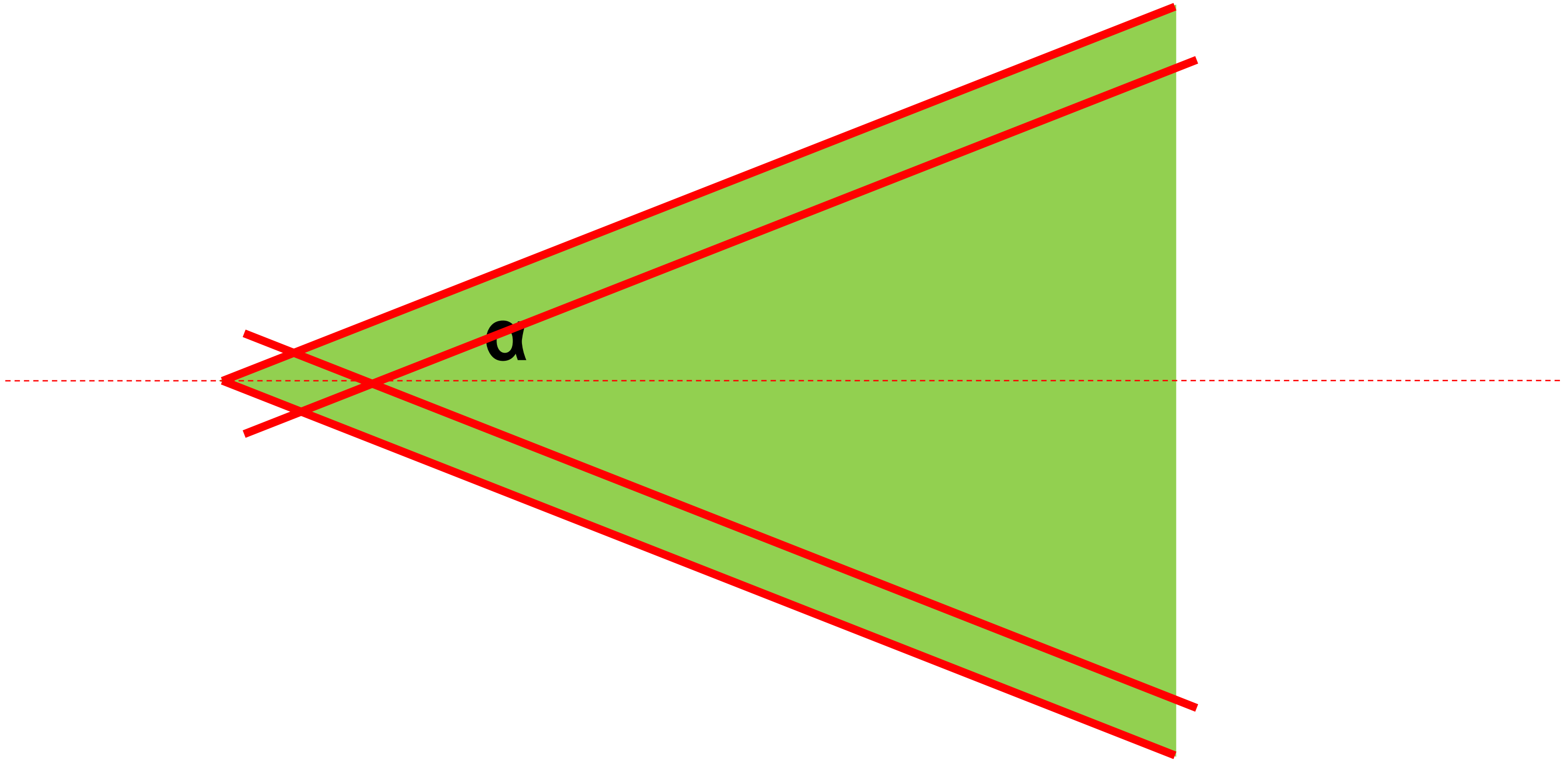
Experimental studies



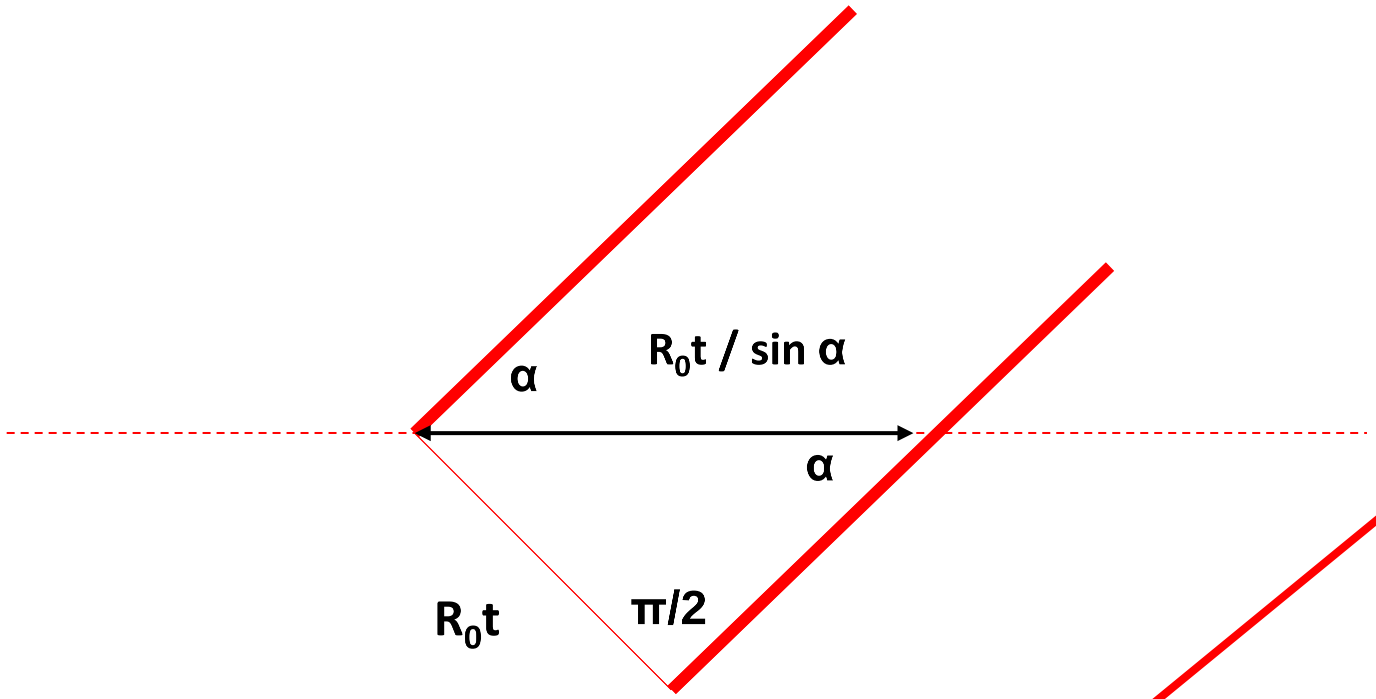
About 8 m



Previous attention has focused on the spread rate of the apex



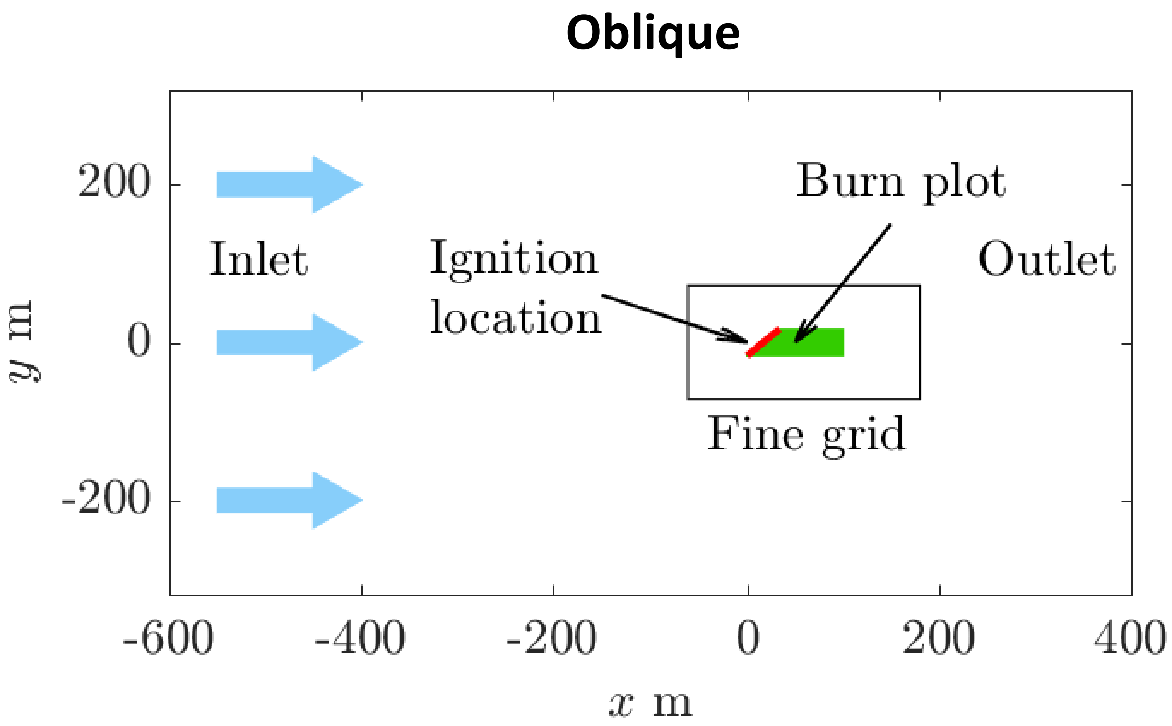
The apex of a quasi-steady junction fire in zero wind should spread proportional to **cosec α**

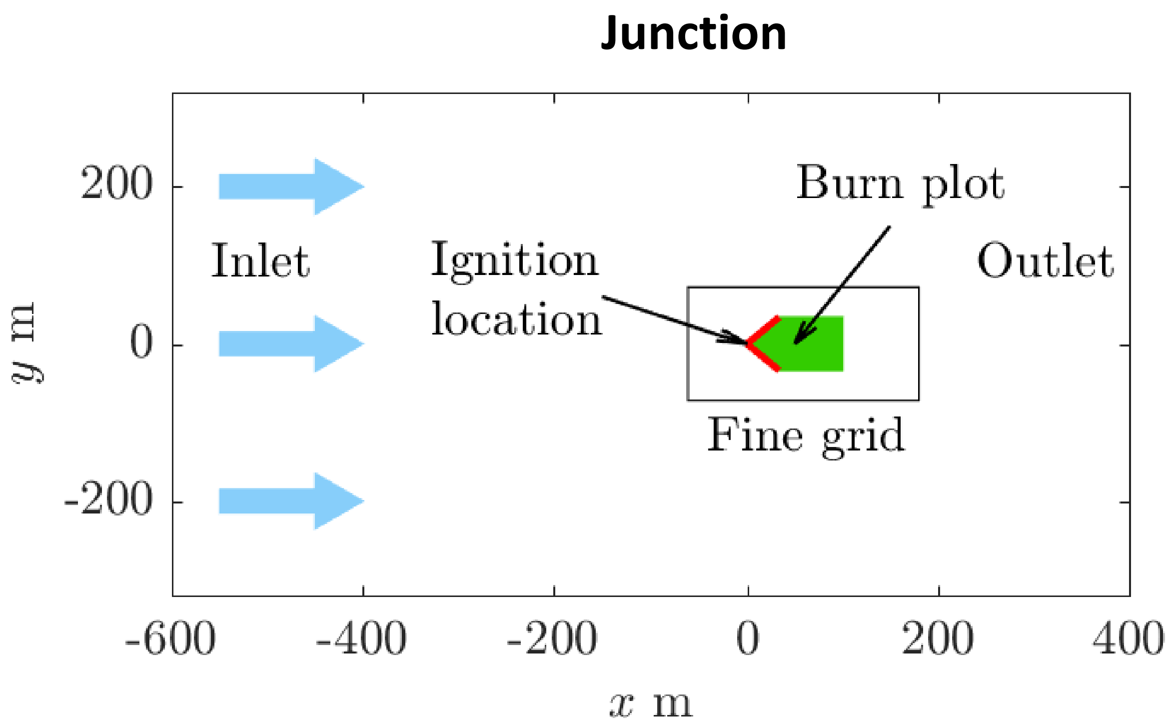


Geometric spread rate: R_0 cosec α

Base rate of spread normalisation
Here, that is the 90 deg oblique line cases under the same wind

A junction fire in nonzero wind conditions should be compared to an equivalent oblique line fire



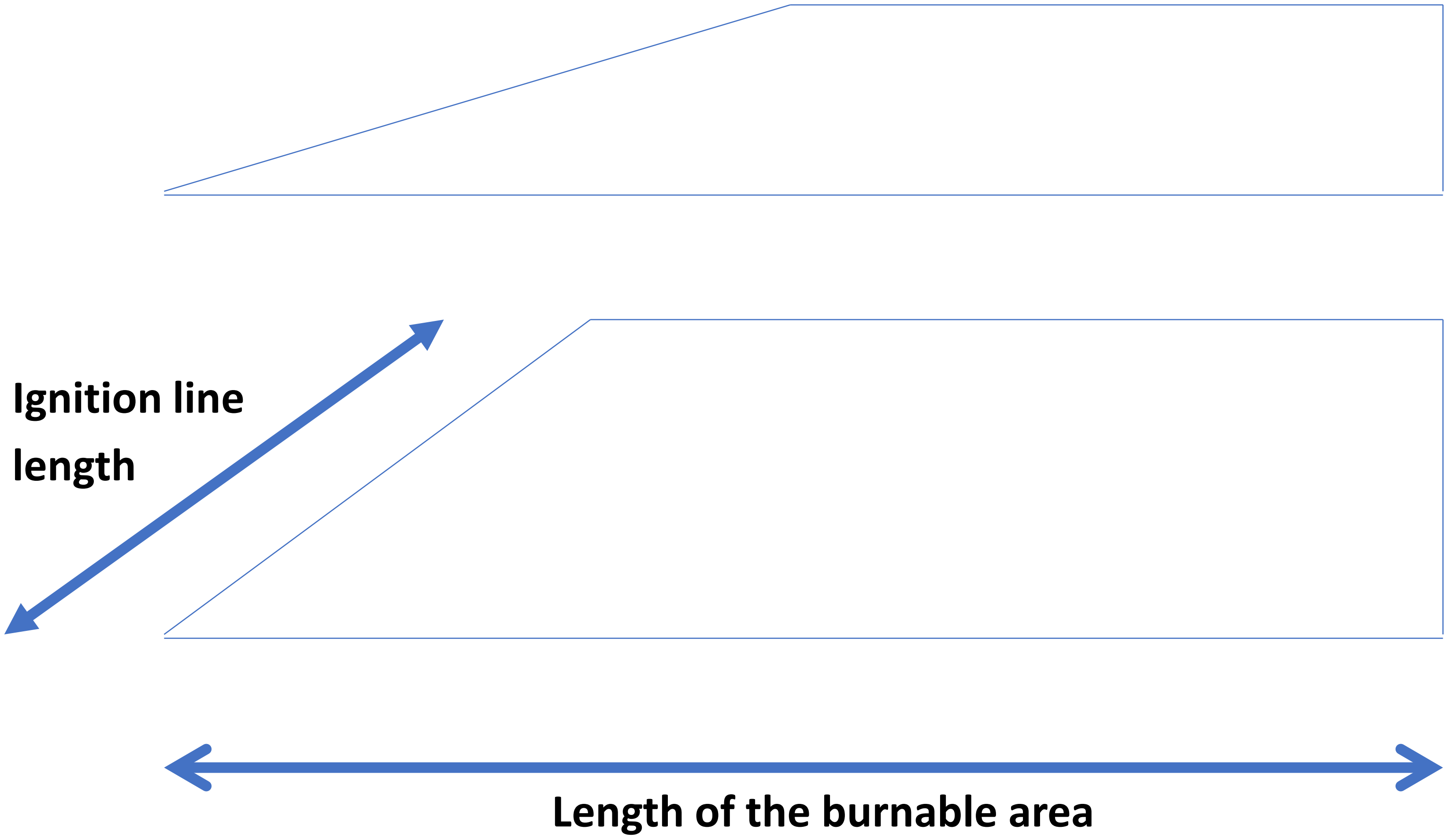


WFDS - fuel parameters: Grass (Moinuddin et al. 2018)

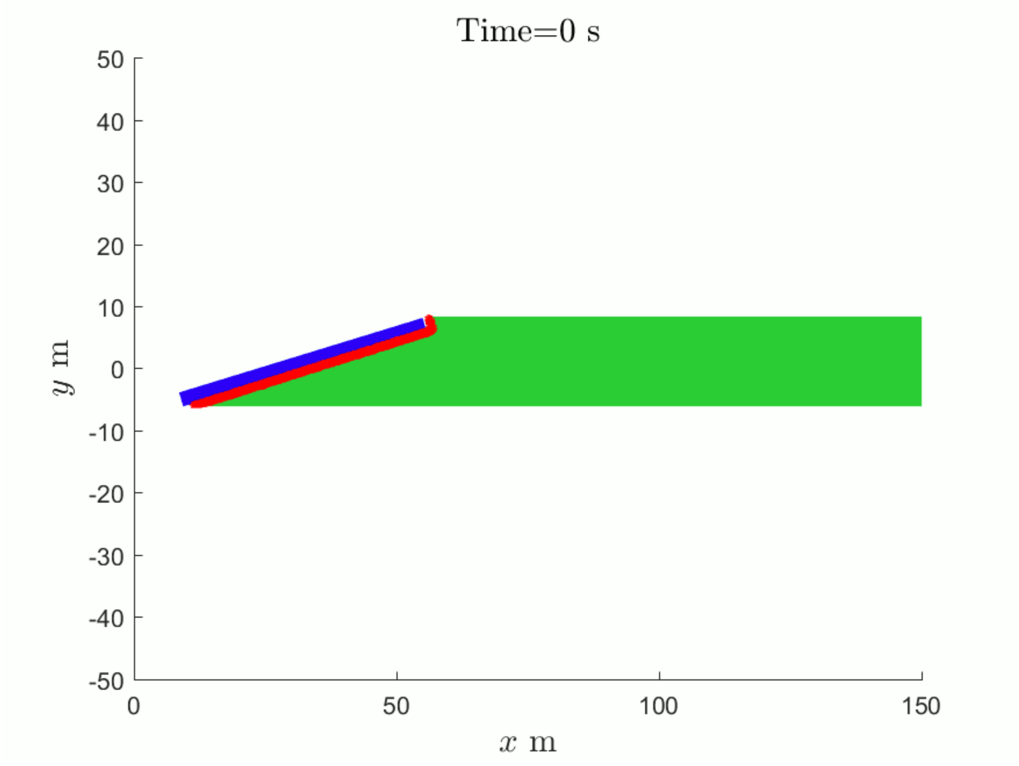
Ignition line length: 48 m instant ignition (Sutherland et al. 2020)

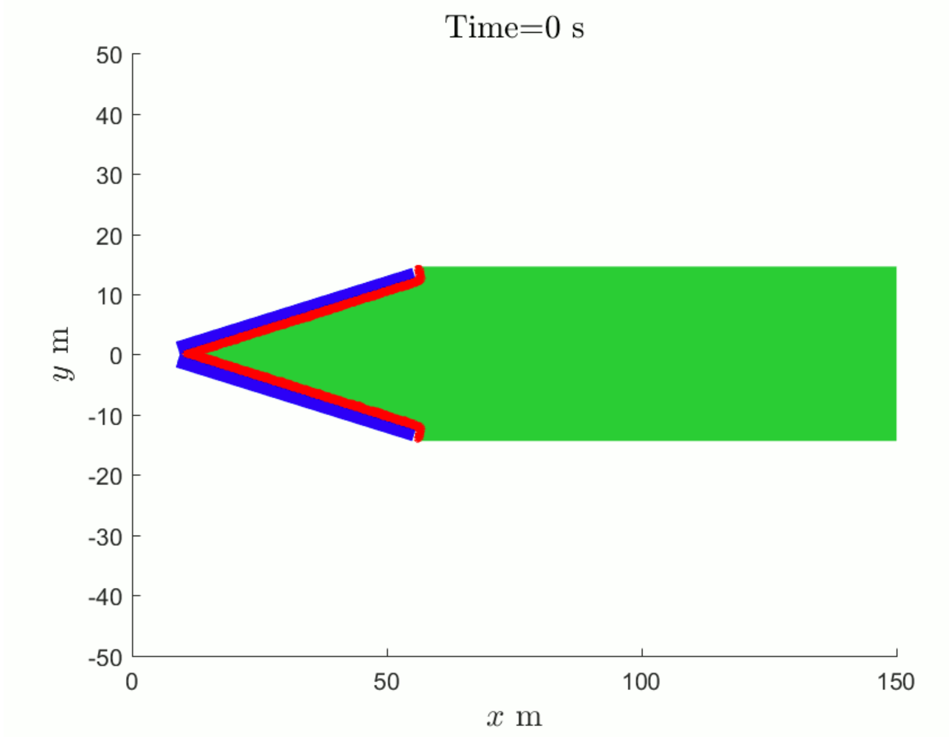
u=3, 6, 10 m/s α=15, 30, 45, 60, 90 deg

Using a constant ignition line length means the final width of the fire depends on α



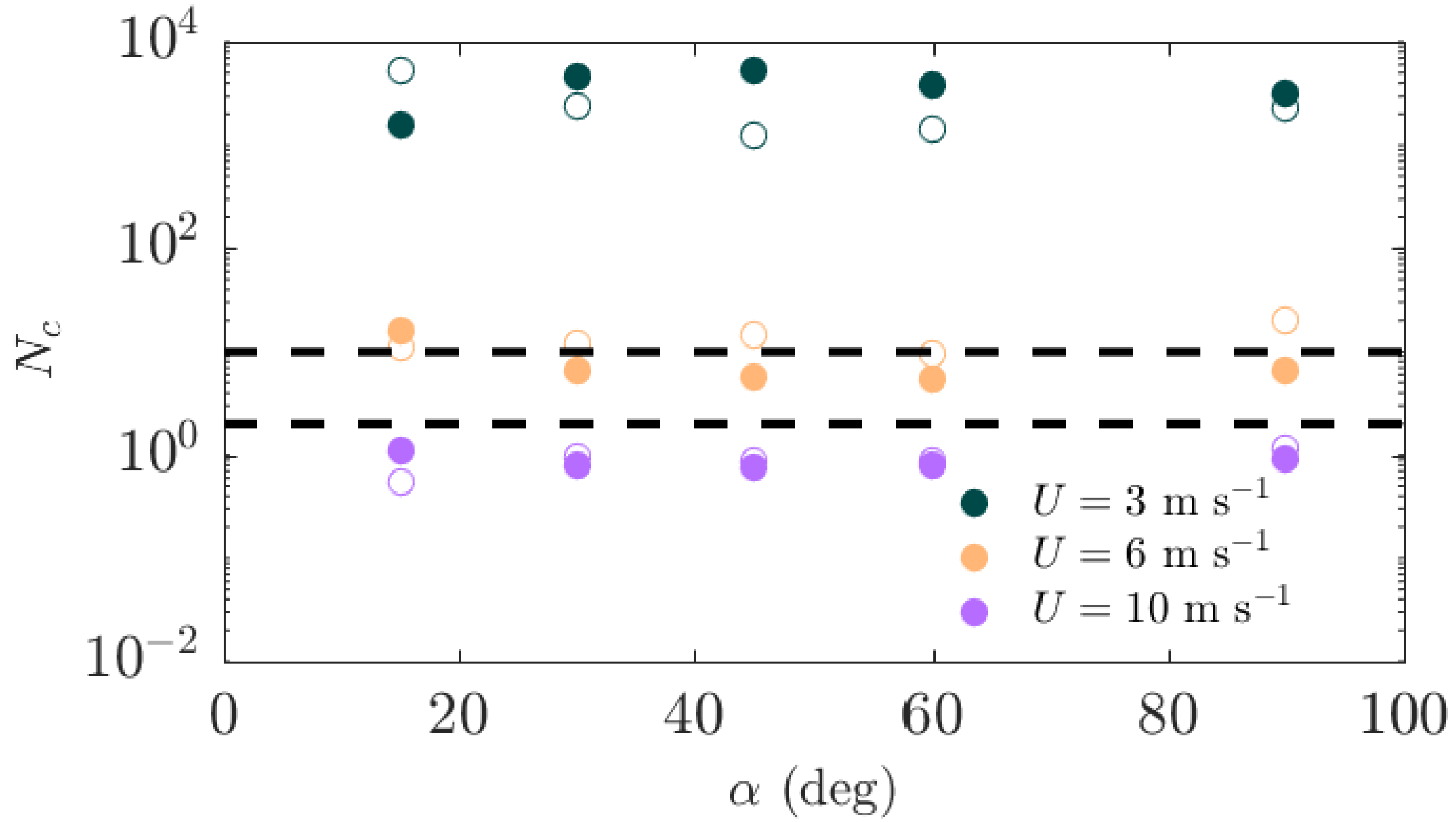
The oblique and junction fires both straighten (u=3 m/s, α=15 deg)



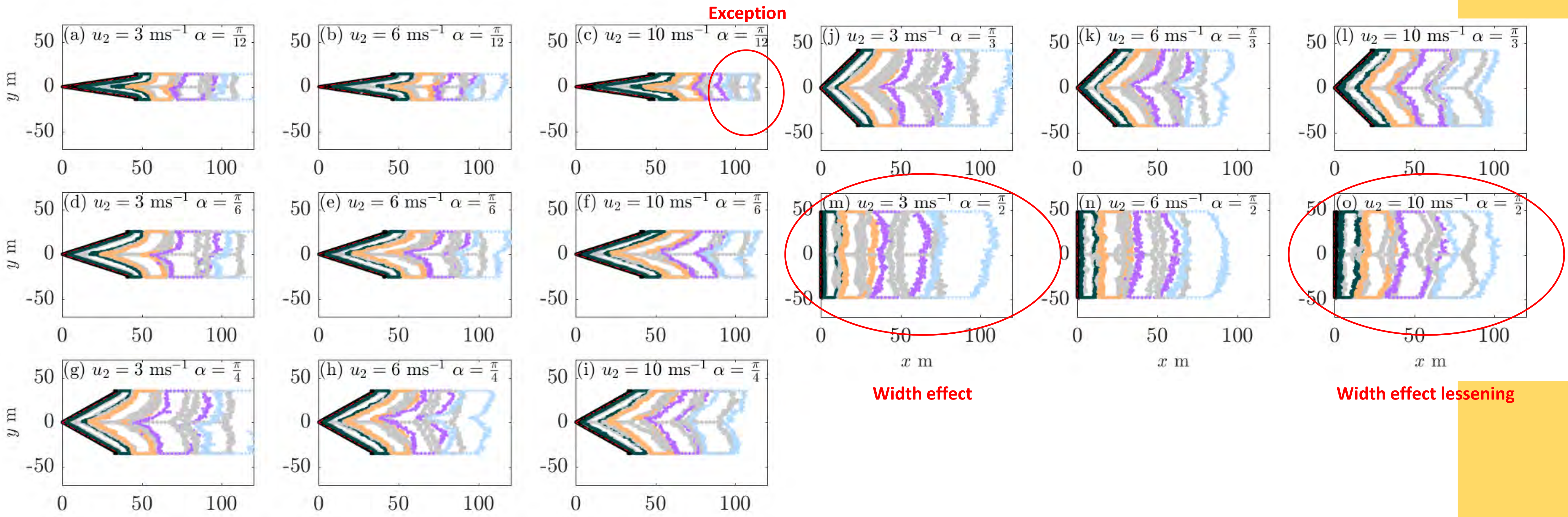


We have a set of buoyancy dominated fires, a set of intermediate fires, and a set of wind dominated fires

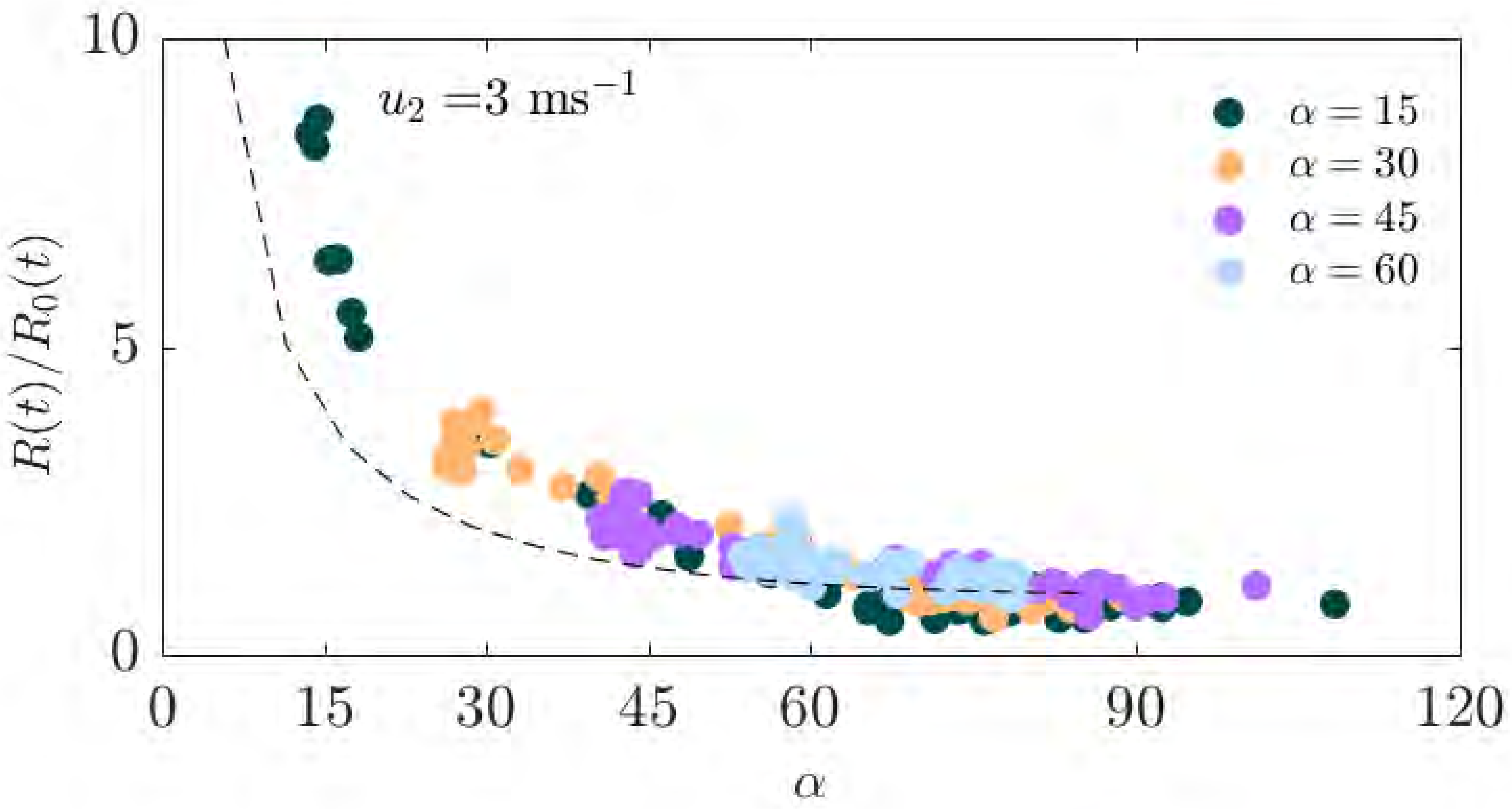
$$N_c = \frac{2g\dot{Q}}{\rho c_p T_a |U_W - R(t)|^3}$$



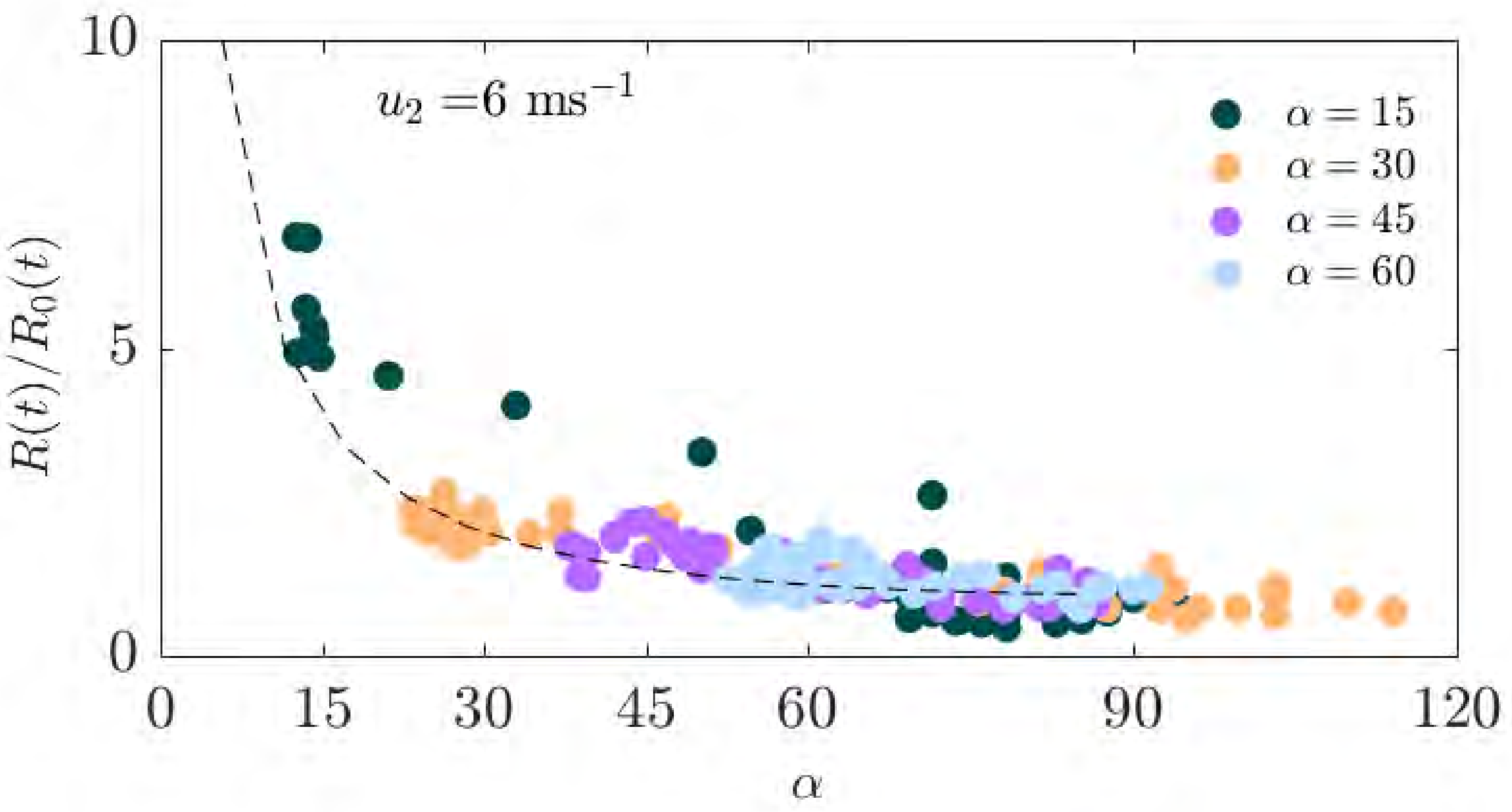
The junction fires (typically) move faster than oblique line fires, but spread rate depends on fire width



Buoyancy-dominated oblique line fires have a (largely) super-geometric spread rate



Wind-dominated (and intermediate) oblique line fires have a (more) geometric spread rate



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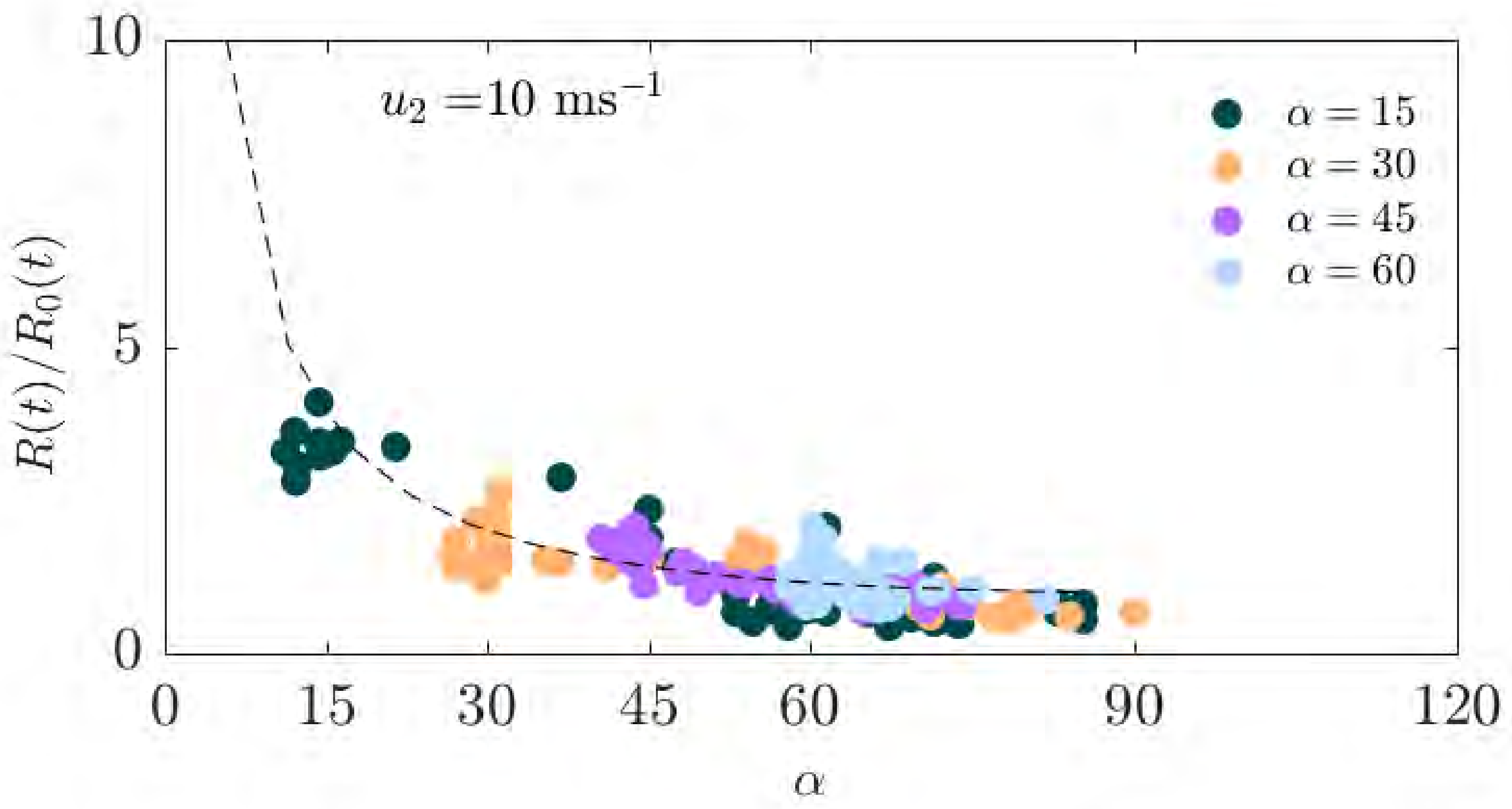
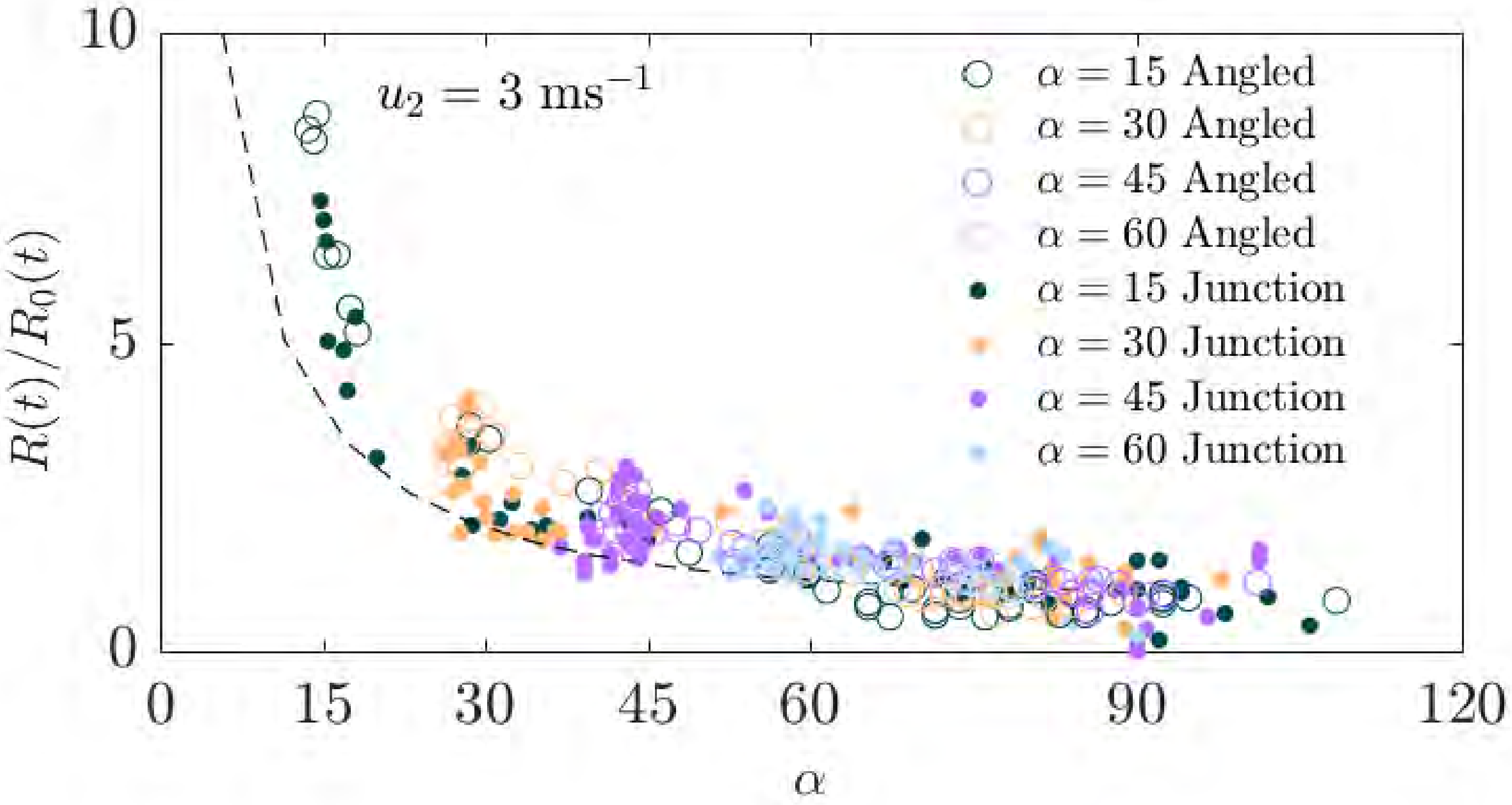
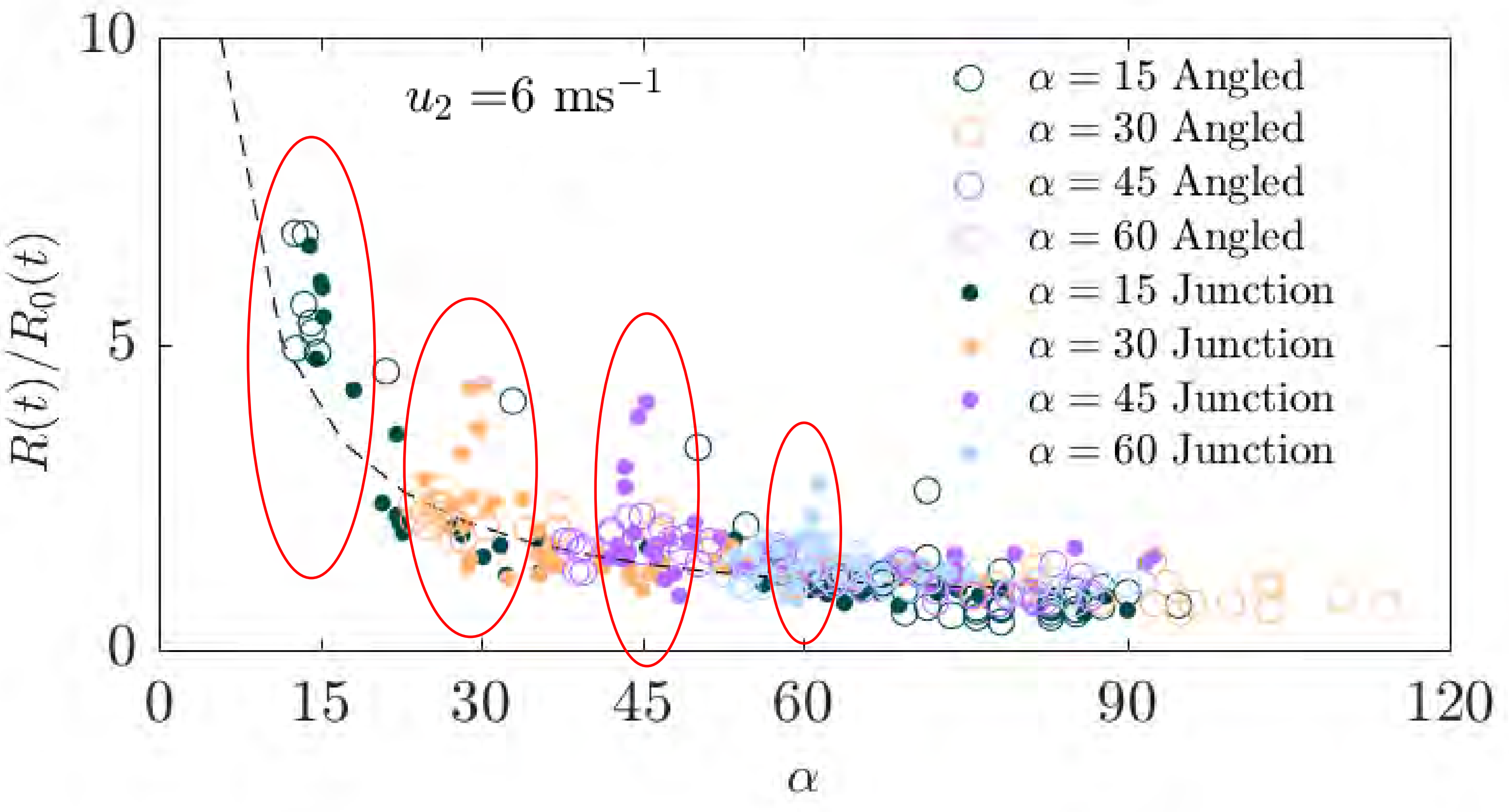


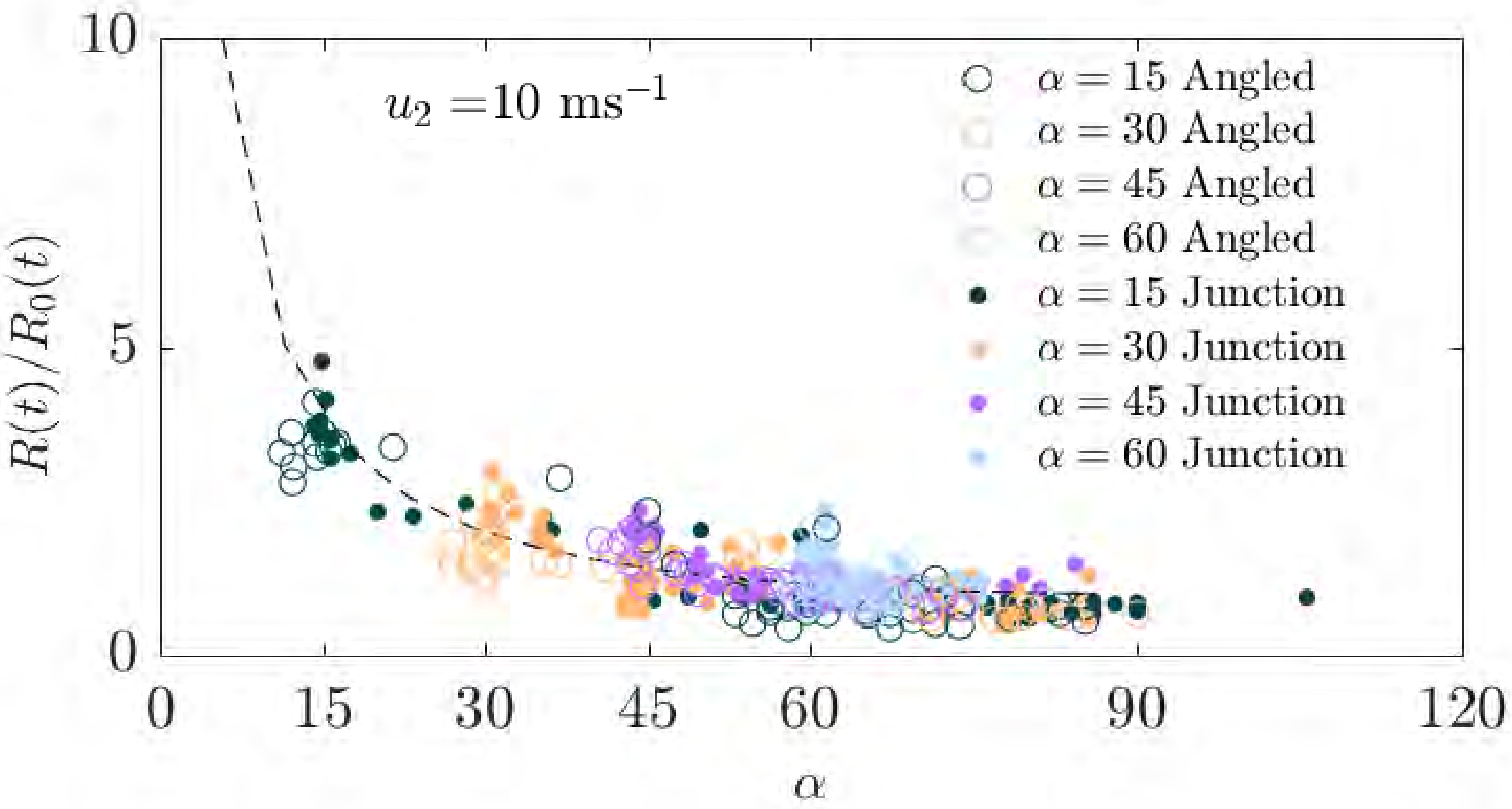
Buoyancy-dominated junction fires have a super-geometric spread rate, but not as much as oblique line fires



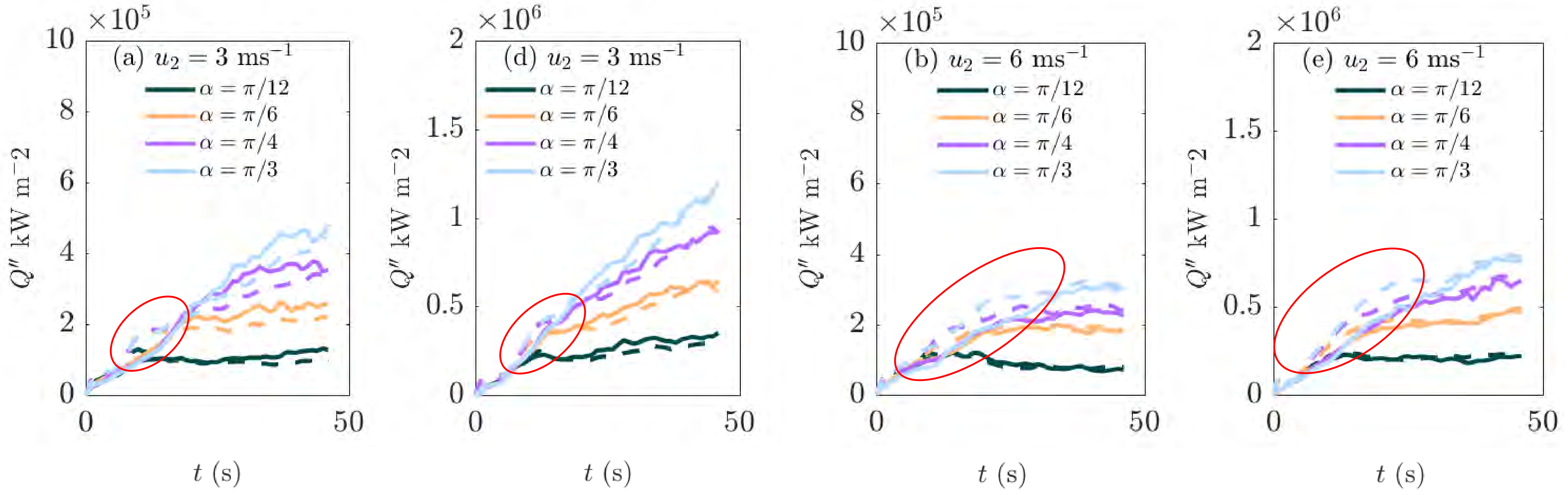
Intermediate junction fires have an early period of super-geometric spread rate at constant apex angle



Wind-dominated junction fires have a geometric spread rate

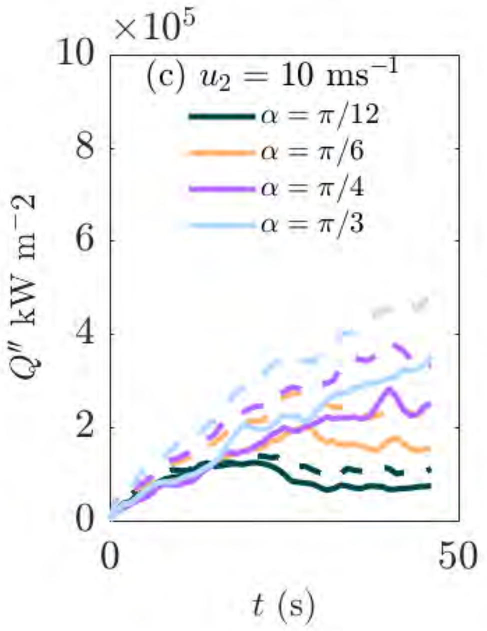


Buoyancy-dominated and intermediate fires tend to spread by both mechanisms of heat transfer; slight dominance of radiation and convection respectively

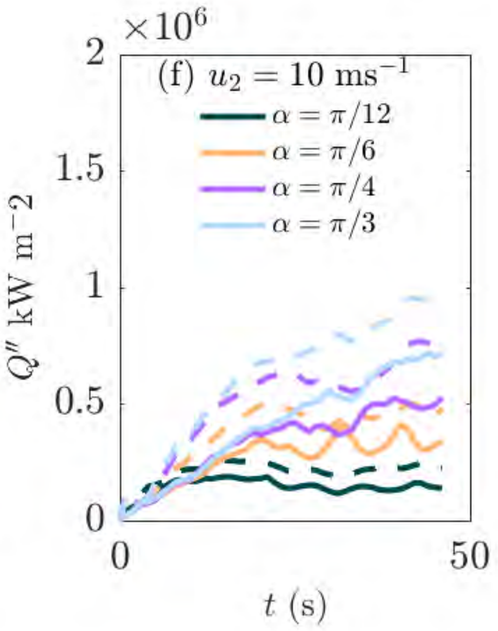


Oblique **Junction** **Oblique** **Junction**

Wind-dominated fires are dominated by convective heat transfer



Oblique



Junction

Future goals

- Understanding the Origin and Development of Extreme and Mega Bushfires
  - Merging fires on slopes, more complicated geometries
  - Comparison to experimental fires, development of better experimental protocols
  - Development of reduced models for operational purposes
- Gravity Current Driven Smoke Dispersion In a Stratified Ambient:
  - Understand the dynamics
  - Mixing and mixing efficiency
- Ember Storm Mitigation on the Urban Fringe:
  - Threshold model relating forest and weather conditions to the onset of ember storms
  - Identification of forest and urban development features that increase and decrease ember accumulation

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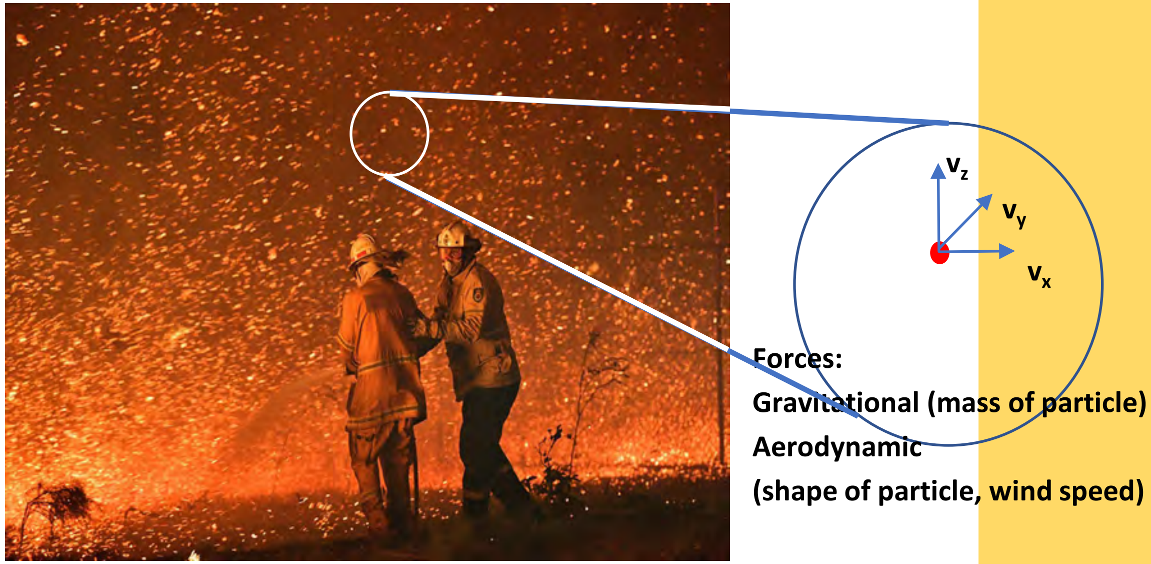
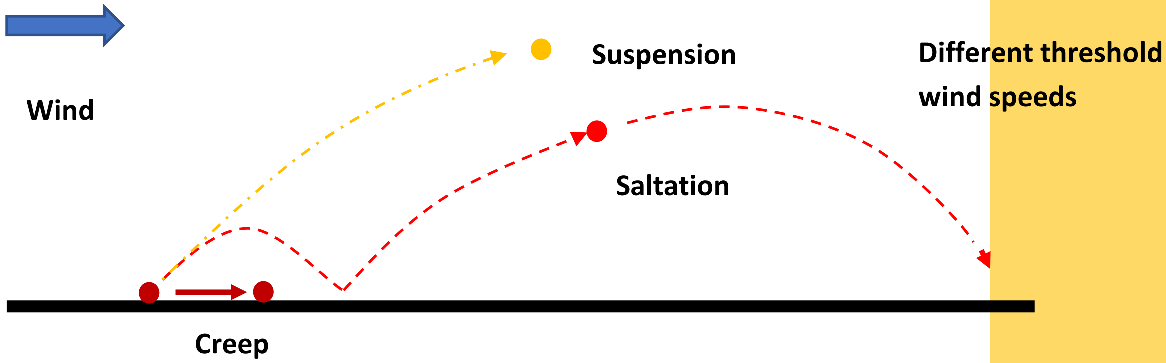
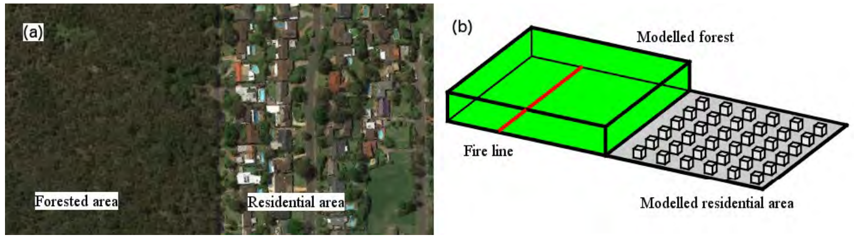


Photo: Saeed Khan / AFP





Questions