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A new granular and scalable model for stochastic WUI fire spread behaviour

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Why wildfires? Personal motivation

- Combustion science: vital for many fields
- Mati fire in Greece (23 July 2018)
  - Fire speed ~4 km/h
  - 104 deaths

Mati fire aftermath

my family’s house destroyed

Prof. Mastorakos’ house (almost) intact

WUI fire phenomenology

Wind direction on the day of the fire

Mati: One year later

The day after

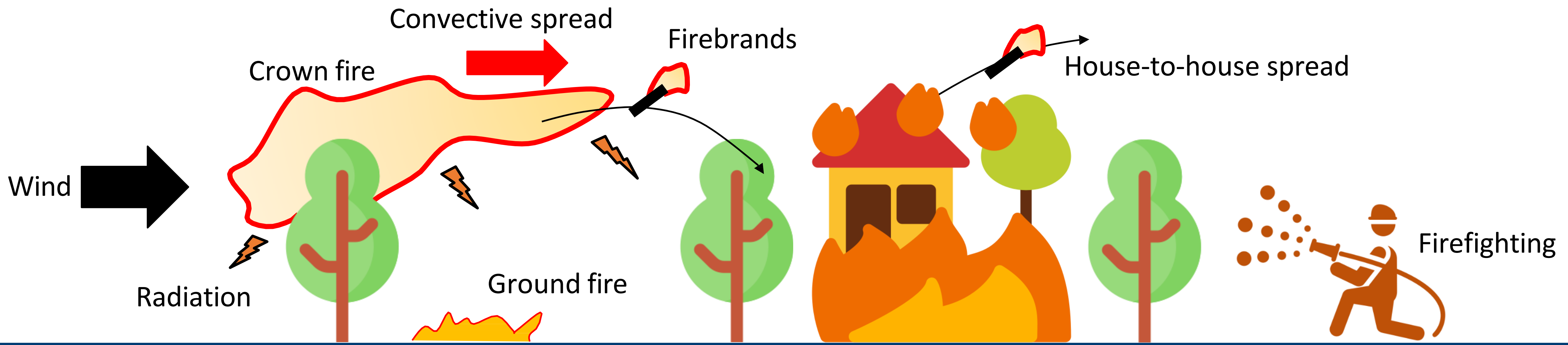
Wind direction on the day of the fire

"Patchy" behaviour very different from wildland fires; confirmed in most WUI fires

- Building to building, tree to building, and building to tree spreading
- Some trees protected by (brick) buildings; pine vs other trees burnt very differently
- Some buildings more vulnerable: more fuel in the alleys/gardens, different materials, different entry point

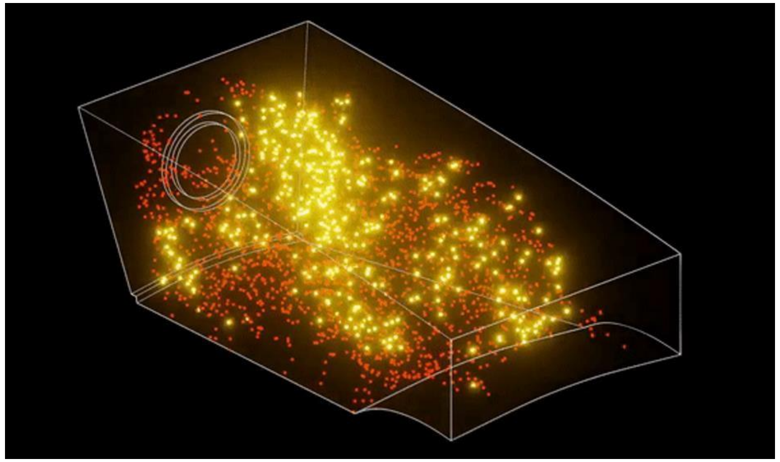
What is the mechanism of wildfire spread?

- **Convection**, **radiation**, **firebrands (from trees and houses)**
- Flammability depends on vegetation/material and climatic conditions
- Terrain and local flow matter a lot ➔ complexity and fine-grained detail
- Every fire is not the same: **stochastic** phenomenon



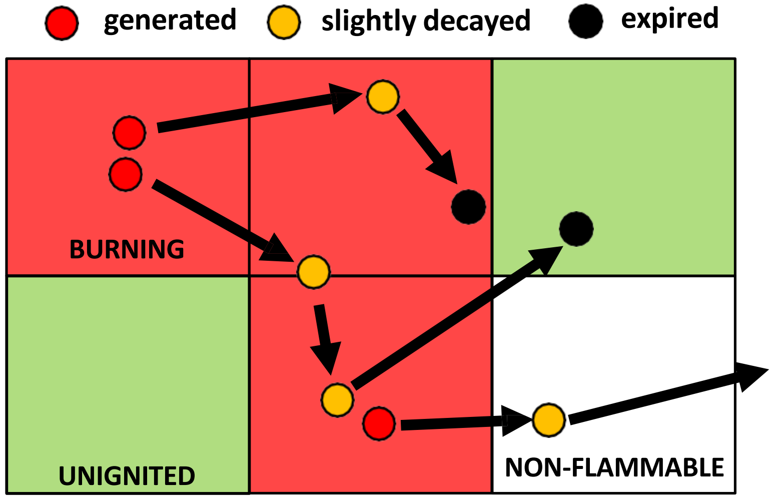
The model: overview

Inspiration: jet engine combustor ignition model



P. M. de Oliveira et al. (2021) IJSCD 13, 20-34

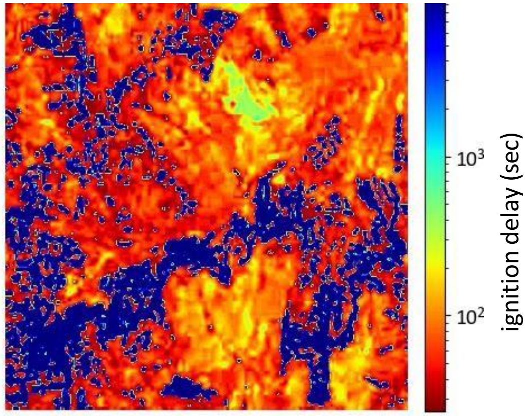
- Very fast and stochastic
- "Emitter" (burning cell) – "Bridge" (particles) – "Receiver" (landing cell)
- Uses weather/climatic conditions and extinction as appropriate
- Flammability and terrain info from fire behaviour and satellite data



CELLULAR AUTOMATON
Uses a grid/map
Terrain + flammability

LAGRANGIAN
Virtual flame particles
Random walk

RGB image ➔ Flammability



Basic principle: if cell visited from a "live" particle ➔ ignition

1 Mastorakos et al. (2022) Proc. Combust. Inst. 39(3), 3853-3862.
2 Efstathiou et al. (2023) Fire Safety Journal 138, 103795..

* ABL: atmospheric boundary layer

The model: motion & energy

- Basic stochastic differential equations for hot gases random walk
- Built-in "start & stop" spread and decay mechanisms

Langevin parameter: fire speed << wind speed

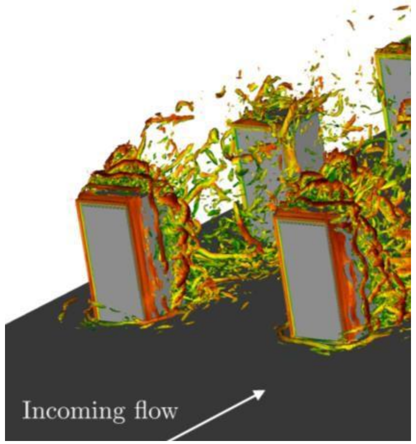
$$\mathrm{d}X_{i,p} = F_l U_{i,p}\,\mathrm{d}t, \text{ where } i = 1, 2;$$

$$\mathrm{d}U_{i,p} = -\frac{(2+3C_0)}{4}\frac{u'}{L_t}(U_{i,p} - U_{w,i})\,\mathrm{d}t + (C_0\,\varepsilon\,\mathrm{d}t)^{1/2}\mathcal{N}_i$$

ε: u'^3/L_t — from ABL*

$\mathcal{N}_i$: Wiener process

Local turbulent fire spread affected by wind characteristics



Energy balance simplified; controlled by terrain flammability

$$\frac{\mathrm{d}Y_{\mathrm{st,p}}}{\mathrm{d}t} = -\frac{Y_{\mathrm{st,p}}}{\tau_{\mathrm{mem}}}$$

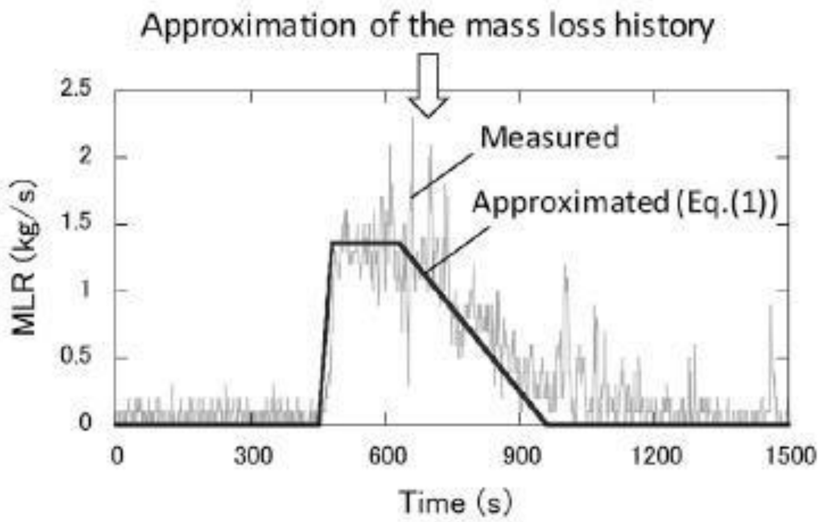
$Y_{\mathrm{st,p}}$: "burning status"

τ_{mem}: mimics flight time before a hot fluid parcel is weakened so it does not ignite neighbours (10-100) seconds

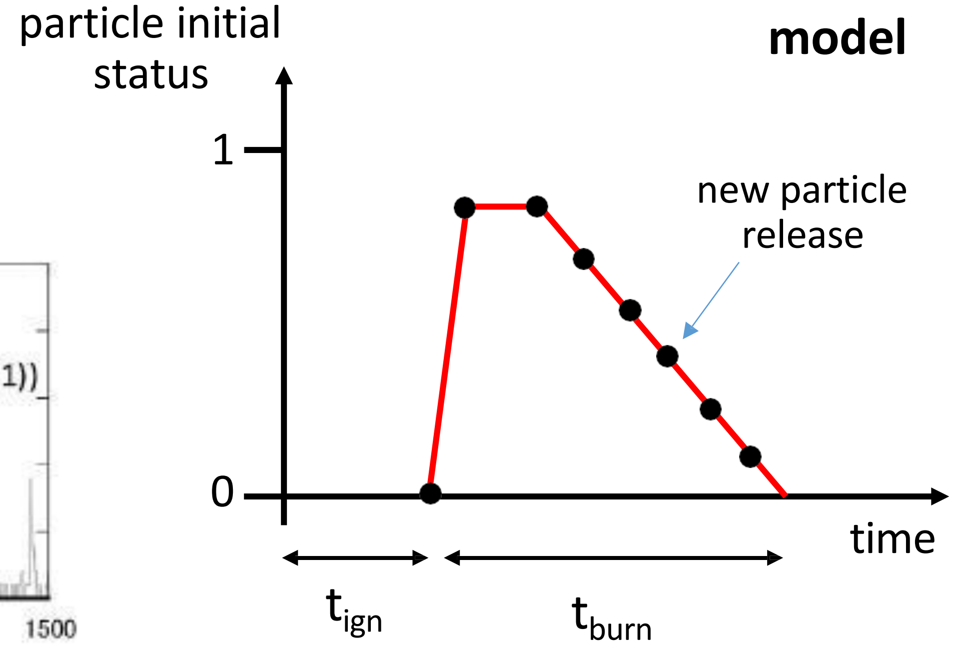
The model: flammability

- Flammability “reinvented” by mapping and discretising the heat release (mass loss) rate
- Readily adjusted to existing fire behavior fuel and ROS models

Burning structure example [1]



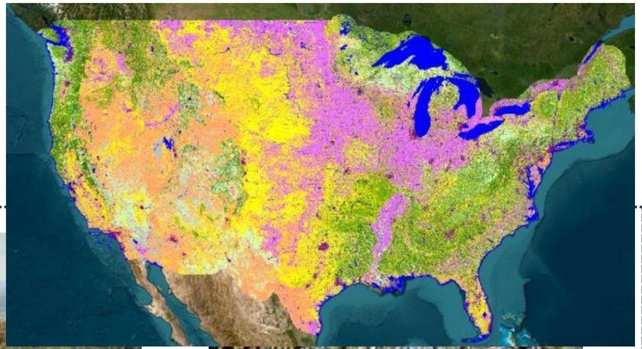
Flammability model



[1] Himoto et al. (2018) Fire Safety Journal, vol. 96, pp. 105–114.

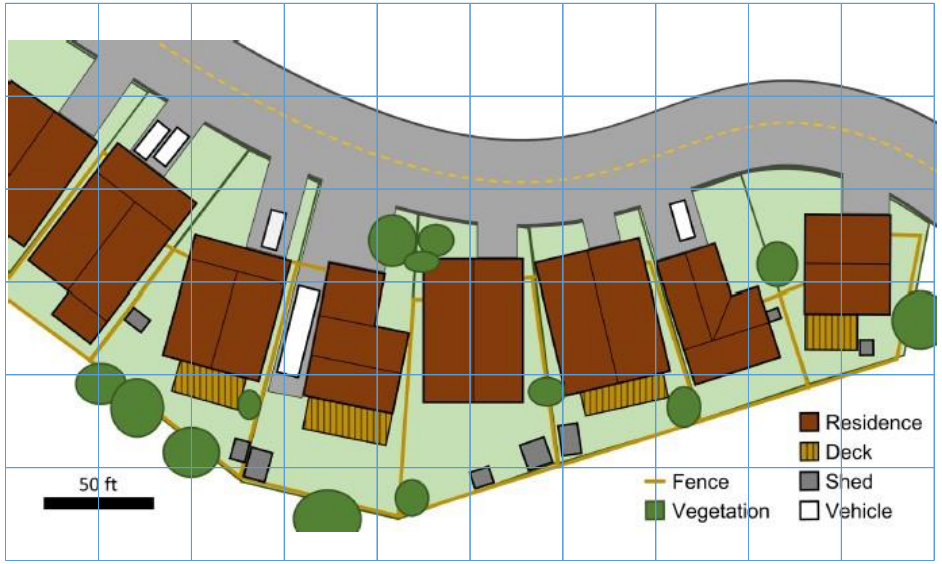
The model: granularity & WUI

LANDFIRE Fire Behavior Fuels



Surface – Crown

WUI community [1]



Unifying modelling framework – "must fit in a pixel"

Any inhomogeneous terrain for either wildland, WUI or urban

built on existing datasets
augmented by computer vision & backtesting

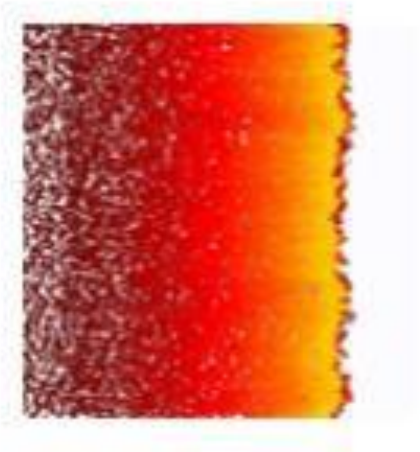
[1] Maranghides et al. (2022), NIST TN 2205.

Toy problems

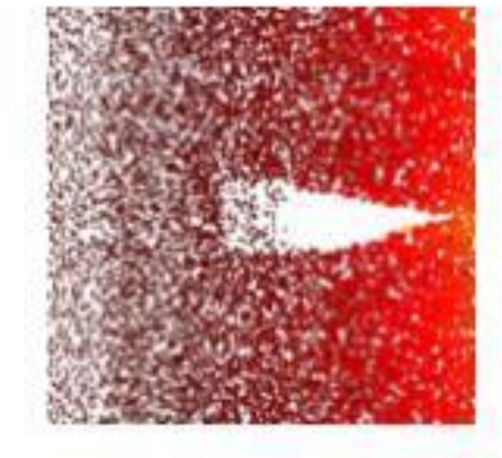
Circular front; no wind

Point ignition; wind

Line ignition; wind



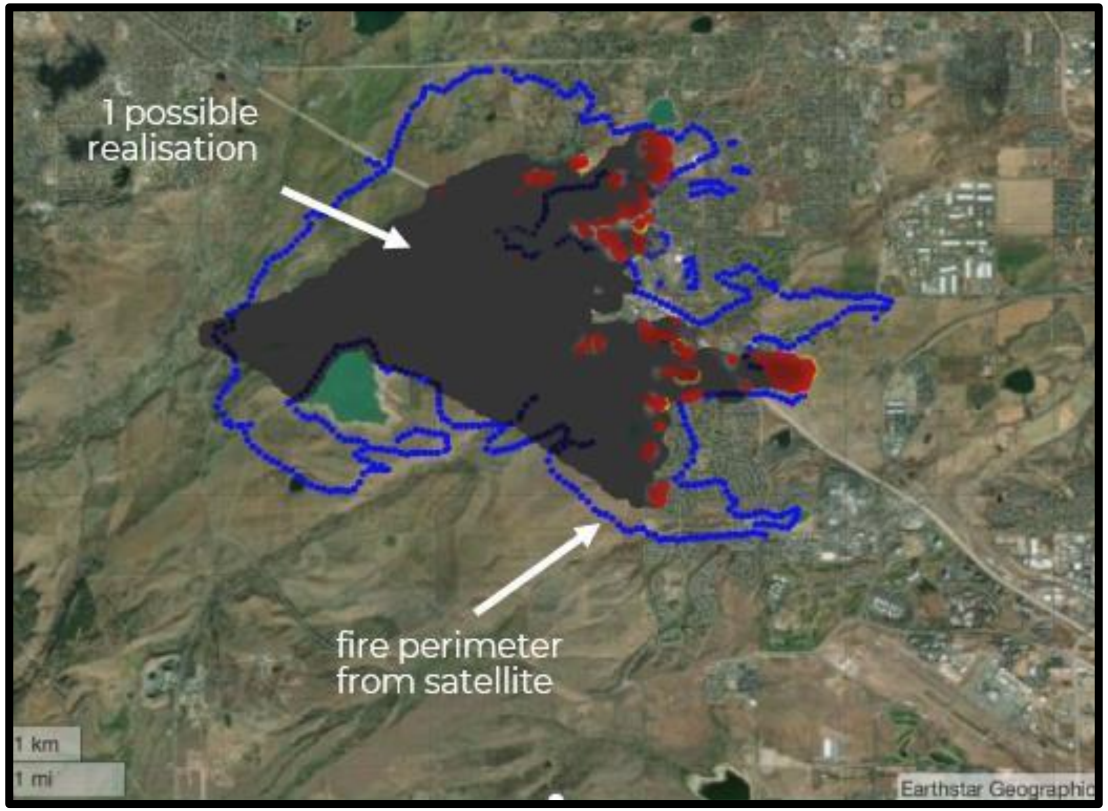
Obstacle; wind



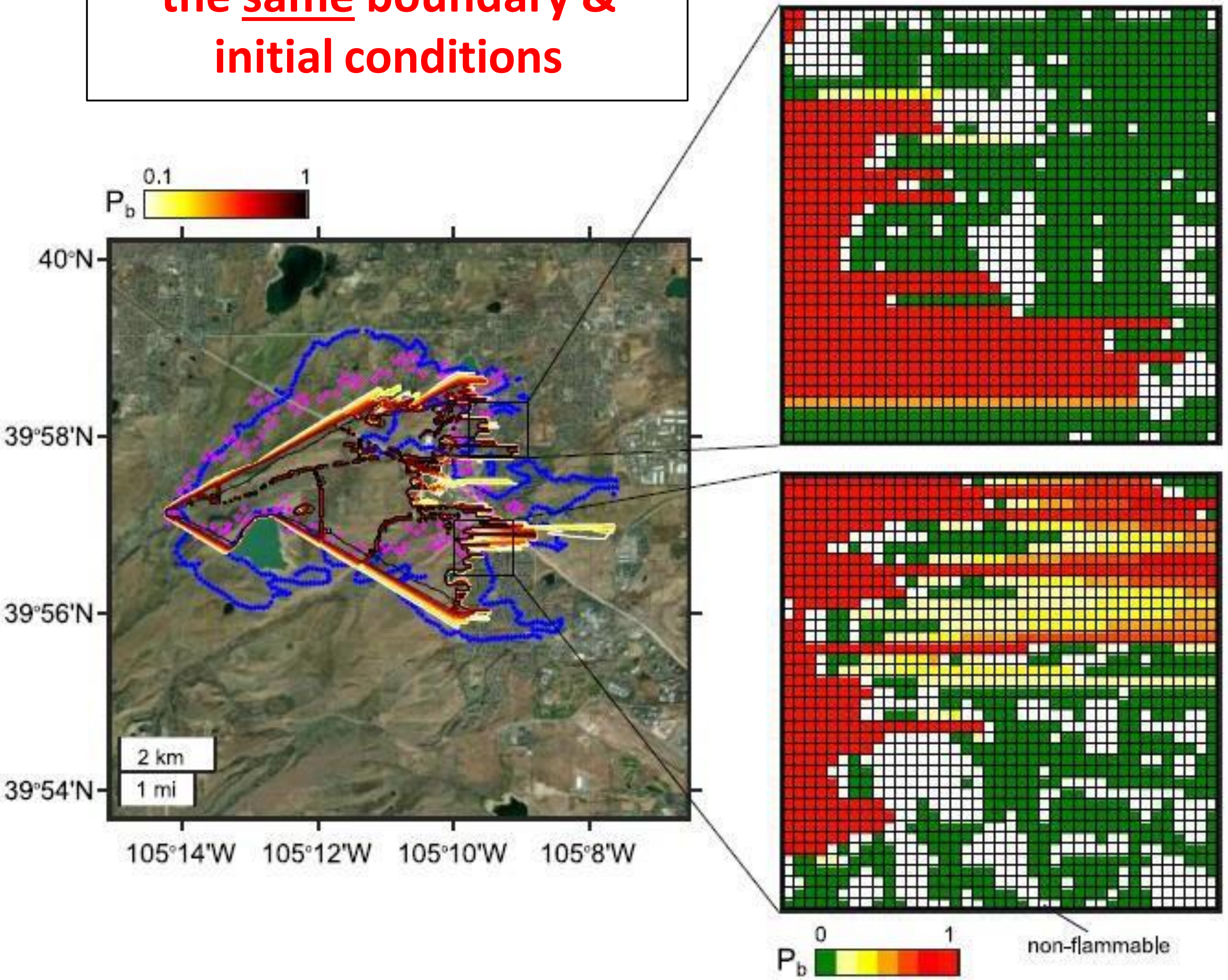
[1] Mastorakos et al. (2022) Proc. Combust. Inst. 39(3), 3853-3862.

Marshall WUI fire

Marshall fire, 31 Dec 2021



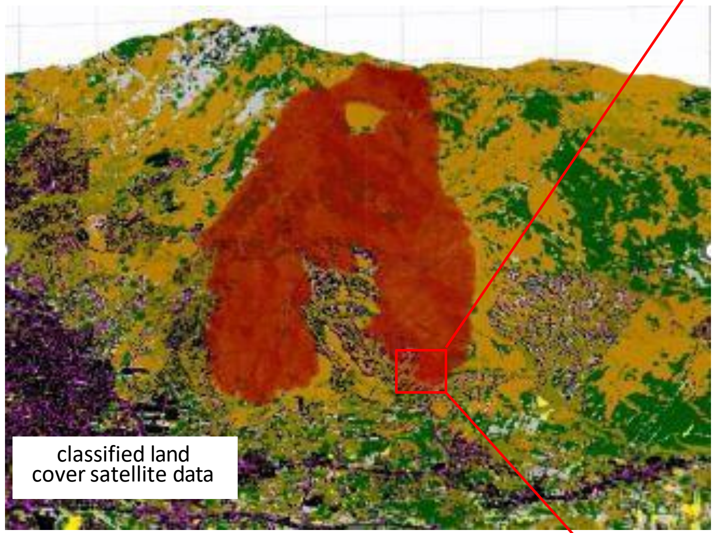
Probabilistic output using the same boundary & initial conditions



[1] Efstathiou et al. (2023) Fire Safety Journal 138, 103795.

Athens WUI fire

- burnt plot of land
- virtual fire particles used in the model to simulate fire propagation from one plausible scenario



extent of fire with 50% chance

Athens fire, 4 Jun 2022

aerial photograph and "grid" used in the model

- **24h prediction in < 2 s** without spatiotemporal wind model
- **"Lumped" firebrands + gas** motion
- **72-91% accuracy** when comparing burnt structures within 50% isoline

Academic validation suggests model is promising

➔ more extensive validation and software development performed by Pinepeak Ltd

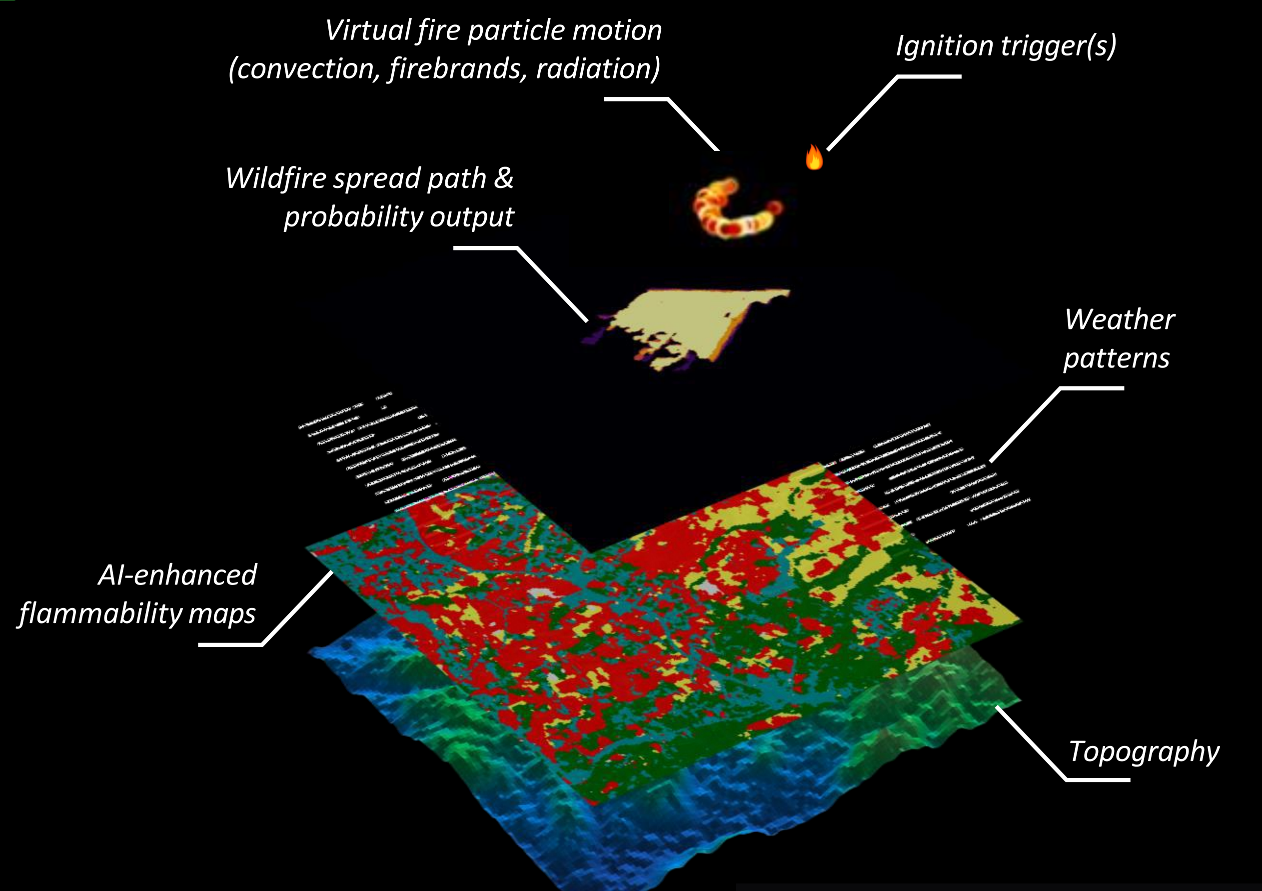
FLAMESIGHT

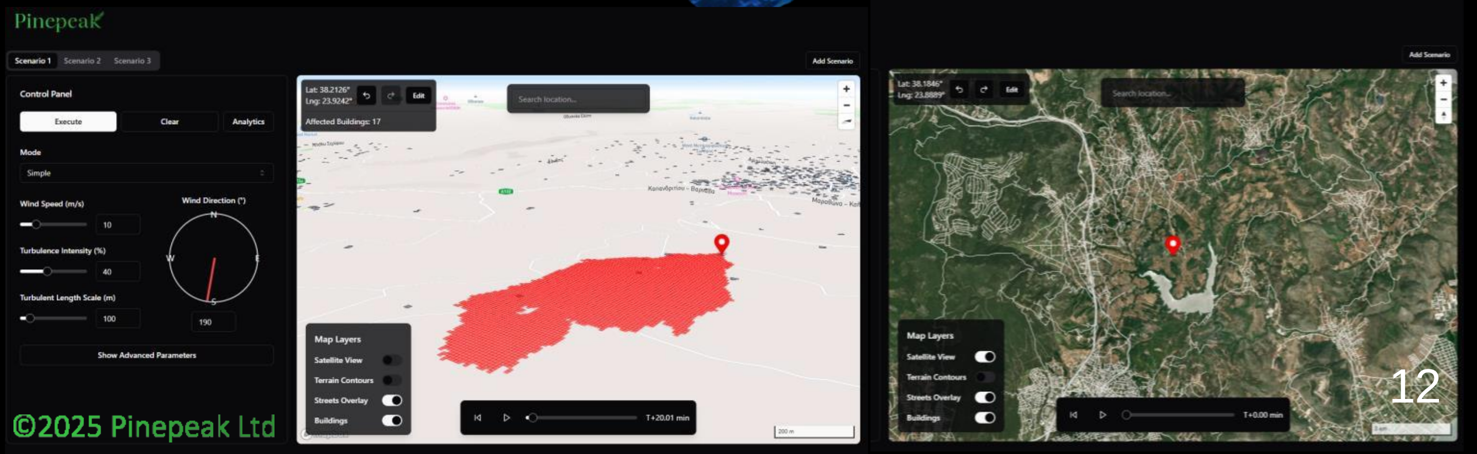
- Large WUI fire portfolio
- Layers of inputs built on *static* or *probabilistic* historical & satellite data
- GPU-enhanced and cloud-based simulations

→ Hazard + Risk maps

→ Risk aggregation

→ Decision aid tools





Connection with other models/research

Enough "placeholders" to accept information from partners/sources

- **Before the fire**: fuel and home "hardening" data, remote sensing & ML for fire biomass classification and behaviour, weather-landscape turbulence data
- **During the fire**: early warning systems; fire/wind interactions; smoke dispersion; firefighting actions; data assimilation

Current developments

- "Poor man's CFD" to get local changes due to ravines, separation or wakes
- Separate gas/flame (many different "particles" from multi-layer cells)
- 3-D motions (ABL anisotropic turbulence, firebrand history and landing distance)
- Optimisation use cases for firefighting and land management

Conclusions

- **Novel model** combining features of Lagrangian turbulent dispersion & cellular automata
- Model **addresses many challenges** in the wildfire spread modelling domain: inhomogeneous terrains & WUI
- **Academic validation** shows promise; model refinements are necessary and ongoing
- **Pinepeak Ltd** performs further validation and software development
- Many opportunities for **data exchange** and coupling

Thank you for your attention!

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