Fire Behavior

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Outline

- **Introduction**
- General Description
- Types of Fire Behavior
- Case Study
- Conclusions

Introduction

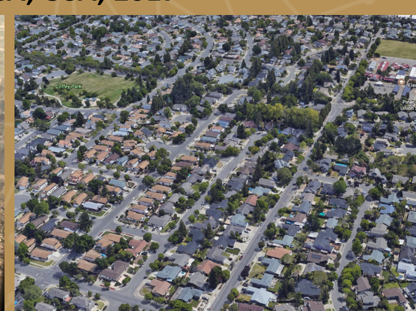
Understanding fire behavior is important because

- It can enhance the safety of the public and the firefighters
- It can help protect property and economic activity
- It can help protect natural resources and the environment
- It can help manage emission for population health and climate change

Aggravating factors are Climate Change that leads to more extreme fire behavior and urban sprawl / population growth that leads to more WUI fires

Liangshan Fire, March 30, 2019
Sichuan province, China
30 firefighters killed
(Total fire area: 15 ha)

Mati Fire, Attica, Greece, 2018



Tubbs fire, CA, USA, 2017

Introduction

Fire behavior phenomena include

- Ignition
- Fire spread
- Flaming
- Smoldering
- Extinction
- Generation and transport of particles (firebrands)
- Fire and plume dynamics and their interaction with the atmosphere

Introduction

What tools are available?

- Risk indices
  - Canada / US / Europe
  - Not doing a very good job for extreme climatic events
- Fire Spread
  - Empirical and Semi-empirical models: landscape scale (FBP, MK5, Behave, Farsite)
  - CFD models: landscape scale (FIRETEC, WRF-Fire) and WUI scale (FDS)
  - Not doing a very good job at quantifying
- Fire Safety
  - Empirical knowledge / analytical approaches
  - Standards/codes (NFPA, ICC, ASTM)
  - Best-practice FireWise (USA), FireSmart (Canada), FireSafe (California)
  - Not very strong scientific bases

Introduction

Some very strong needs to be able to achieve any quantification

- Better understand fire fundamentals
  - Combustion
  - Coupling fire / vegetation (solid / gas interaction, layers interaction…)
- Better understand the fire dynamics
  - General fire behavior
  - Fire / ambient interaction (wind, topography, atmosphere, vegetation)
  - Extreme phenomena
- Capture the changing environment
  - All year round fire seasons
  - Change in vegetation cover
  - Expansion of areas at risk of wildfires
  - Vulnerabilities of the Wildland-Urban Interface (WUI)

Outline

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- **General Description**
- Types of Fire Behavior
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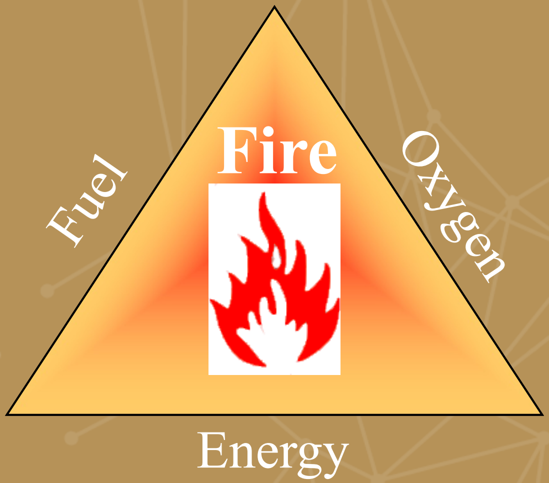
General Description

Fire Spread is governed by the

- Physical laws
  - Available Fuel
  - Available oxygen

  } combustion

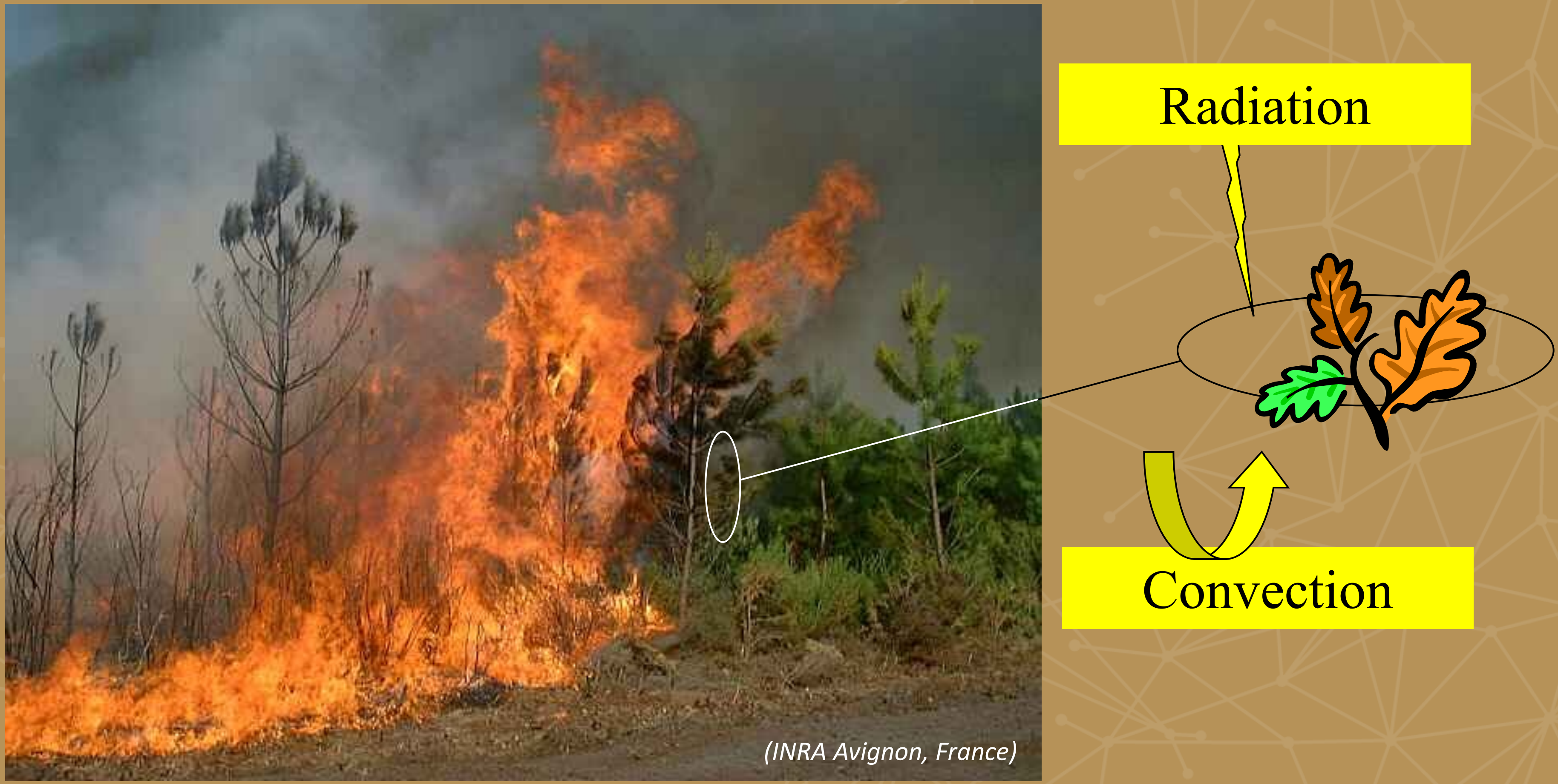
  - Heat transfer (mainly convection and radiation)



- Environmental data
  - Vegetation properties (species, fuel moisture content…)
  - Atmospheric data (wind field, air temperature, air humidity…)
  - Topography (slope, canyons, ridges…)

General Description – Fire Spread

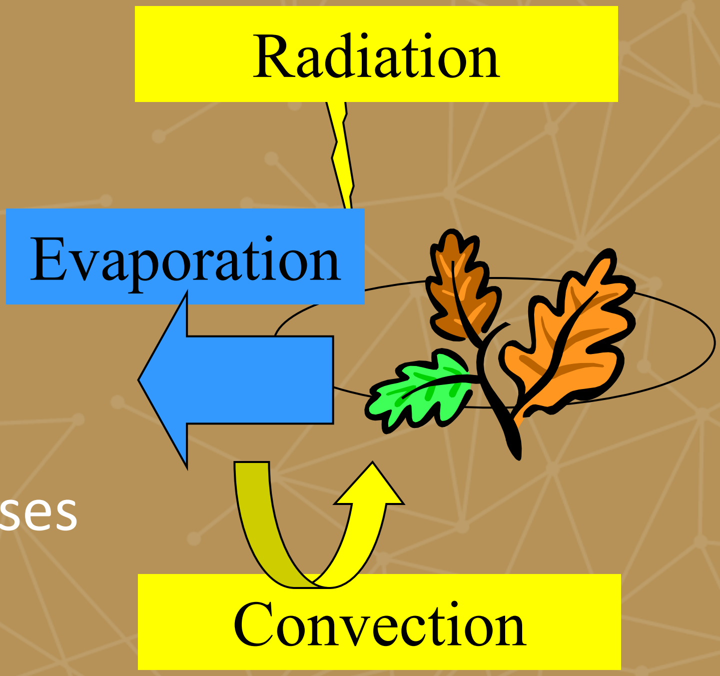
A Simple Description of Fire Spread



General Description – Fire Spread

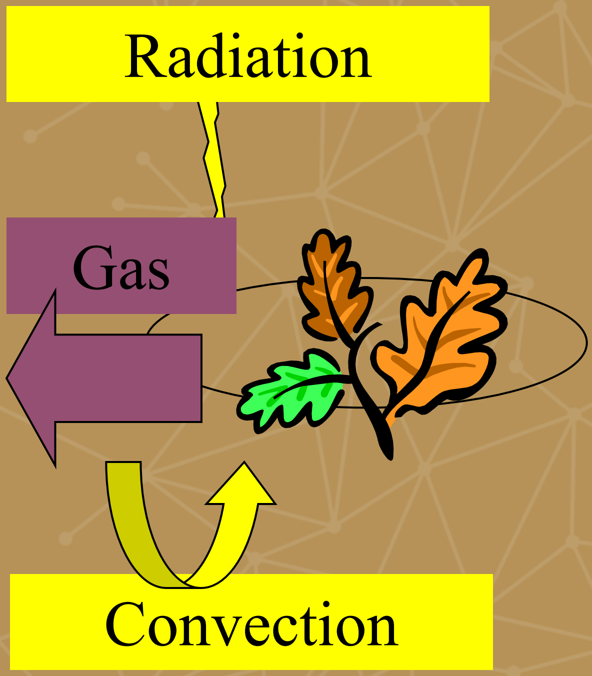
1. A particle is submitted to
   - Radiation
   - Convection

2. Its temperature increases and it looses water



General Description – Fire Spread

3. After drying
   - The particle temperature still increases
   - The dry particle releases pyrolysis gases



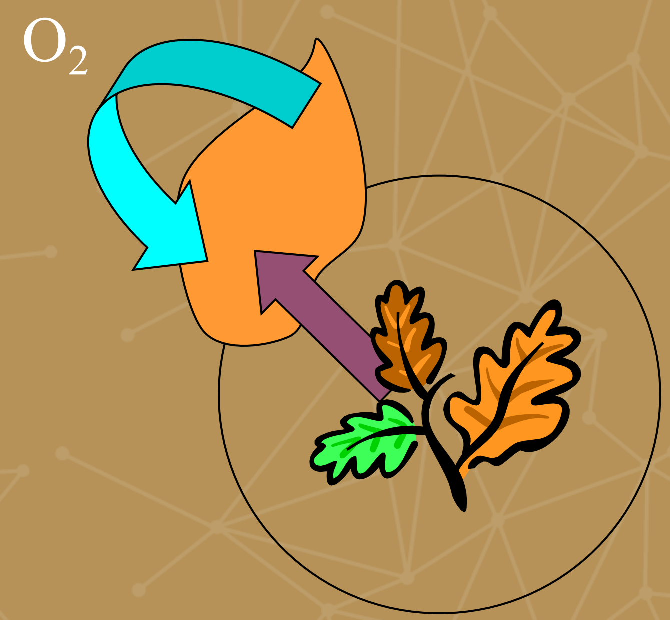
General Description – Fire Spread

4. At a given temperature (assumption)

Pyrolysis gases + Oxygen

→ Flame

→ The fire has spread

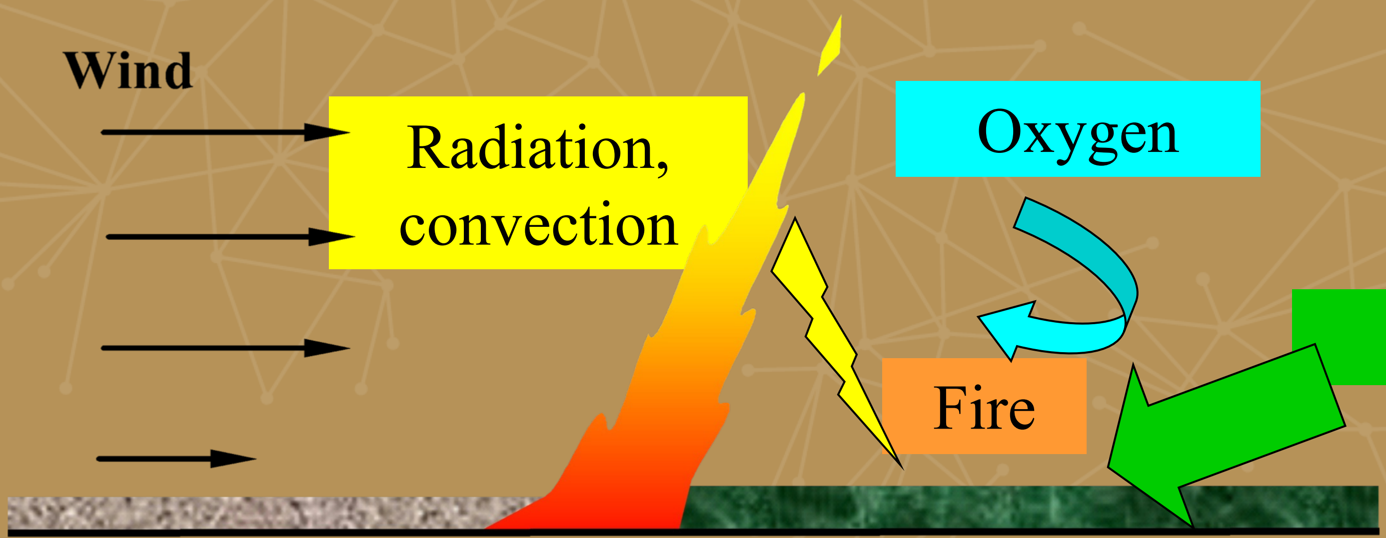


5. The particle degrades
   - To form char
   - And then ashes

General Description – Fire Spread

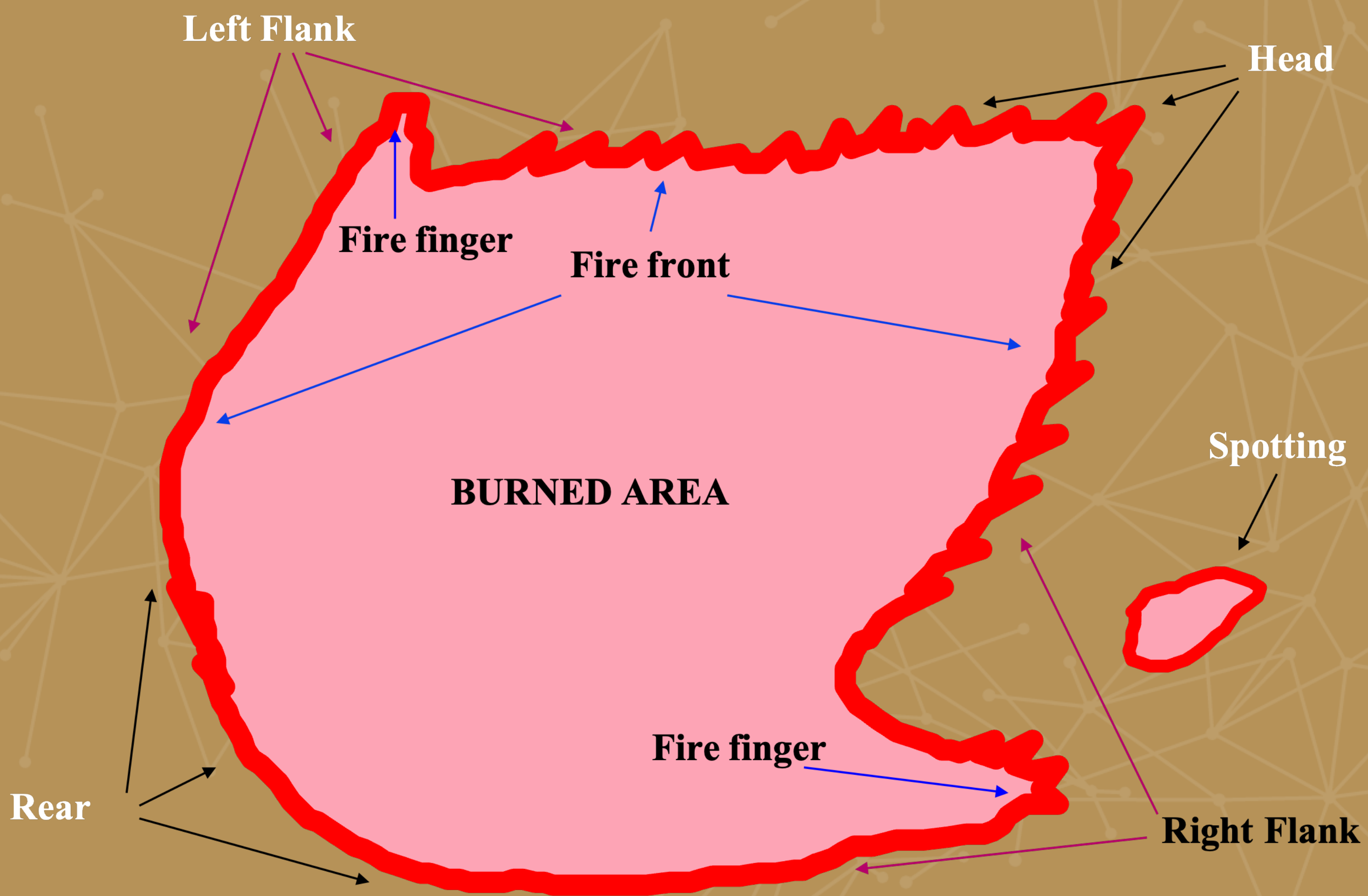
To understand and describe the fire spread implies to understand and describe:

- Thermal transfer (radiation and convection)
- Mass transfer (dehydration and pyrolysis)
- Combustion (flaming and smoldering)



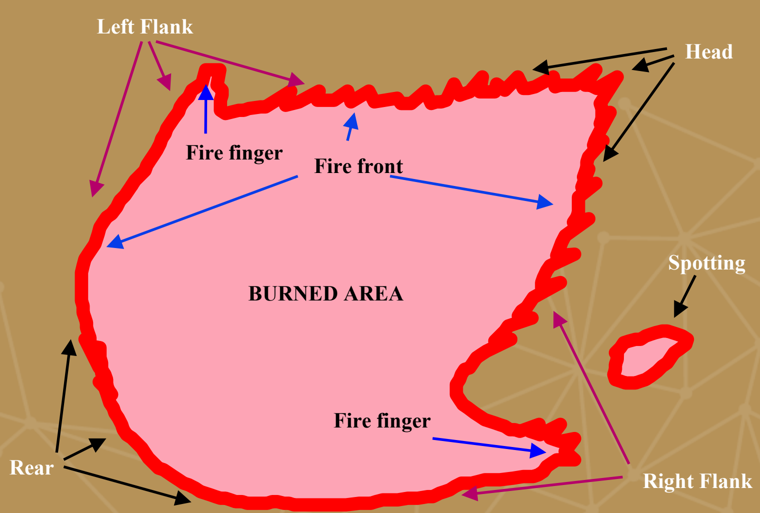
General Description – Fire Dynamics

Fire Front Shape



General Description – Fire Dynamics

Fire Front Shape



Head: Most active zone of the fire front (highest rate of spread)

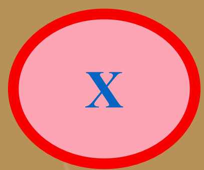
Flanks: Or sides (between head and rear)

Rear: Less active zone (fire spreads against the conditions that favor the head)

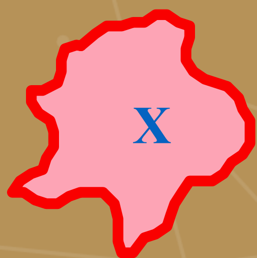
- Under certain volatile conditions (i.e. slope, wind), a head can quickly become a flank and vice-versa
- Spotting is due to firebrands (flying embers)

General Description – Fire Dynamics

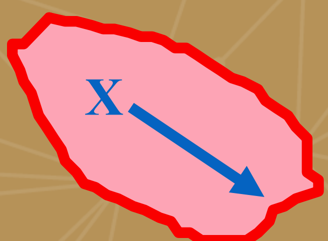
Fire Front Shape



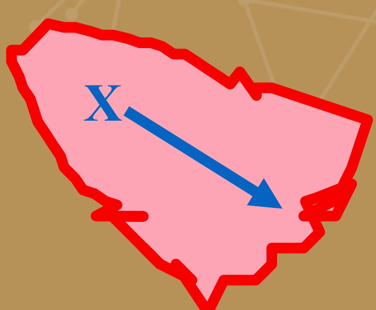
No (or weak) wind, flat ground, homogeneous vegetation



Weak wind, heterogeneous vegetation, complex topography



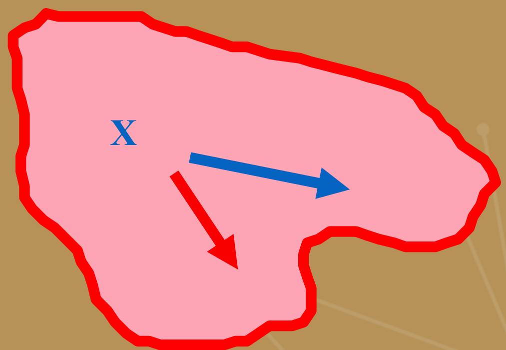
Homogeneous vegetation, low and constant wind, complex topography



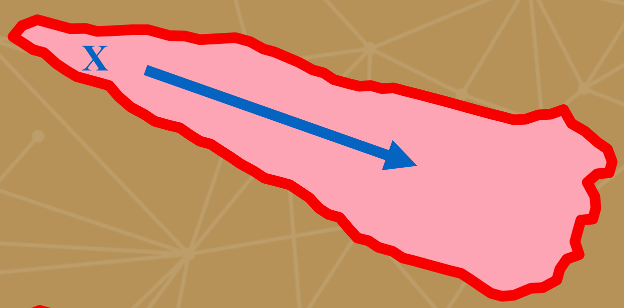
Homogeneous vegetation, high and constant wind, complex topography

General Description – Fire Dynamics

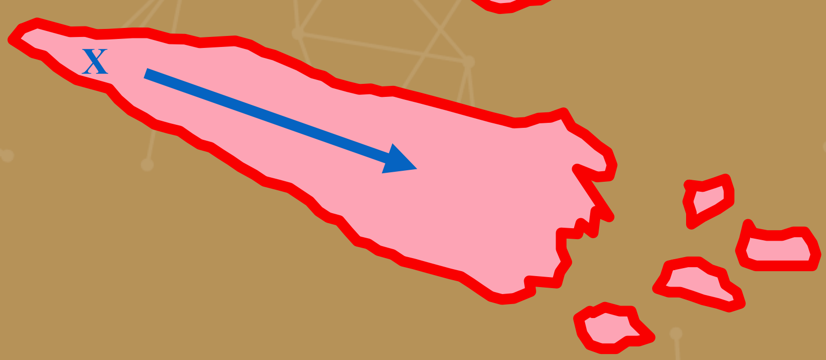
Fire Front Shape



Changing wind or slope



High wind, grass (fire spreading quickly)



High wind, spotting, change in fire regime

General Description – Parameters

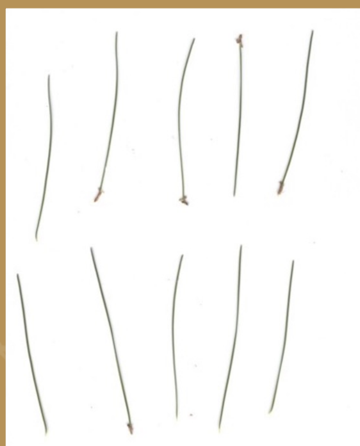
Fuel

To characterize fire behavior, it is necessary to describe

- The type of fuel
  - Fuel flammability.
  - Physical, chemical and geometrical properties.
  - Particle classes (leaves, branches, trunk…). The thinnest ones are more involved in fire spread.
- The fuel layout
  - Fuel distribution inside the fuel layer.
  - Spatial distribution of vegetation (horizontal and vertical).

General Description – Parameters

Fuel



Pinus Halepensis

L ≈ 8 – 10 cm	Ø < 1 mm

Pinus Pinaster

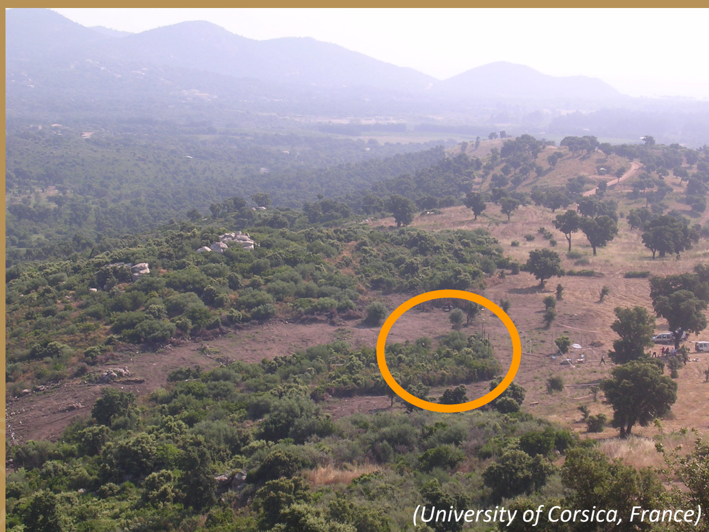
L ≈ 15 – 20 cm	Ø > 3 mm

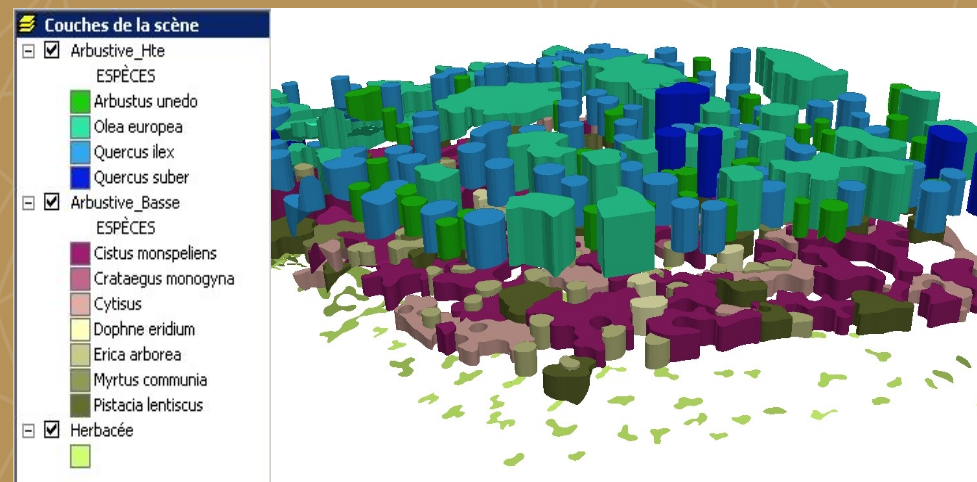
- Particles are classified by size
  - 1-h: 0 – ¼ in. (0.635 cm)
  - 10-h: ¼ – 1 in. (2.54 cm)
  - 100-h: 1 – 3 in. (7.62 cm)
  - 1000-h: 3 – 8 in. (20.32 cm)

The finest particles (1-h) are more involved in fire spread than the others

General Description – Parameters

Fuel

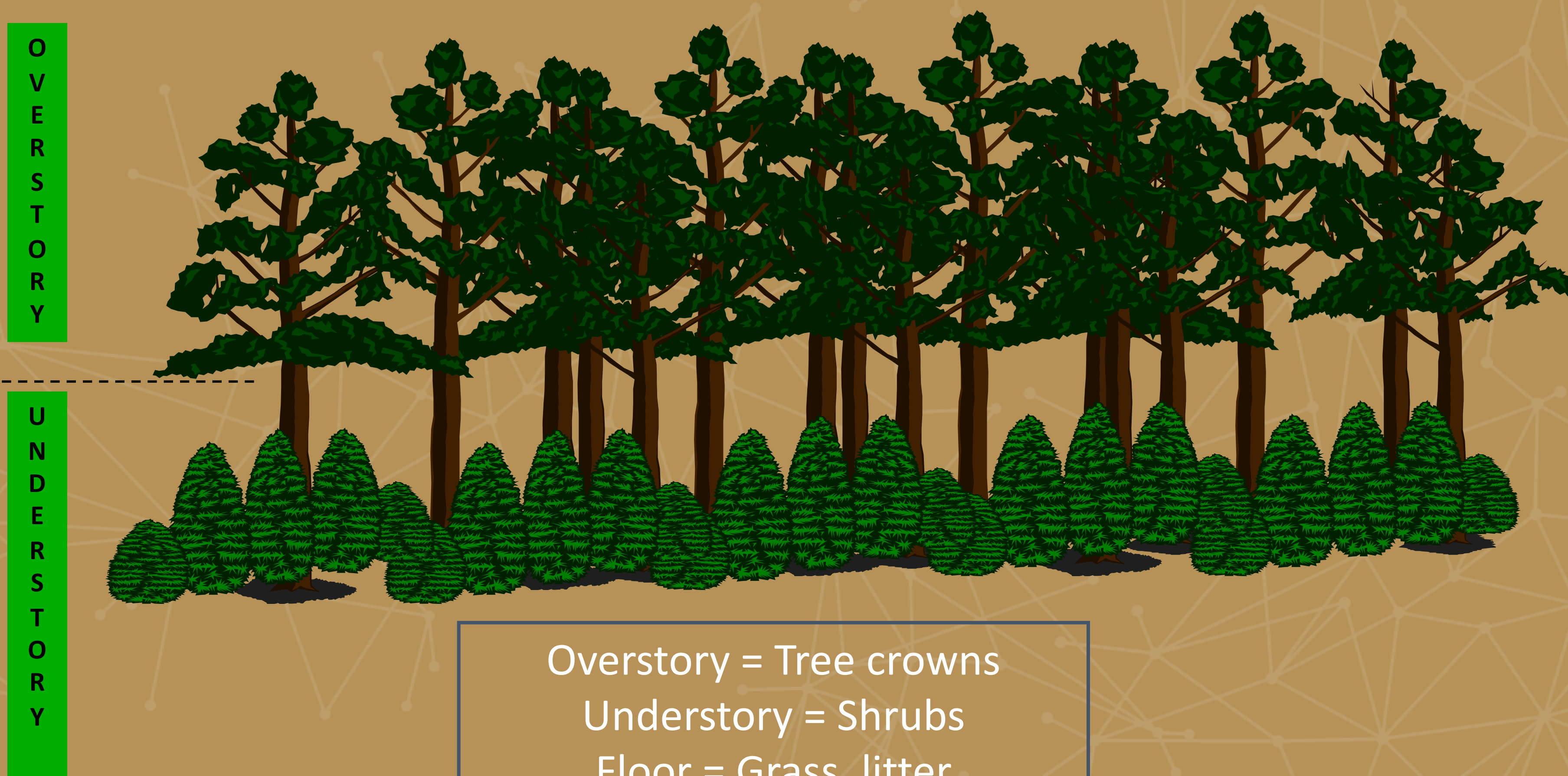




- Particle properties: Fuel moisture content, surface-to volume ratio, heat capacity…
- Fuel layer properties: layout, bulk density, radiation attenuation, permeability…

General Description – Parameters

Fuel



Overstory = Tree crowns
Understory = Shrubs
Floor = Grass, litter
Soil = Humus, peat

General Description – Parameters

Fuel

1 Litter 2 Shrub 3 Tree

General Description – Parameters

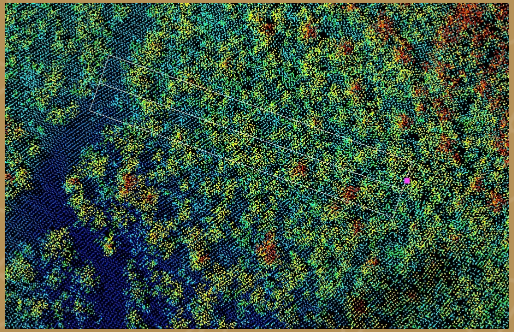
Fuel

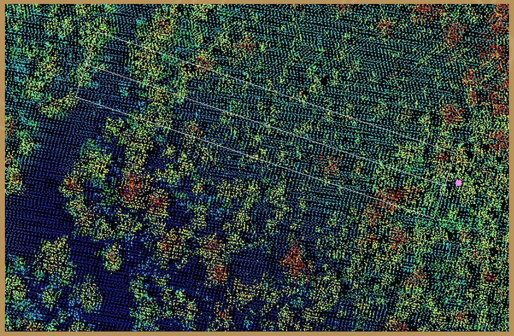
Continuous Discontinuous Continuous

General Description – Parameters

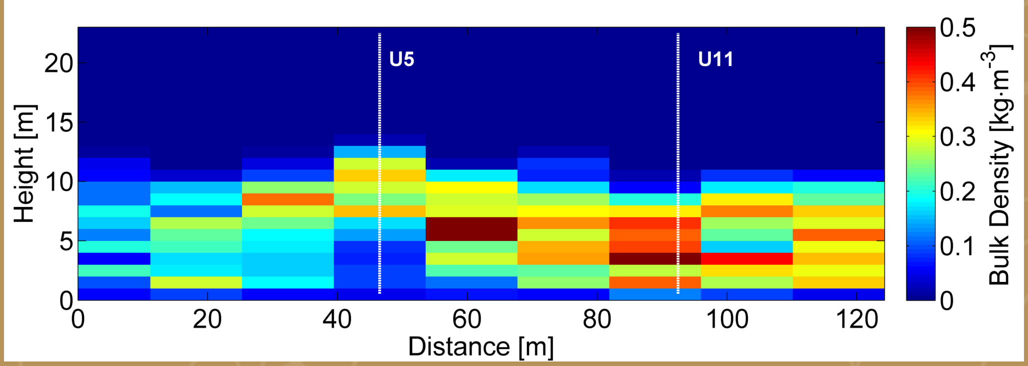
Fuel

- Destructive fuel sampling
- Vegetation measured, cut and weighed
- Local sampling
- Needs to be extrapolated





- LiDAR - Laser Scanning data (airborne and ground)
- Provides (modeled) canopy height and bulk density



General Description – Parameters

Wind

Low wind → Vertical flame

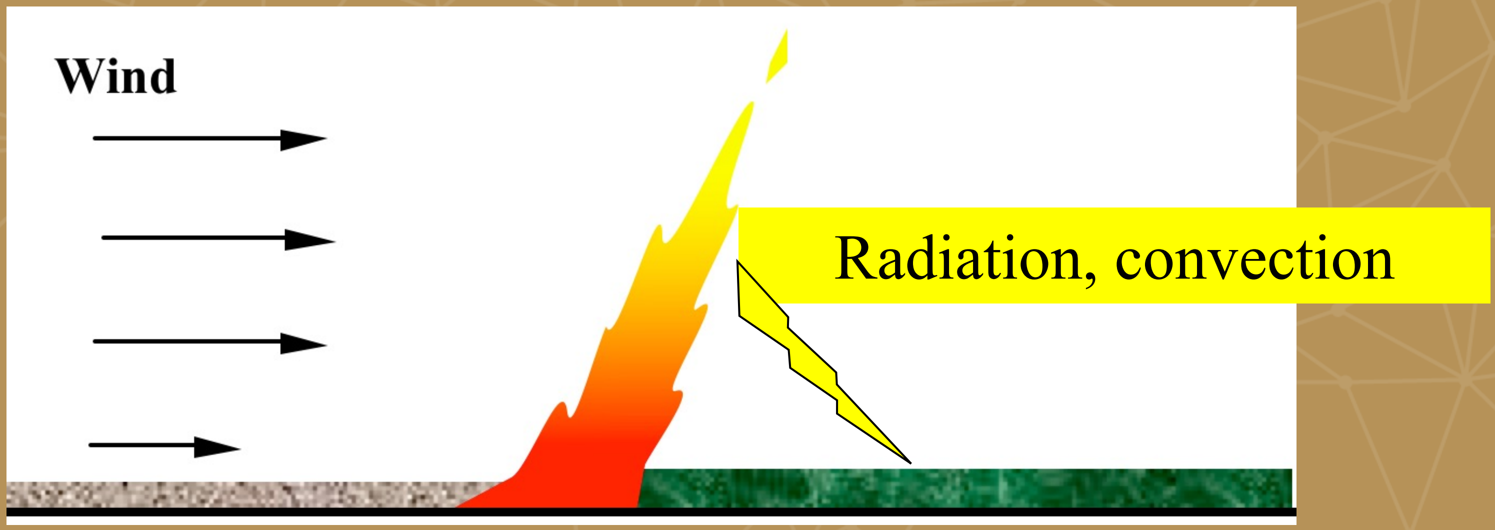
Strong wind → Tilted flame

General Description – Parameters

Wind

Main effect: Tilting flames towards unburned fuel

- Increasing heat transfer
- Speeding up drying and pyrolysis
- Supplying oxygen (fresh air)



General Description – Parameters

Slope

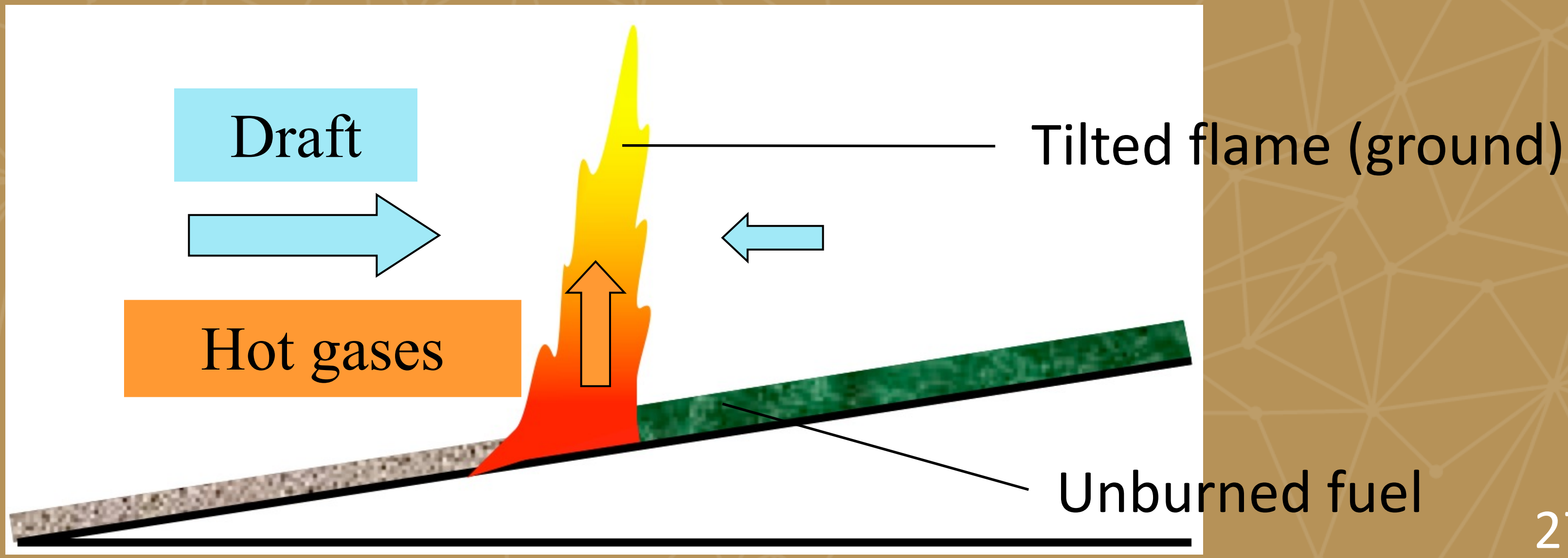
- Effects similar to wind but…
  - Slope = pointed fire head (radiation view factor from flow)
  - Wind = translation of the fire front (tilt of the whole flame front)

General Description – Parameters

Slope

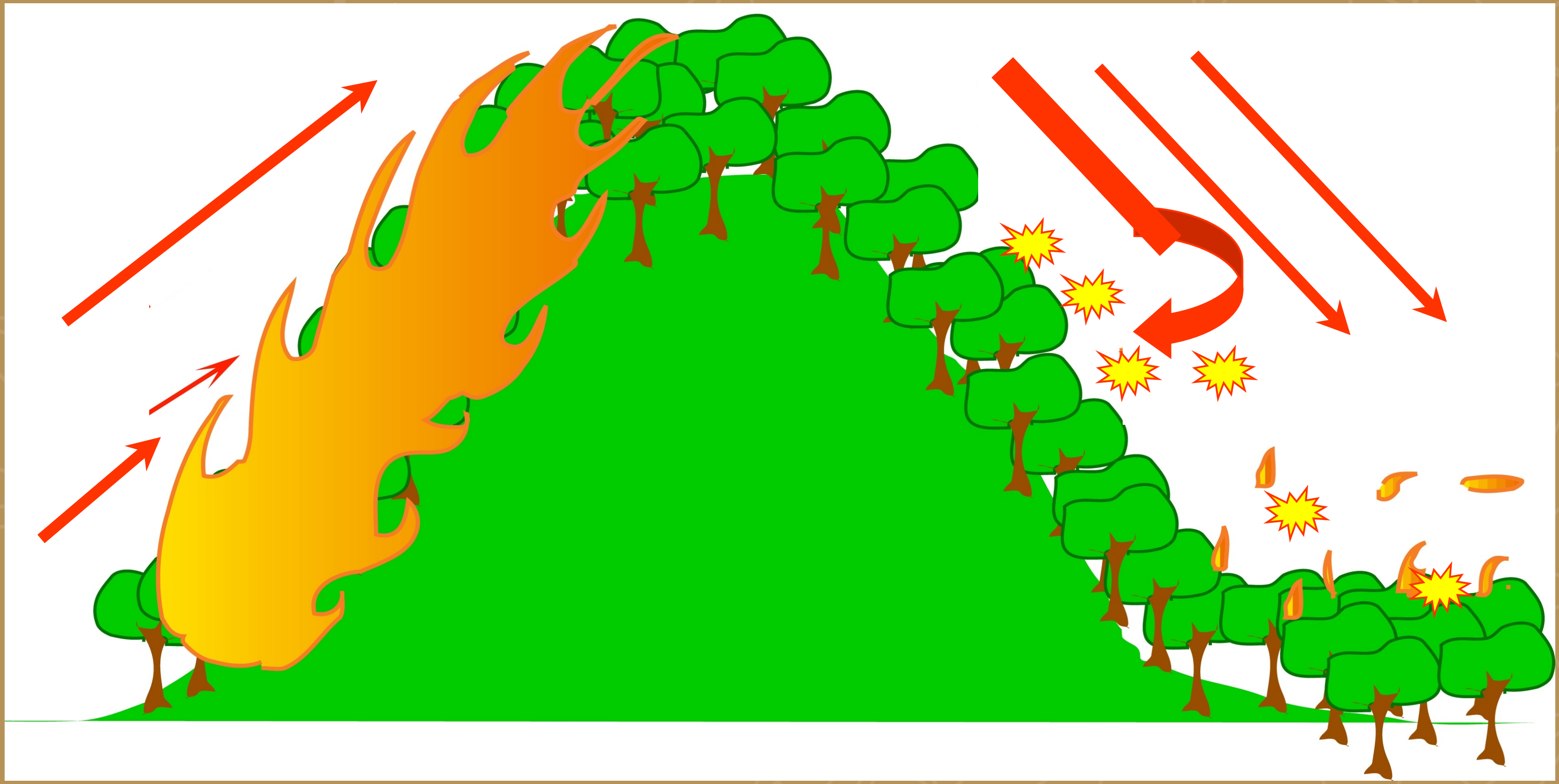
Main effect: Tilting flames like wind (until flame attachment)

- Increasing heat transfer
- Speeding up drying and pyrolysis
- Supplying oxygen (through fresh air)



General Description – Fire Dynamics

Slope and Wind



General Description – Heterogeneities

- Built-up areas
- Rocks
- Fire Scars

- Different vegetation
- Different moisture contents
- Role of wind and topography

General Description – Plume

Plume as an Indicator of Fire Dynamics

- Grey smoke: medium intensity
- Vertical: no wind

- Grey smoke: medium intensity
- Tilted: medium wind

Dark smoke: high intensity (fully developed)

Black smoke with red eddies: very high intensity (all oxygen consumed)

White smoke: low high intensity (moist vegetation or extinction)

Outline

- Introduction
- General Description
- **Types of Fire Behavior**
- Case Study
- Conclusions

Types of Fire Behavior

➢ Plume-dominated and wind-driven fires

- Plume-dominated
  - Fire spread is mainly influenced by the fire itself and weakly by the wind
  - Erratic fire behavior: strong updrafts with rapid growth, followed by strong downdrafts after air is cooled in the atmosphere. Collapse of the plume can happen, with possible high winds and short distance spotting

Types of Fire Behavior

➢ Plume-dominated and wind-driven fires

- Wind-driven
  - Plume and flames are strongly deflected by the wind. Fire spreads very quickly in direction of wind and rate of spread is quasi proportional to wind speed.
  - Can hop forward by projecting firebrands and creating long-distance spot fires

Types of Fire Behavior

WPI

➢ Peat fires


(University of Edinburgh, UK)

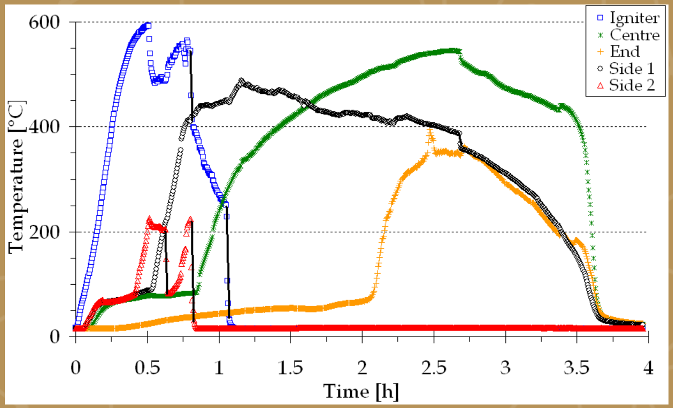

(Fire Service of North Corsica)

- Peat contains as carbon as stored in the Atmosphere (non renewable source)
  - Water resource and biotope
  - CO_2 and CO emissions (among others)
  - Contaminants stored
- Deep layers from 50 cm to 12 m
  - Can burn for weeks and even months
  - Very difficult to locate and to extinguish
- Humus quite deep in forests and dense scrublands
  - Contains soil’s life
  - Can be very dry in summer
- Shallow layers from 10 to 50 cm
  - Hot spots lasting days and weeks
  - Very difficult to locate and to extinguish

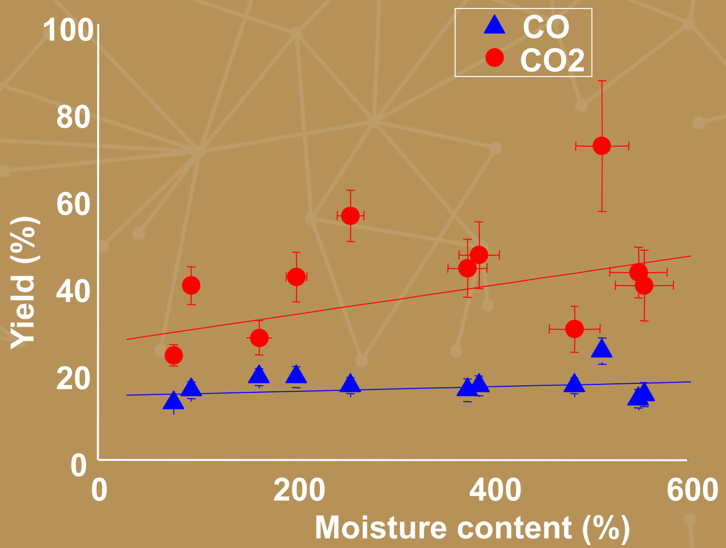
Types of Fire Behavior

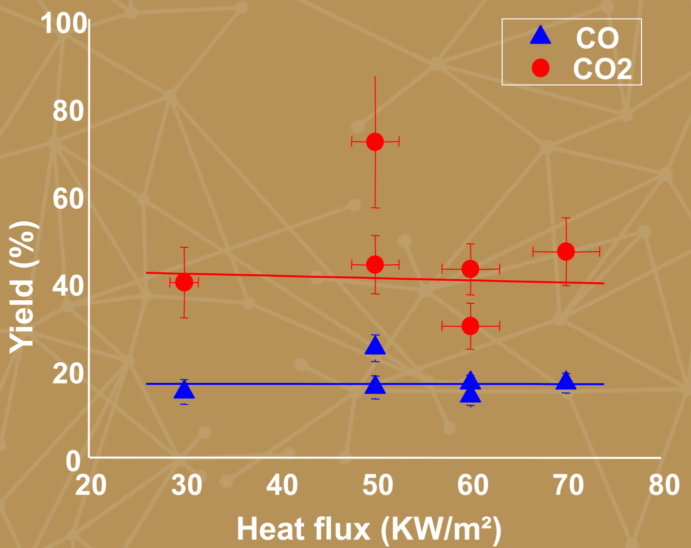
- Peat fires

Fire spread and fire severity



Emissions





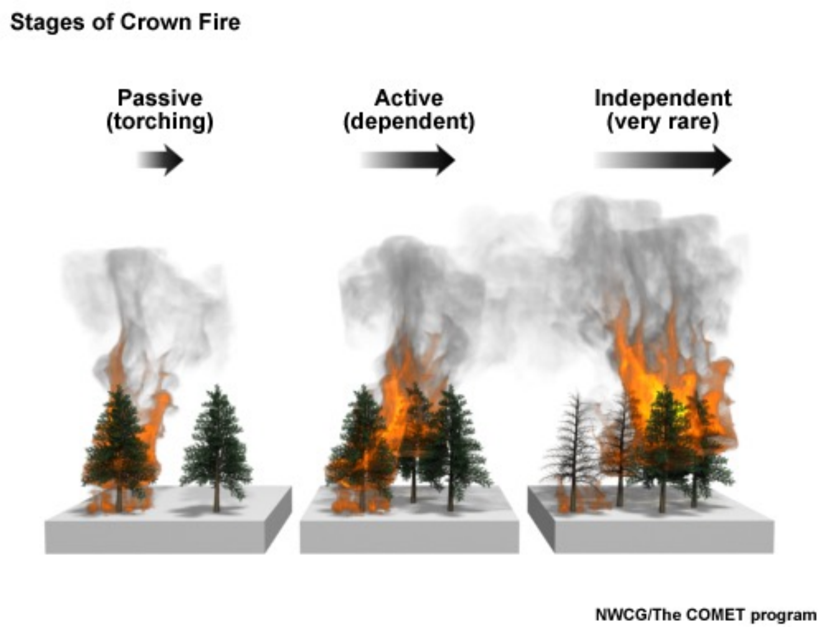
Types of Fire Behavior

- Crown fires
  - Fires that burn through the canopy layer in a forest or in an elevated shrub layer
  - Crowning (when fire climbs to the crowns of trees) depends on the underlying surface fire

- Usually very intense events
- Mostly driven by a surface fire
- Crown fire spread exists only for a range of tree densities

Types of Fire Behavior

➢ Crown fires



Three different types (by increasing intensity)

- Passive (fire spreads only through surface fire)
- Active (fire spreads in both layers but is supported by surface fire)
- Independent (fire spreads independently through canopy – needs optimal fuel density)

Types of Fire Behavior

➢ Extreme fire behavior

- Characterized by
  - Elevated rate of spread
  - High heat fluxes
  - Ember showers / spotting
  - Merging fires
  - Fire whirls
- Will affect
  - Safety
  - Smoke
  - Evacuations

Types of Fire Behavior

- Extreme fire behavior

- Fire whirls
  - Can enlarge fire front very quickly
  - Create local winds that fan flames
  - Can eject a lot of firebrands
  - Can be larger, creating a tornado

Types of Fire Behavior

- Extreme fire behavior

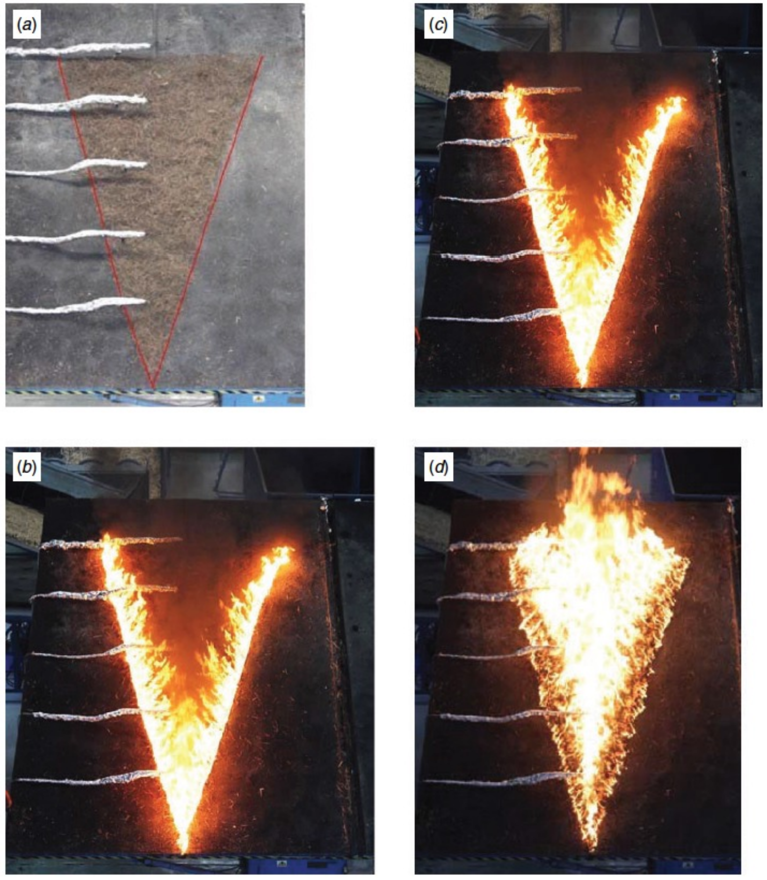
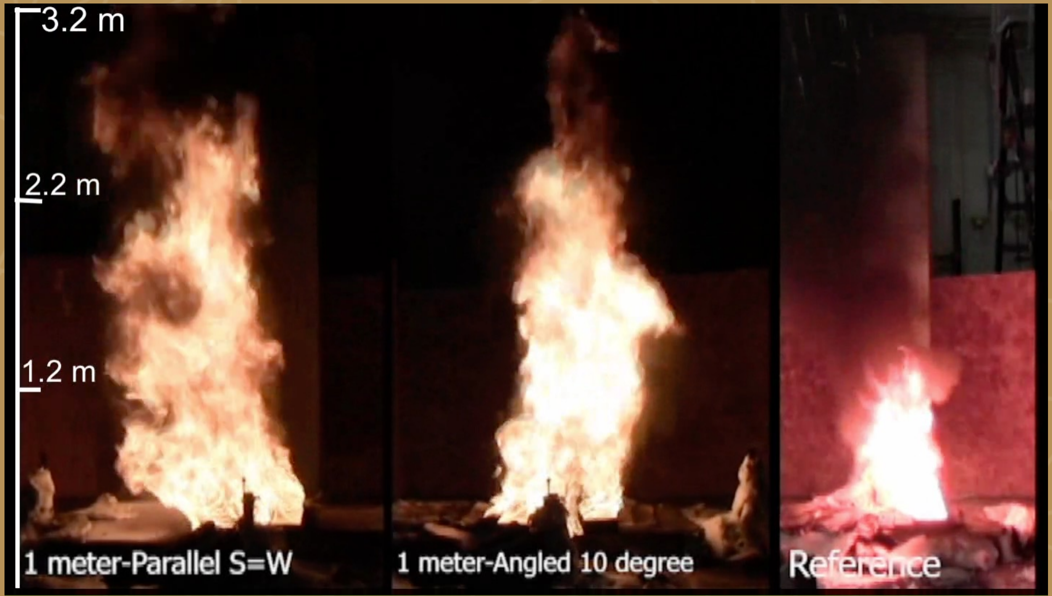


Fig. 2. General view of combustion table DE4 during the preparation and the performance of test L3030PP-63. (*a*) Reference image before the test. The Pitot tubes can be seen on the left side of the table. (*b*) At ignition: time $t = 0$ s; (*c*) $t = 2$ s; (*d*) $t = 18$ s.

- Merging Fires
  - Acceleration of flank fire fronts
  - Larger, more intense fire than initial fires



Types of Fire Behavior

- Extreme fire behavior
  - Lateral Fire Growth
    - Sharp acceleration of fire laterally behind a ridge
    - Much larger fire front spreading after ridge than initial fire front reaching the ridge

Fig. 2. General view of the combustion wind tunnel of the Forest Fire Research Laboratory of the University of Coimbra with the model of the two-dimensional hill. The length of the working section is 8 m and its width is 6 m. Maximum flow velocity is 8 m s^{-1}.

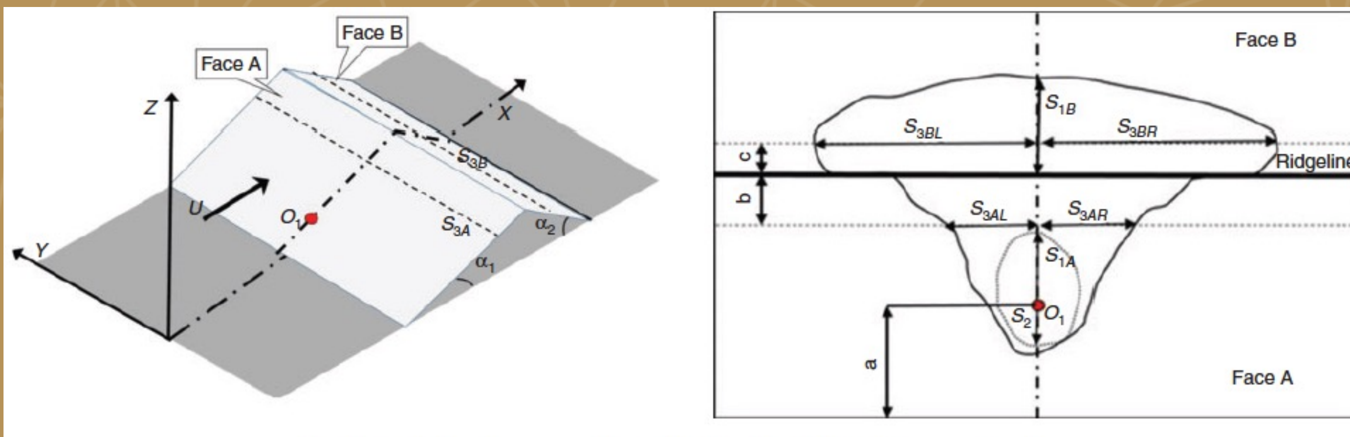
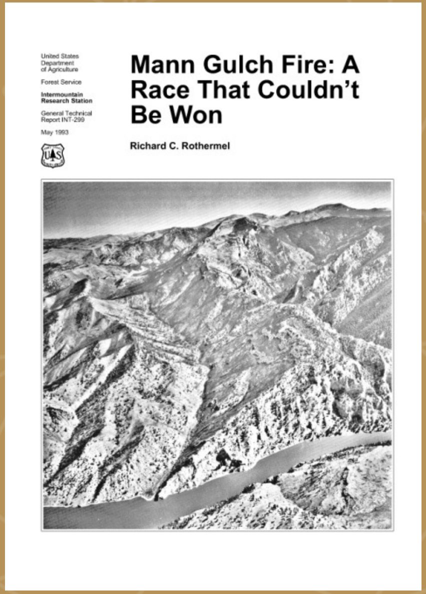
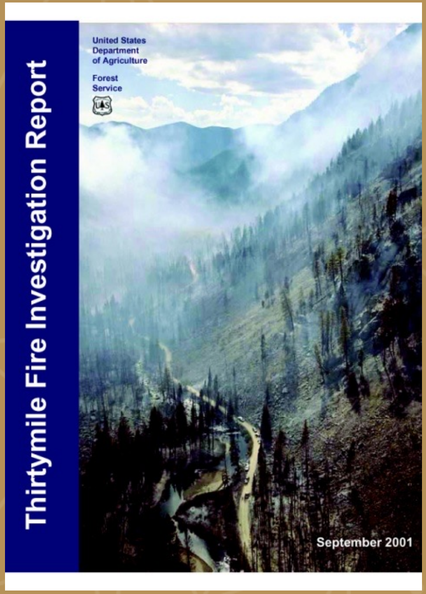


Fig. 1. (*a*) Schematic representation of the fire; (*b*) details of the fire spread analysis.

Types of Fire Behavior

- Extreme fire behavior
  - Fire Eruptions
    - Self-accelerating fires in canyons, most likely due to flame attachment
    - Most commonly from slope effect
    - Wind effect
    - Well documented in case studies





Types of Fire Behavior

- Extreme fire behavior
  - Fire Eruptions

Palasca Fire, December 17, 2000
Corsica, France
(Blowup area: circa 6 ha)

- **2 firefighters died, 5 severely injured**
- Fire eruptions: self-accelerating fires in canyons
- Estimated rate of spread: 20 km/h
- Quickly controlled by aerial means after the accident

Types of Fire Behavior

- Spot fires
  - **Different steps**
    - Generation

(Dragon, NIST, USA)

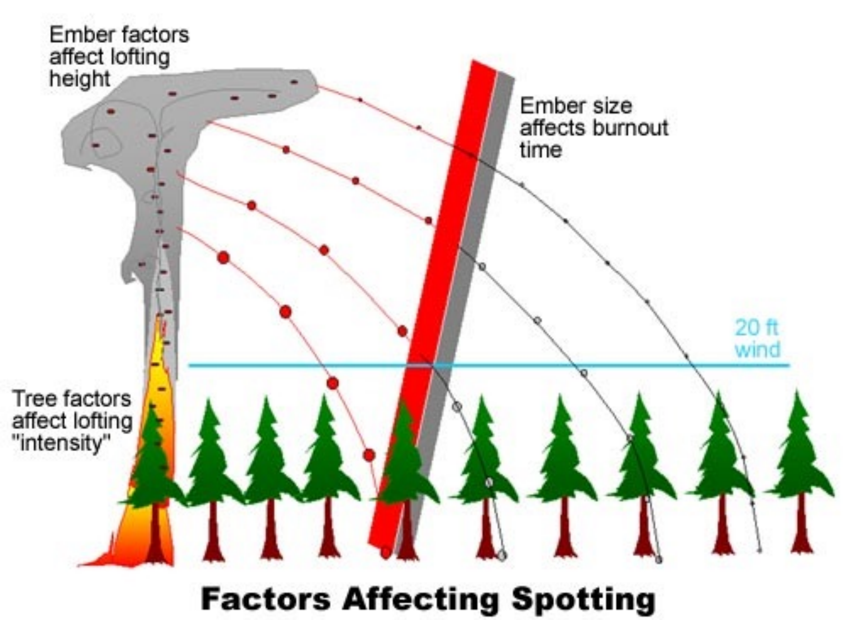
    - Trajectory

$$\vec{F}_{Drag} = \frac{1}{2} C_D \rho_{air} A_{proj} \left| \vec{V}_R \right|^2 \frac{\vec{V}_R}{\left| \vec{V}_R \right|}$$

    - Combustion

$$\frac{dm}{dt} = \frac{\pi \rho \tau}{4} \frac{dD^2}{dt}$$

    - Ignition of vegetation



(FARSITE Technical guide, USDA)

Types of Fire Behavior

- WUI Fires
  - Spread mechanisms
    - Convective transfer / Flame contact
    - Radiative transfer
    - Firebrands
  - Can be vegetation-to-structure or structure-to-structure
  - Complex interaction between topography, wind, vegetation and structures
    - WUI and community geometry channeling wind, flames, and firebrands
    - Spread corridors exist through communities

Types of Fire Behavior

➢ WUI Fires

- Whole areas are wiped out
- Fires often transition from wildland fires to urban / suburban fires
- WUI fires involve other types of fuels
- Ornamental vegetation can be left almost untouched

Types of Fire Behavior

- Firebrand showers
  - Very intense and short distance spotting
  - Can create acceleration bursts of the fire front
  - Very strong impact at the WUI
  - Can spread fire by flows of embers on the ground

Outline

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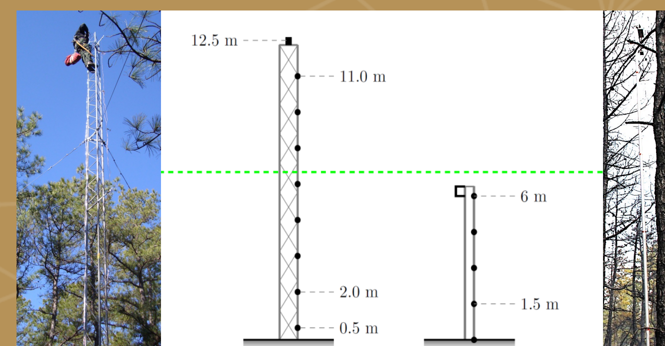
- **Case Study**
- Conclusions

Case Study

Field Experiment - Measurements

- Aerial imagery: Series of georeferenced stills taken using RIT's Wildfire Airborne Sensor Program (WASP)

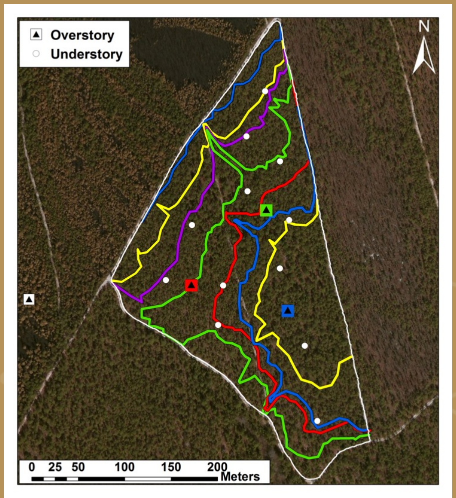
- Towers: Overstory (8 thermocouples and 1 3D Sonic Anemometer) and understory (5 thermocouples, 1 vertical flow sensor, 1 vertical dual-band radiometer)

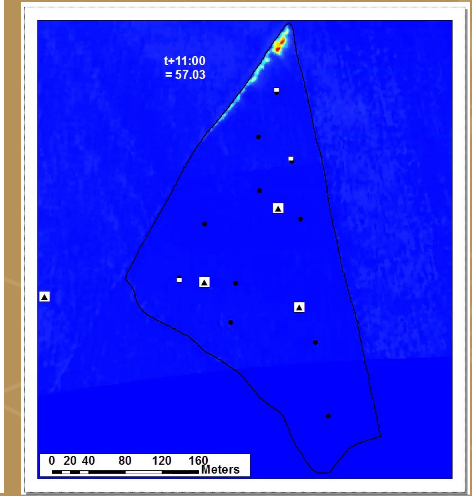


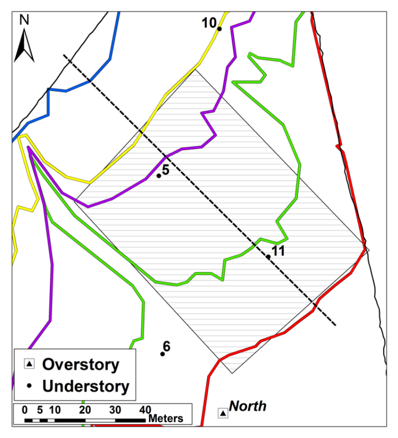
- Fire behavior packages: 4 thermocouples, 6 thin-skin calorimeters (total heat flux), 3D flow velocity

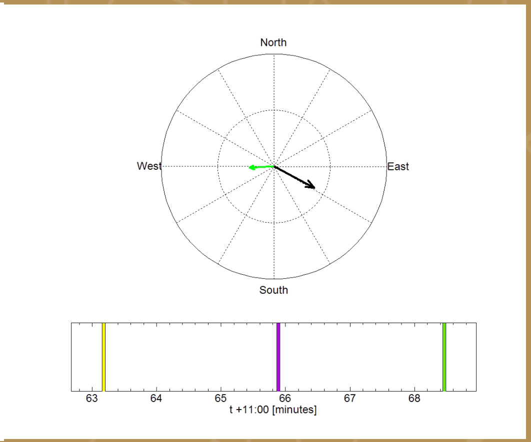
Case-Study

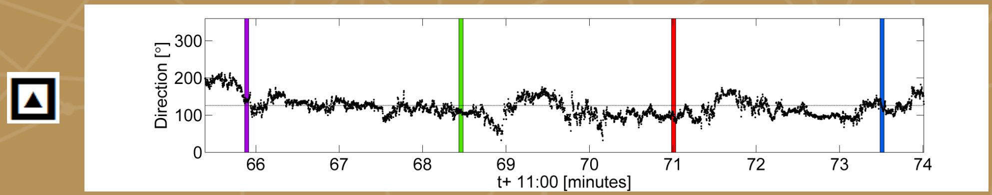
Field Experiment - Fire Spread

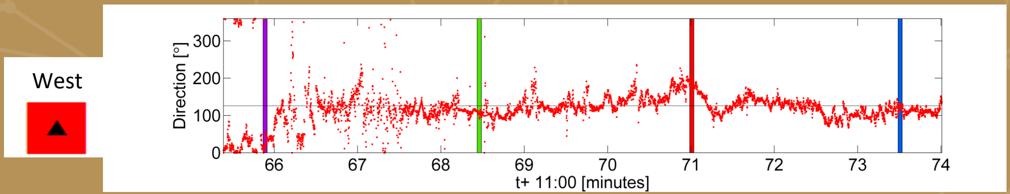


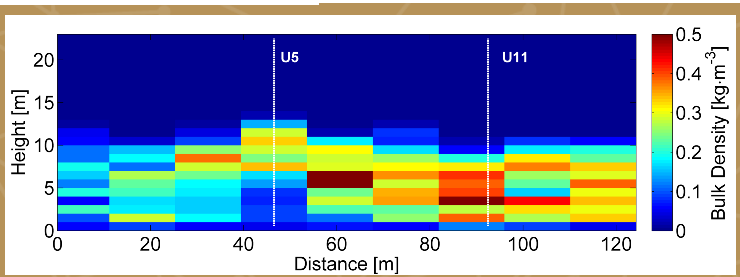


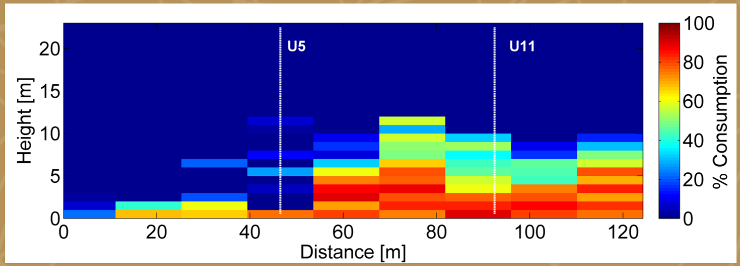












Case Study

Field Experiment - Fire Spread

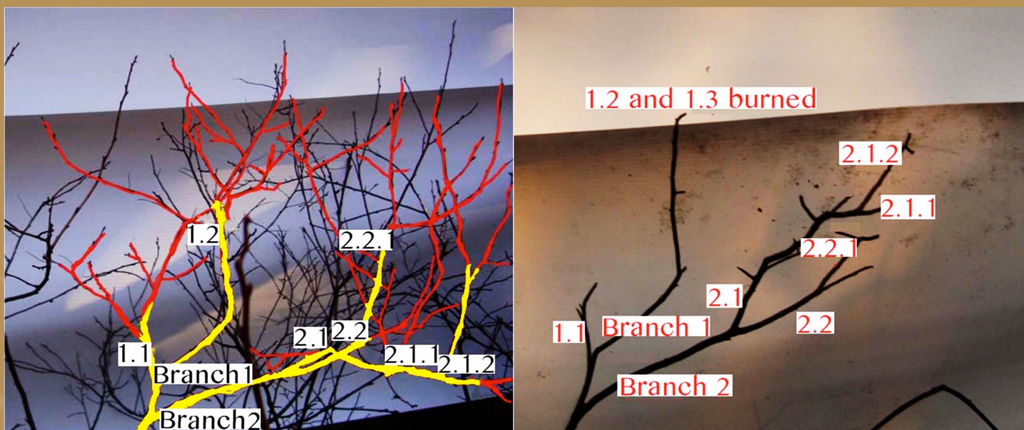
Case Study

Field Experiment - Fire Spread

- Fuel consumption is dependent on fire dynamics (and vice versa)
- Difficult to differentiate what was burned during / after fire

Case Study

Field Experiment - Fuel Consumption



Pre- and post-fire photographs and branch size measurements were used to estimate fuel consumption

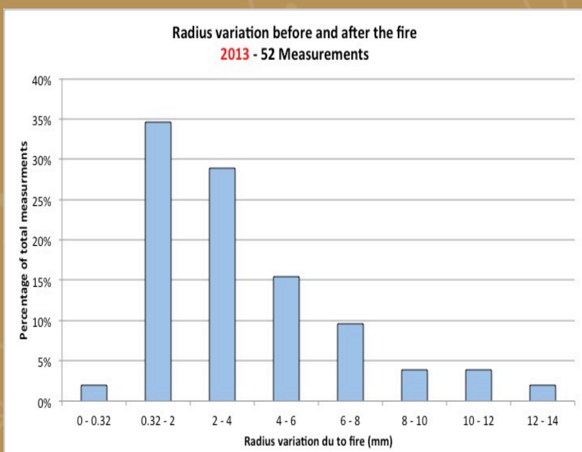
Not all 1-hour fuels were consumed (contrarily to common assumption):

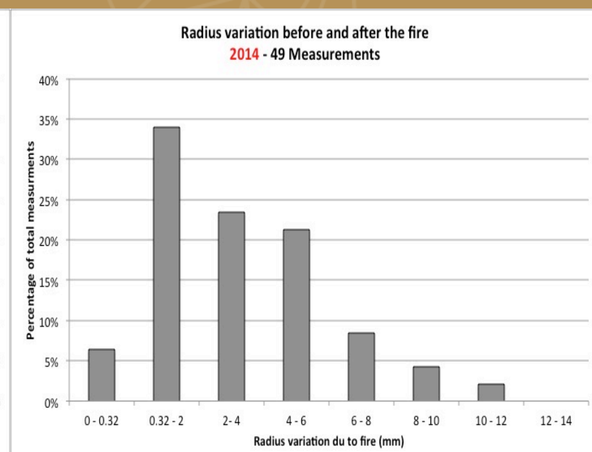
- For better estimation of fuel consumption and to better support modeling, this calss should be divided into sub-groups: $S_1 < 2.00$ mm; $S_2 = 2.01\text{-}4.00$ mm; $S_3 = 4.01\text{-}6.35$ mm.
- All S_1 consumed but less than 50% of and no S_3.

Case Study

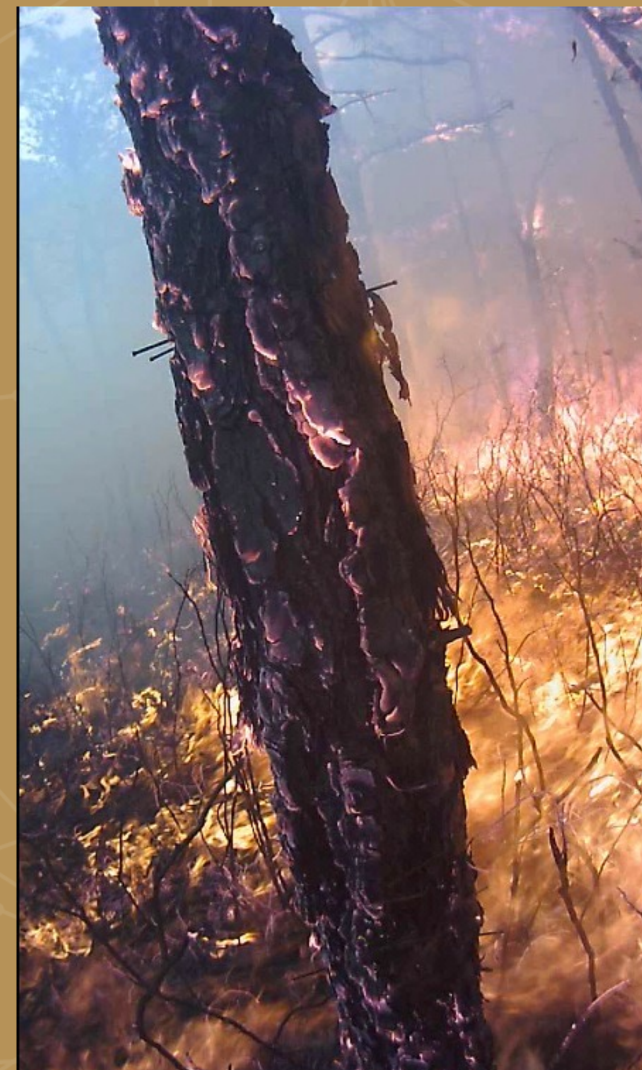
Field Experiment - Fuel Consumption

- Bark consumption estimated by measuring trunk circumference regression



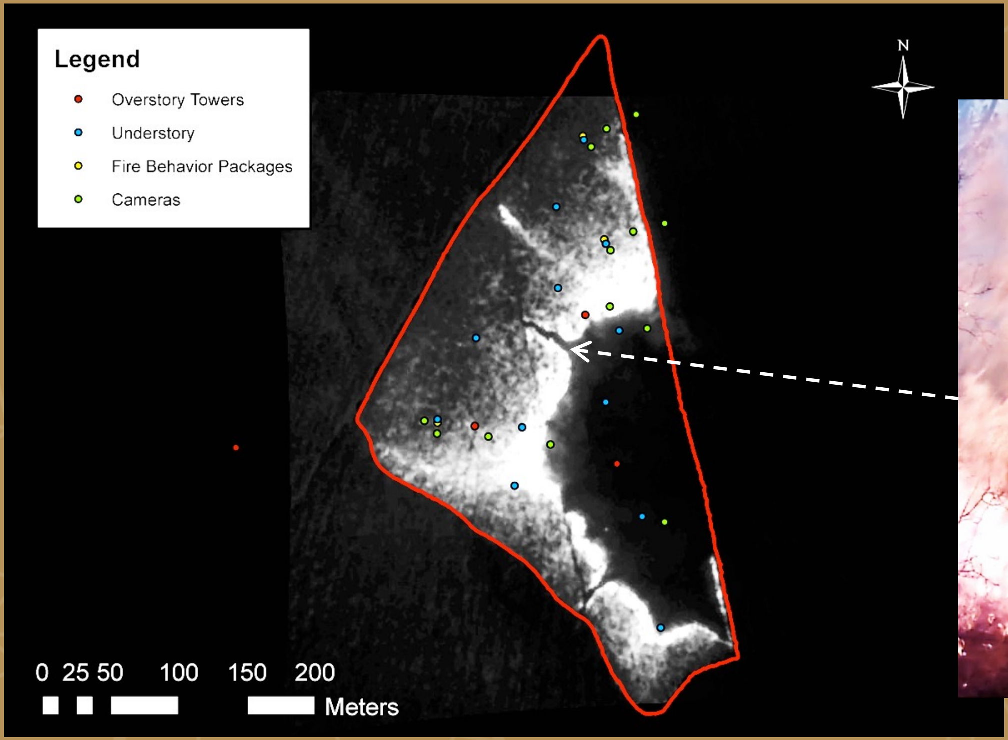


  - Most Radius variations between 0.32 and 6 mm
  - Same thickness as bark pieces collected in pans



Case Study

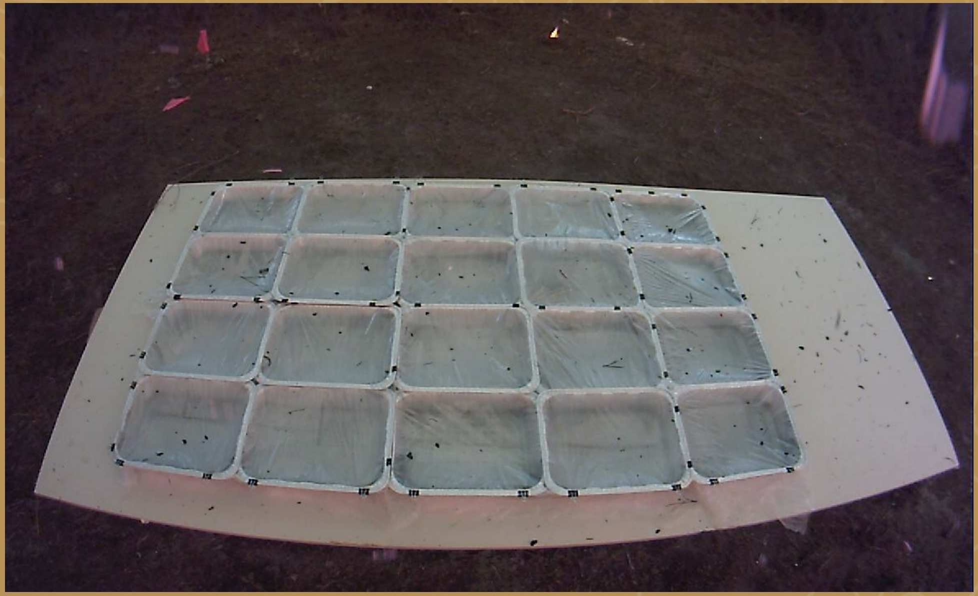
Field Experiment - Firebrands

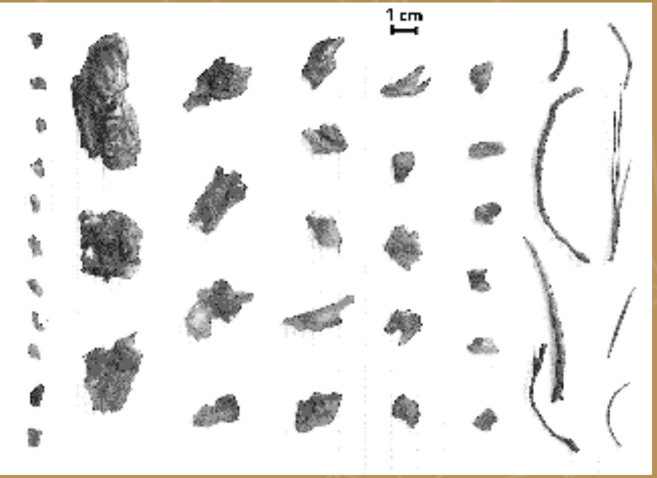


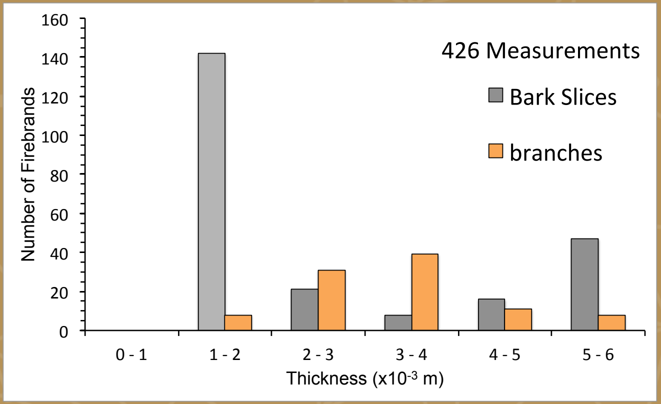
Flaming firebrands allowed a surface fire to cross easily a narrow fuel break

Case Study

Field Experiment - Firebrands





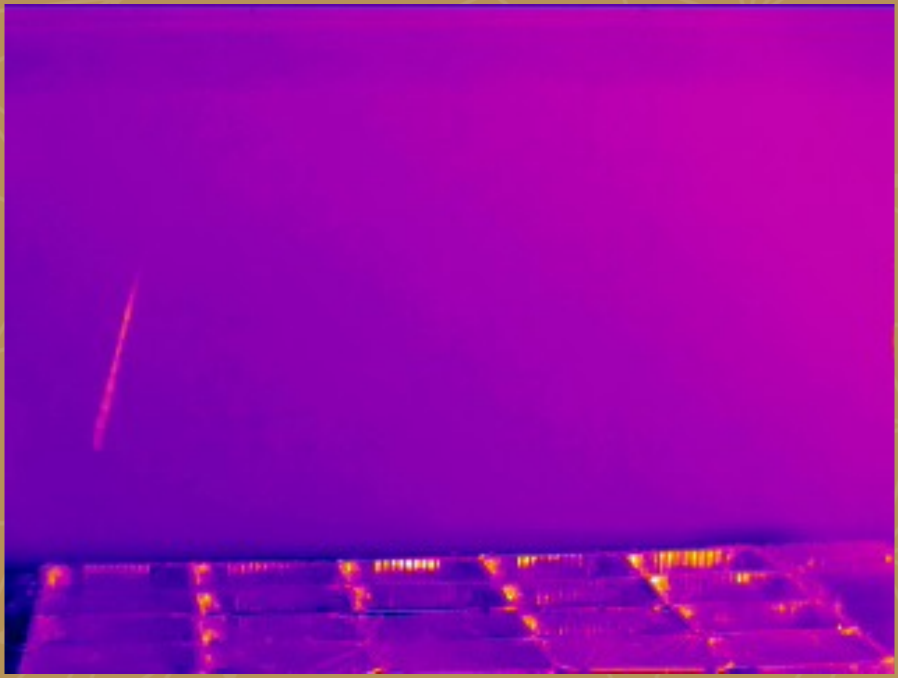


Over 70% of firebrands were made of bark

Case Study

Field Experiment - Firebrands

- Particle tracking with infrared camera
- Early firebrand production
- Erratic motion of firebrands with recirculation was observed



Case Study

Field Experiment - Firebrand Impact Experiment

Experimental conditions

- Wind
- Wood material
- Amount of firebrands
- Size and material of firebrands
- Wedge angle
- Tilt angle
- Sample gap

Flaming ignition occurred after fire punched through the sample

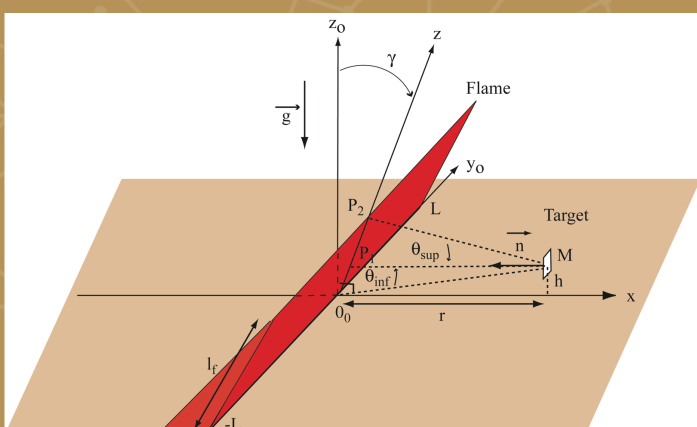
Flaming occurred on the back face of the sample

Outline

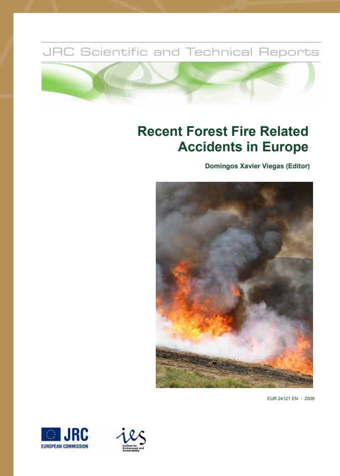
- Introduction
- General Description
- Types of Fire Behavior
- Case Study
- **Conclusions**

Conclusions

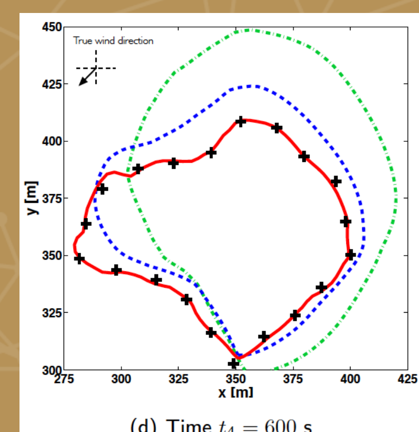
- Wildand fires are extremely complex phenomena involving many different mechanisms
- We still know little about the fundamentals of these mechanisms and how to quantify strongly coupled phenomena
- Extreme fires are a growing problem that correspond to very specific regimes of fire behavior
- Engineering solutions can and should be designed for specific issues



Safety distances



Eruptions - Blowups



Data assimilation