# Smouldering Combustion in Wildfires

TOC

1. What is smouldering?
2. Why is it important?
3. How does it ignite, spread and emit?

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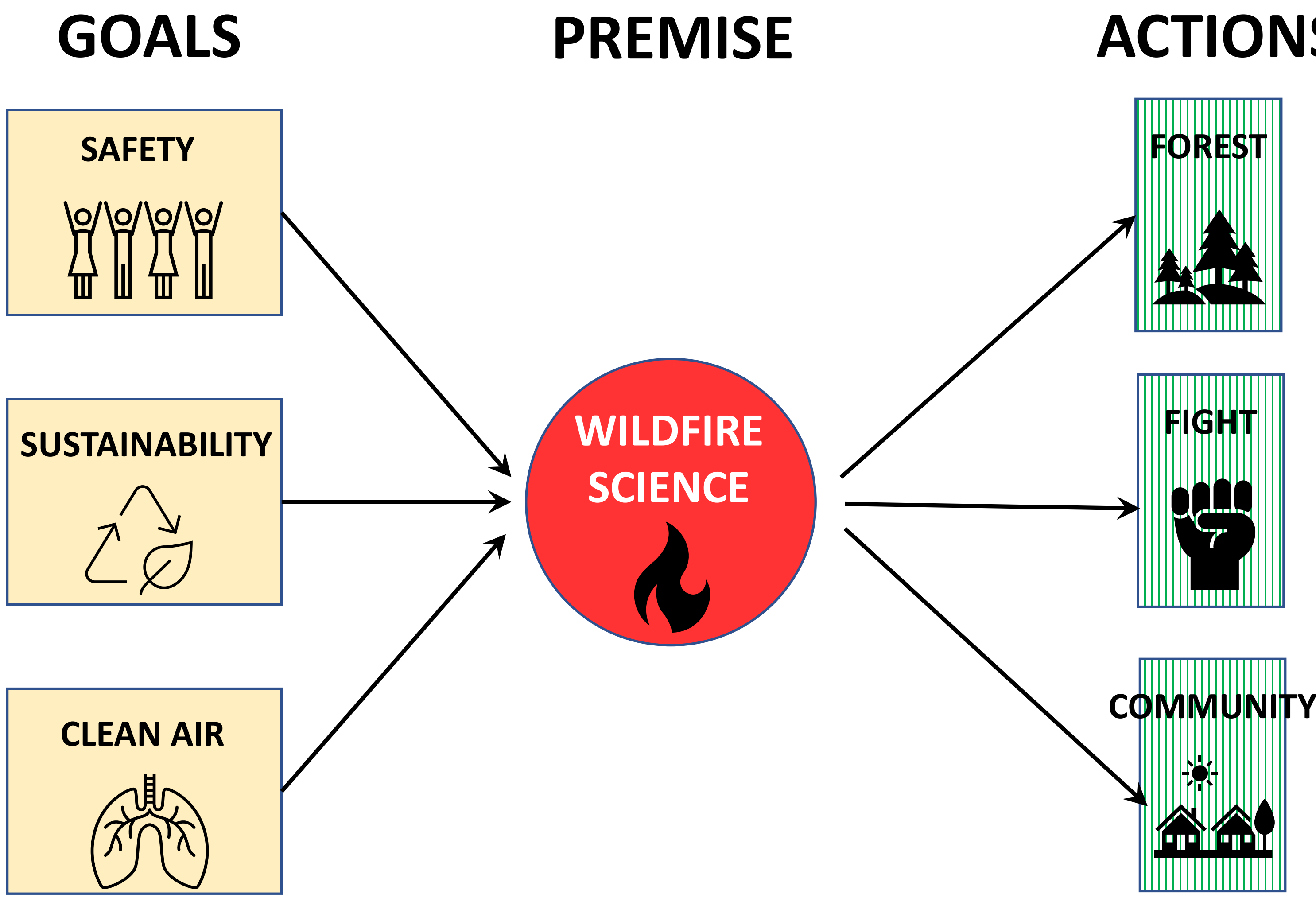
Imperial College London

@GuillermoRein

UMD Summer School of Wildfires

**“If we understand the problem, we can manage it. If we don't understand it, we can only fight it”**

A. Elliott, 2022.



# Multiple scales in Wildfires

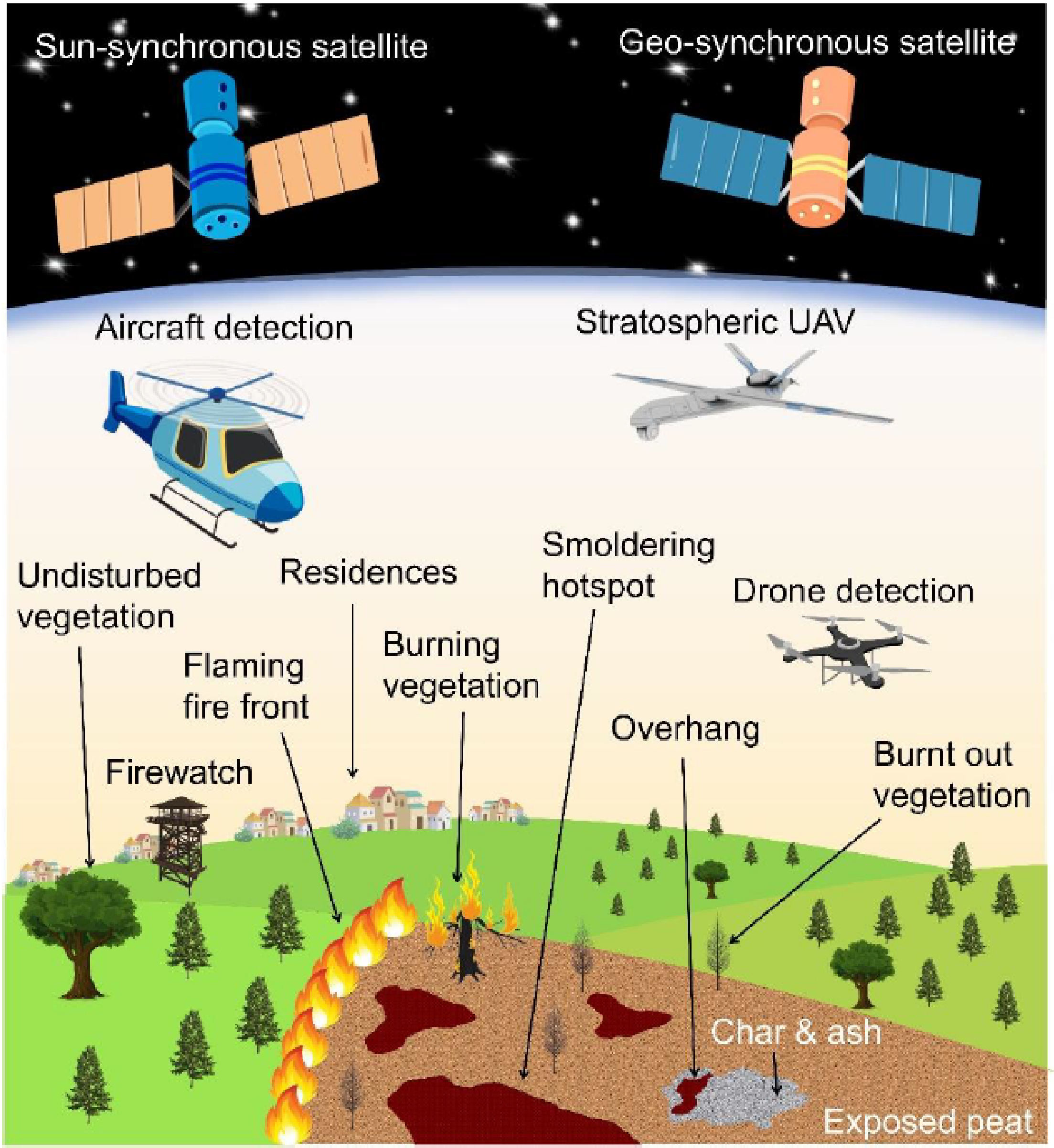



Figure by Purnomo & Imperial Hazelab, 2021

IMPERIAL HAZELAB

Imperial College London

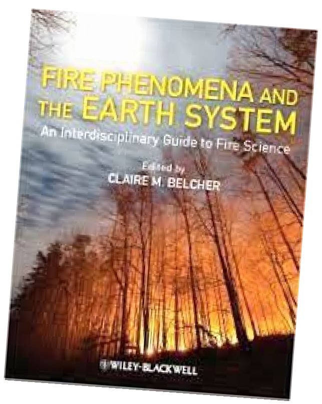

erc · The Leverhulme Trust · ARUP · HORIZON 2020 · Canada · NRC·CNRC · NIST · UKRI · BASF We create chemistry · China Scholarship Council · SFPE Engineering A Fire Safe World · Royal Academy of Engineering · FM Global

# The content of this lecture is based on the work of Hazelab, mostly from:


**Smoldering Combustion**,

Chapter 19 in: *SFPE Handbook of Fire Protection Engineering*, 5th Edition, Springer, 2016.

DOI:10.1007/978-1-4939-2565-0_19




**Smouldering Fires and Natural Fuels**,

Chapter 2 in: *Fire Phenomena in the Earth System*, Wiley 2013. DOI:10.1002/9781118529539.ch2

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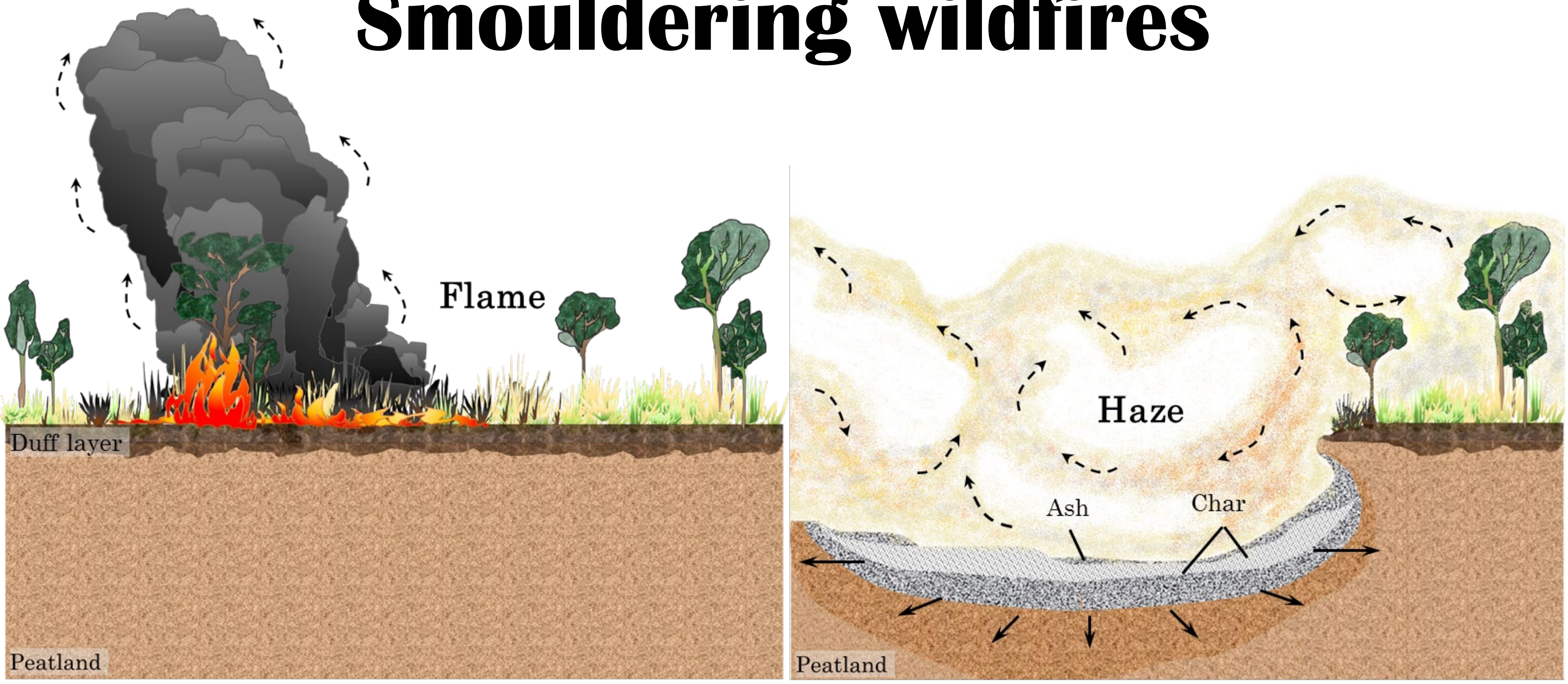
# Smouldering wildfires




**Day-long flaming forest fire**

- Strongly buoyant fire plume
- Surface phenomenon
- Fast-moving diffusion flames
- Black smoke (abundant soot)

**Month-long smouldering peat fire**

- Weakly buoyant fire plume
- Volumetric phenomenon
- Creeping flameless reaction
- Whitish/yellowish smoke (abundant organic carbon)

**Since 2003, I argue that smouldering is essential to understand wildfires.**

**Here is my case,
and the science behind it.**

# Three Types of Wildfires

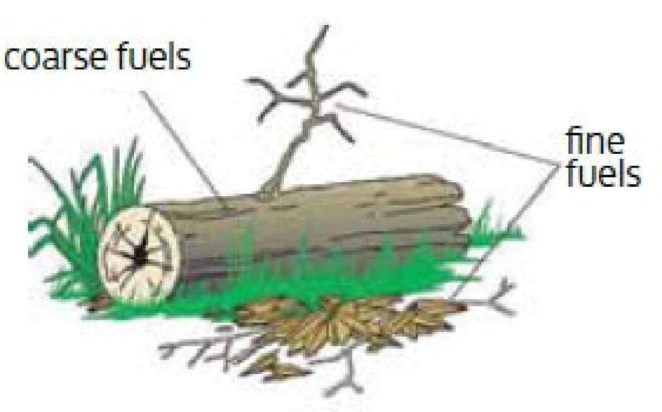

- **Crown fires** burn the top of trees.
- **Surface fires** burn shrubs, grass, and litter.
- **Ground fires** occur in accumulations of duff, humus, and peat in the soil.

smouldering

Based on Met Office slide, 2023.

# Two types of fuels

| Fine fuels | Coarse fuels |
| --- | --- |
| **Leaves, needles, grass, twigs, surface litter.** | **Branches, logs, snag, soil.** |
| Dry and burn **quickly.** | Dry and burn **slowly.** |
| | |
| Burn towards the front of the fireline. | Burn towards the back of the fireline. Even outside. |
| Dictate the flame spread. | Dictate the depth of the fireline, and emissions. |




smouldering

# Three main Phenomena of Smouldering Combustion in Wildfires

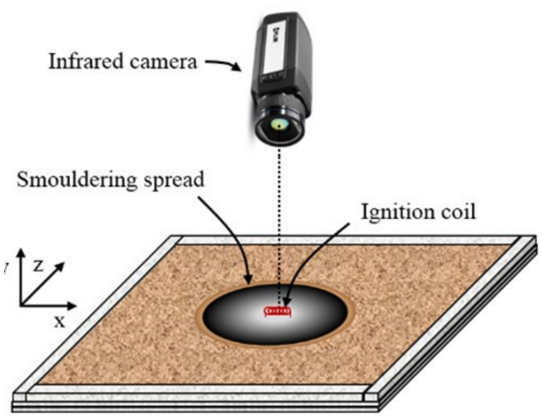
(a) Peat fire

(b) Residual burning

(c) Firebrands

# Smouldering Spread

*speeded up 600 times*

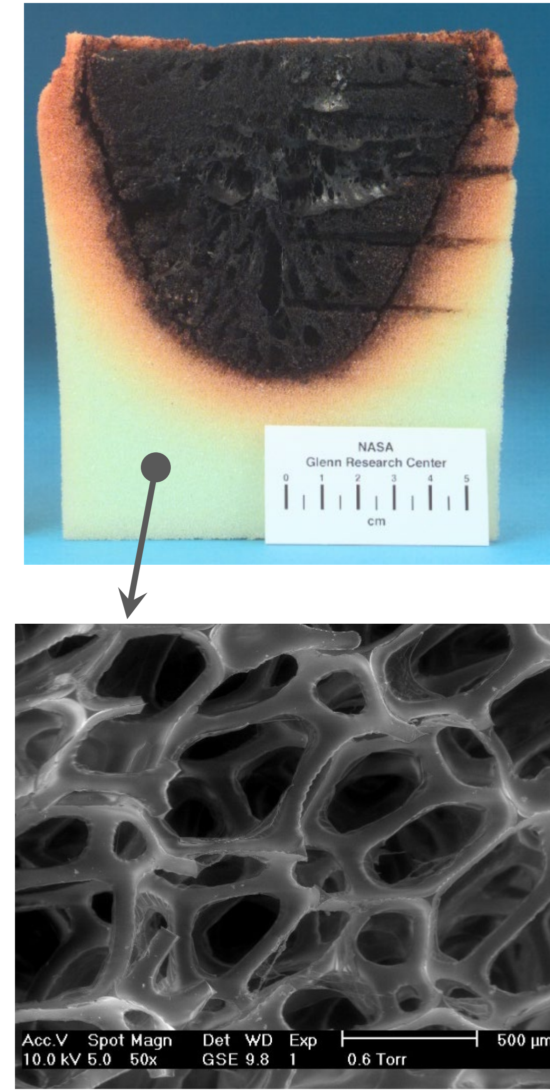

- Low peak temperature ~600°C.
- Low heat of combustion ~5 kJ/g.
- Creeping propagation ~1 mm/min.

# What is smouldering combustion?

- **Smoldering combustion** is the slow, low temperature, flameless burning of porous fuels.
- **Heterogeneous combustion**: Heat is released when oxygen directly attacks the surface of a solid fuel.
- It is especially common in:
  - ⌘ **Natural fuels:** wood, **peat**, litter, coal.
  - ⌘ **Synthetic fuels:** cellulose, insulation like **polyurethane** foam.

# Smouldering Nature

- *In chemical terms:* fuels **form a char** on heating.
- *In physical terms*: fuels consist of a permeable medium formed by grains, fibres or some other **porous matrix.**
- This porous nature provides large surface area per unit volume, which facilitates **heterogeneous reaction** with oxygen while permits **transport of oxygen** through the fuel bed.



# Most persistent fires on Earth

- **Smouldering fires are the easiest to ignite**
  - Ignition with much smaller heat sources (8 vs. 15 $kW/m^2$)
  - Self-heating possible at ambient temperatures (ie, 30 $^oC$)

- **Smouldering fires are most difficult to suppress**
  - Larger amounts of water (>50% larger $kg_{H2O}/kg_{fuel}$)
  - Lower critical oxygen concentration (10% [$O_2$] vs. 16%)
  - Much longer holding times for smothering (~months vs. min)

- The **oldest** continuously burning fire on Earth is a smouldering coal seam in Australia ignited >6,000 years old


# The Burning Mountain in Wigen, Australia

The **oldest** continuously burning fire on Earth is a smouldering coal seam in Australia. Ignited >6,000 years ago.

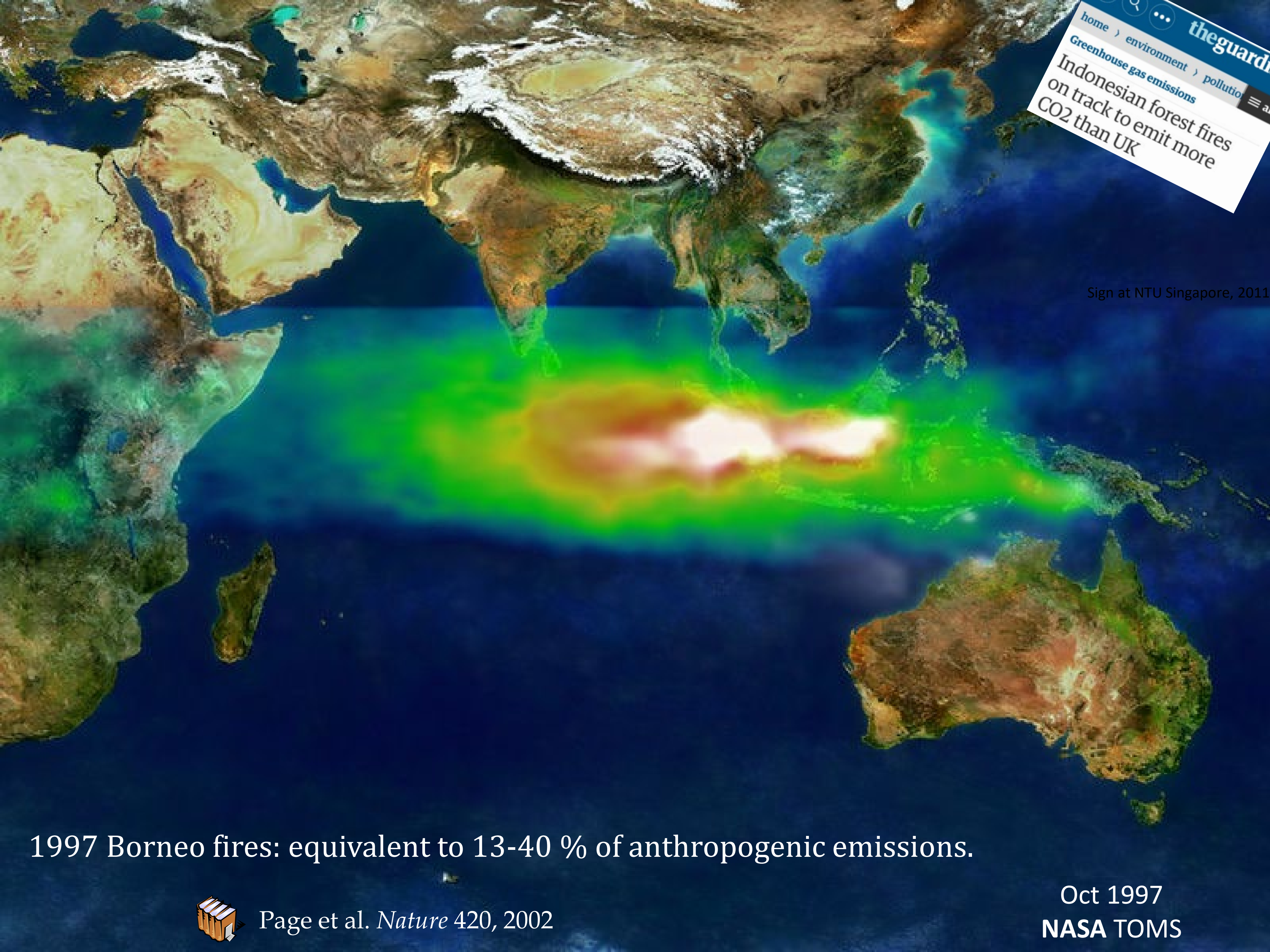
EXTRACT FROM *THE AUSTRALIAN.*

Sydney, March 19, 1828.

"A Volcano has just been discovered in the vicinity of Hunter's River. It is situated among the mountains at the distance of about one hundred miles in a north-westerly direction from New-castle—twelve miles beyond Houldsworthy's Plains, and fourteen from Segenhoe. The distance of the Volcano from the sea is calculated to be about ninety miles. Of the existence of this phenomenon there can be no doubt. It has been visited by several persons. Dr. Little, we understand, has been to it, and we have at this moment a portion of the lava, consisting chiefly of sulphur, taken from the side of the mountain, in our possession. When discovered the Volcano emitted a brilliant light, and had every appearance of being long in a state of activity. It is thought that it has not hitherto claimed particular observation, on account of its resemblance at a distance to the sight, which is



# Some Case Studies Worldwide




1997 Borneo fires: equivalent to 13-40 % of anthropogenic emissions.

Page et al. *Nature* 420, 2002

# The Evans Road fire
# Summer 2008, North Carolina, USA

During worst drought on record

- 16,500 ha burned (2x year avg.)
- 1 m deep into the soil
- by flooding and excavation
- $20 million in suppression costs

# Largest fires on Earth are smouldering peatlands

## Equivalent to 15% of anthropogenic global carbon emissions (and not account for by IPCC yet)

**2015**

theguardian

home › environment › pollutio ≡ all

**Greenhouse gas emissions**

## Indonesian forest fires on track to emit more CO2 than UK

Greenpeace warns fires raging across forest and peatlands will match the worst year ever and exceed the total annual carbon output of the UK

**2013**

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Africa Asia Europe Latin America Middle East US & Canada

23 June 2013 Last updated at 14:59

3K Share

## Malaysia declares state of emergency over smog in south

**2002**

BBC NEWS

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Africa
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Europe
Middle East
South Asia

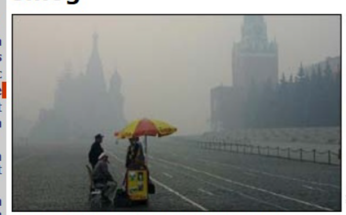
From Our Own Correspondent

Letter From America

UK
England
N Ireland
Scotland
Wales

Thursday, 5 September, 2002, 11:02 GMT 12:02 UK

## Moscow 'suffocated' by smog



Carbon monoxide is double the permissible level

Asthma sufferers and pregnant women have been advised to leave Moscow because of a smog emergency caused by forest fires.

**2010**

## Past Errors to Blame for Russia's Peat Fires

James Hill for The New York Times

Firemen and soldiers tried to put out a smoldering fire in a forest planted in a peat field near the town of Elektrogorsk.

By ANDREW E. KRAMER
Published: August 12, 2010

The New York Times

ELEKTROGORSK, Russia — For two weeks, soldiers with chain saws felled every tree in sight.

RECOMMEND
TWITTER

**1999**

The St Petersburg Times

**1972**

"Smoke Shrouds Moscow as Peat-bog fire rages" The New York Times

# View from the top: Saddleworth 2018

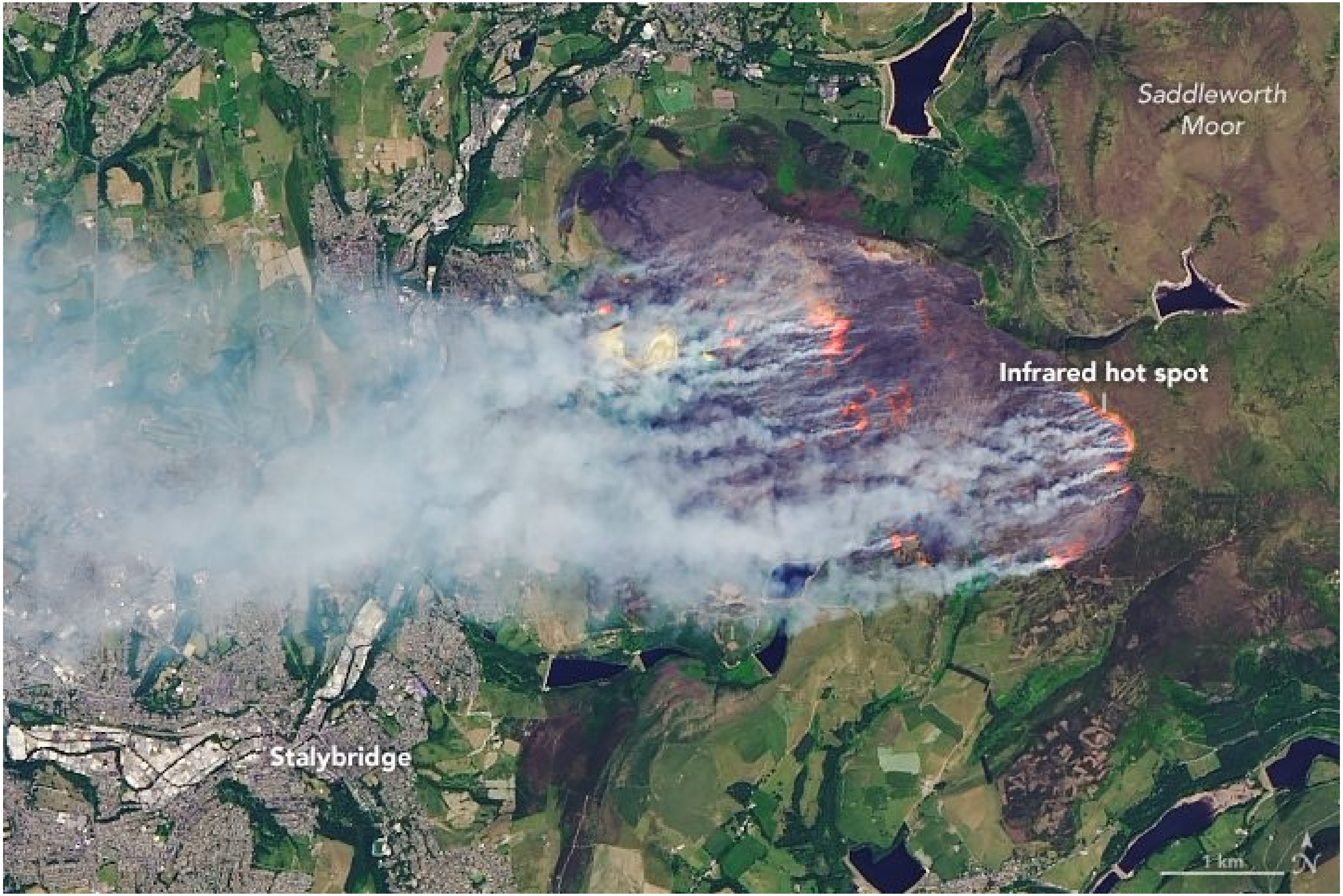
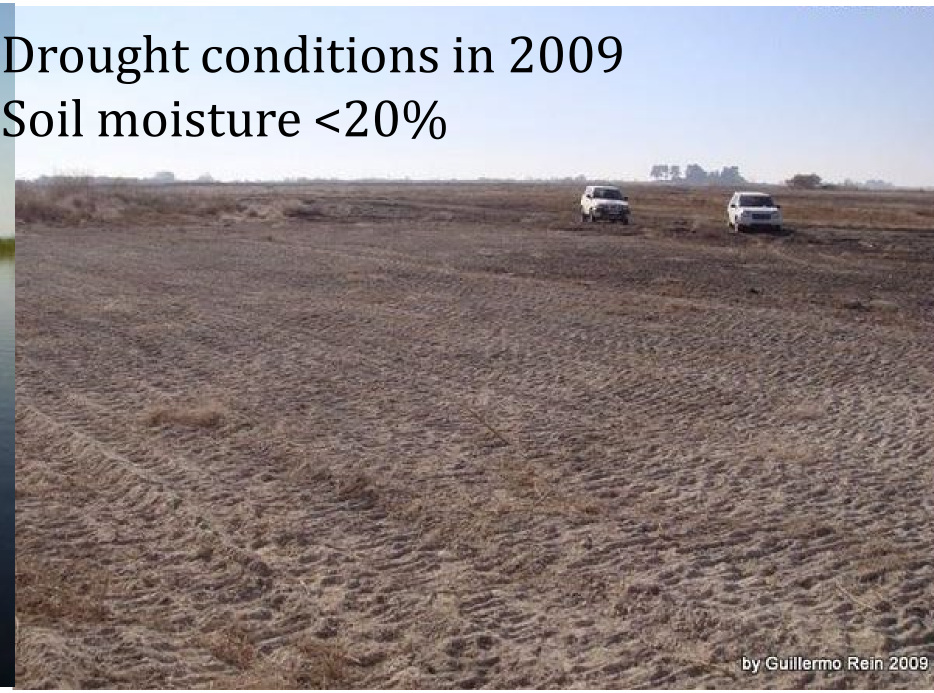



Photo By NASA

# View from the bottom: Saddleworth 2018

Photo by Stacey New, 2018

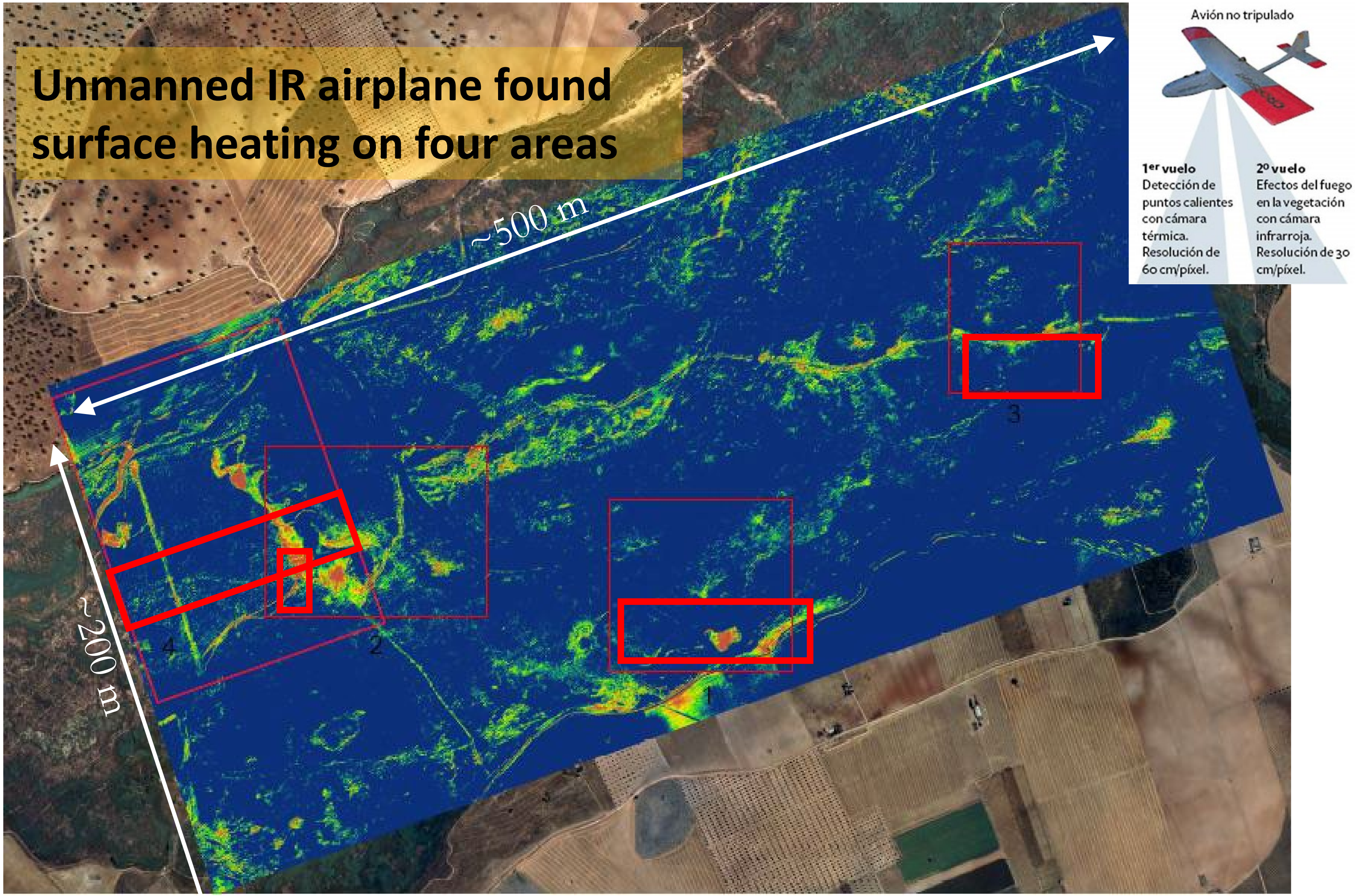
# Case Study: 2009 Las Tablas de Daimiel National Park, Spain


- Exceptional case of Southern European wetlands
- Smallest National park in Spain
- Surface area 1,680 ha (11 x 3 km)
- Peat average depth up to 5 m (average 0.91 m)

# 2009 Las Tablas de Daimiel, Spain

- Lasted from Aug 2009 to Feb 2010 – stopped by heaviest winter rains in 50 years.
- Emitted ~ 10 tons of carbon per day (2000 t-C in total).


Unmanned IR airplane found
surface heating on four areas
~500 m
~200 m
1
2
3
4
Avión no tripulado
1er vuelo
Detección de puntos calientes con cámara térmica. Resolución de 60 cm/píxel.
2º vuelo
Efectos del fuego en la vegetación con cámara infrarroja. Resolución de 30 cm/píxel.

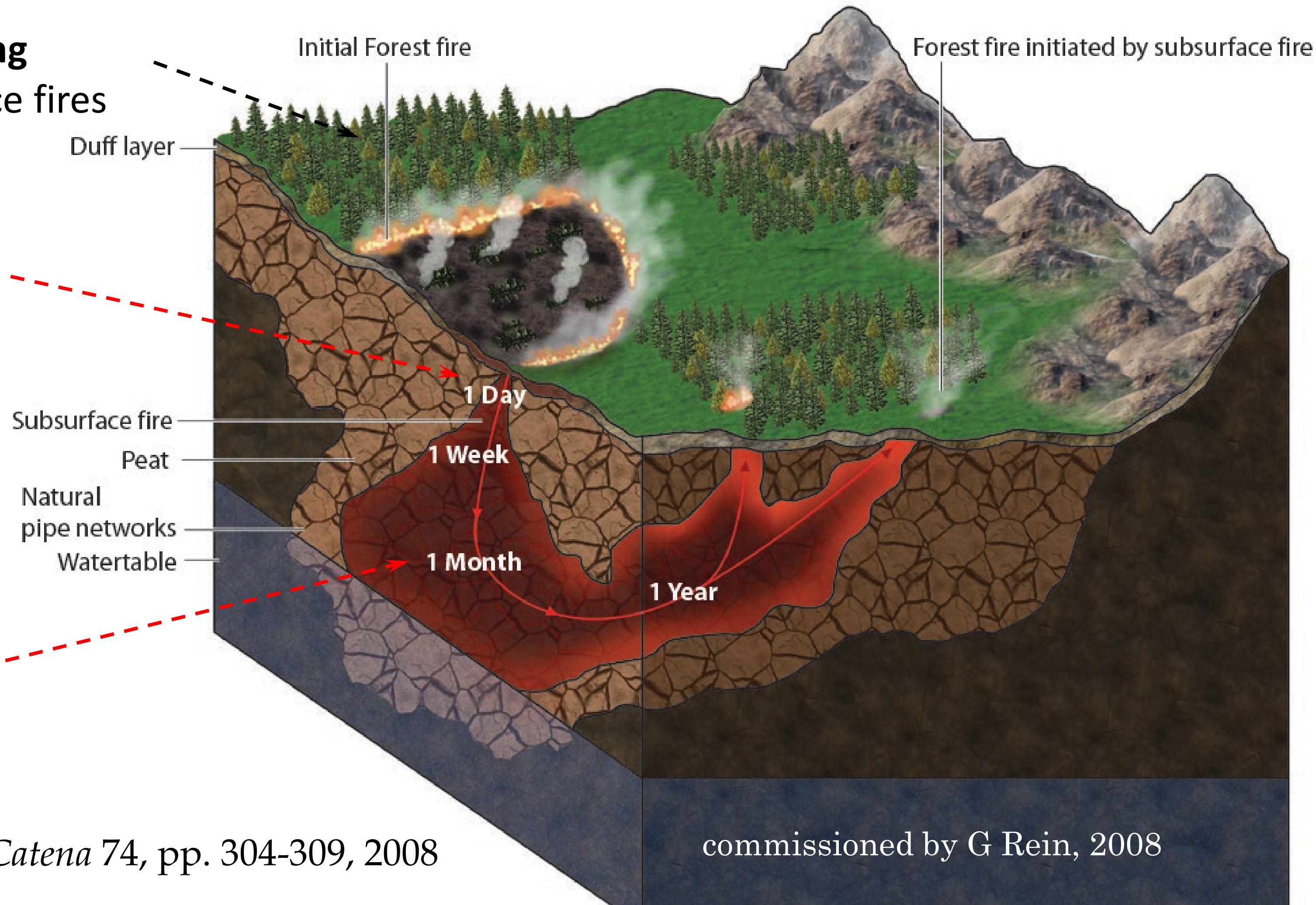
# Smouldering – Shallow and Deep

1. Composition – *organic content, water content, inert content*
2. Oxygen availability – *free surface, cracks/channels, galleries*
3. Heat losses – *convection, radiation, conduction, thermal mass*

**Flaming** surface fires

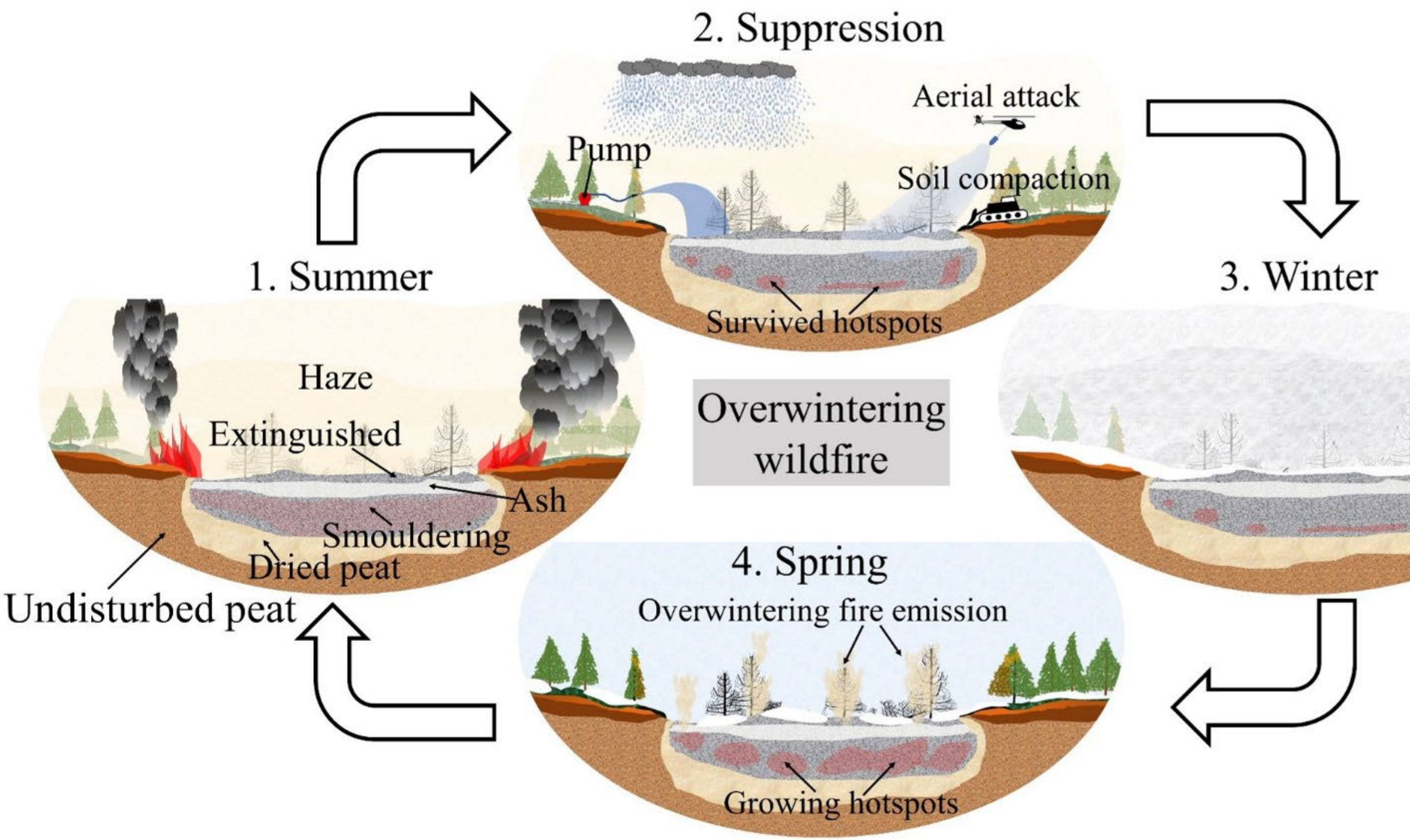
<1m **Shallow** fires

>1m **Deep** fires




Rein et al. *Catena* 74, pp. 304-309, 2008

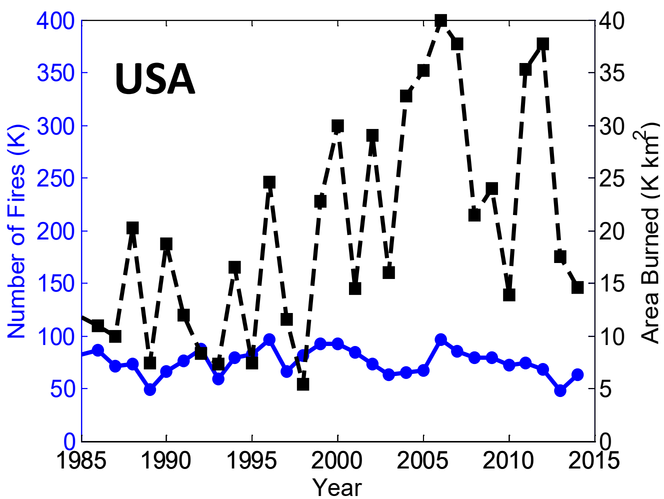
# Zombie wildfires - in the Arctic



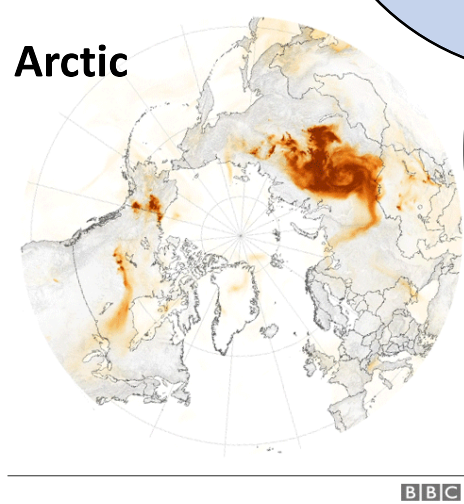

Rein & Huang, *Current Op. Environ. Science & Health*, 2021

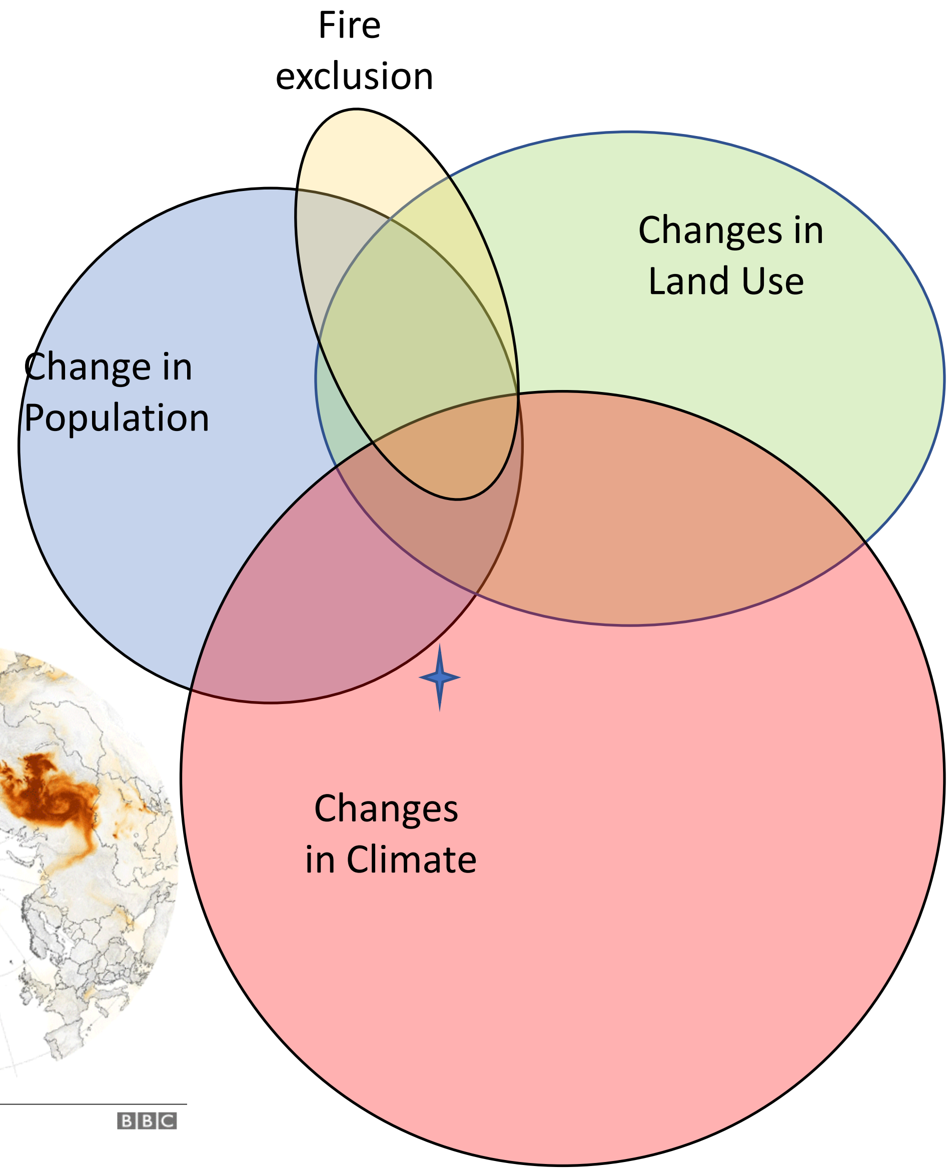
# Unprecedented Wildfire Behaviour

- Wildfire is natural but current data shows unprecedented wildfires.
- Alterations of the **natural fire regimes**.
- Changes in land use, population and climate.




*National Interagency Fire Center Statistics, USA*



# Chemistry

# Smouldering vs. flaming combustion

- **Pyrolysis:** breakdown of polymer chains by heat

  Biomass (s) → Pyrolyzate (g) +Char (s)

- **Smouldering** (heterogeneous oxidation): pyrolysis followed by char oxidation.

  Biomass (s) → Pyrolyzate (g) +Char (s)

  Char (s)+$O_2$ (g) → $CO_2$+$H_2O$+emissions+Ash (s)

- **Flaming** (homogeneous oxidation): pyrolysis followed by pyrolyzate oxidation.

  Biomass (s) → Pyrolyzate (g) +Char (s)

  Pyrolyzate (g) +$O_2$ (g) → $CO_2$+ $H_2O$+ emissions

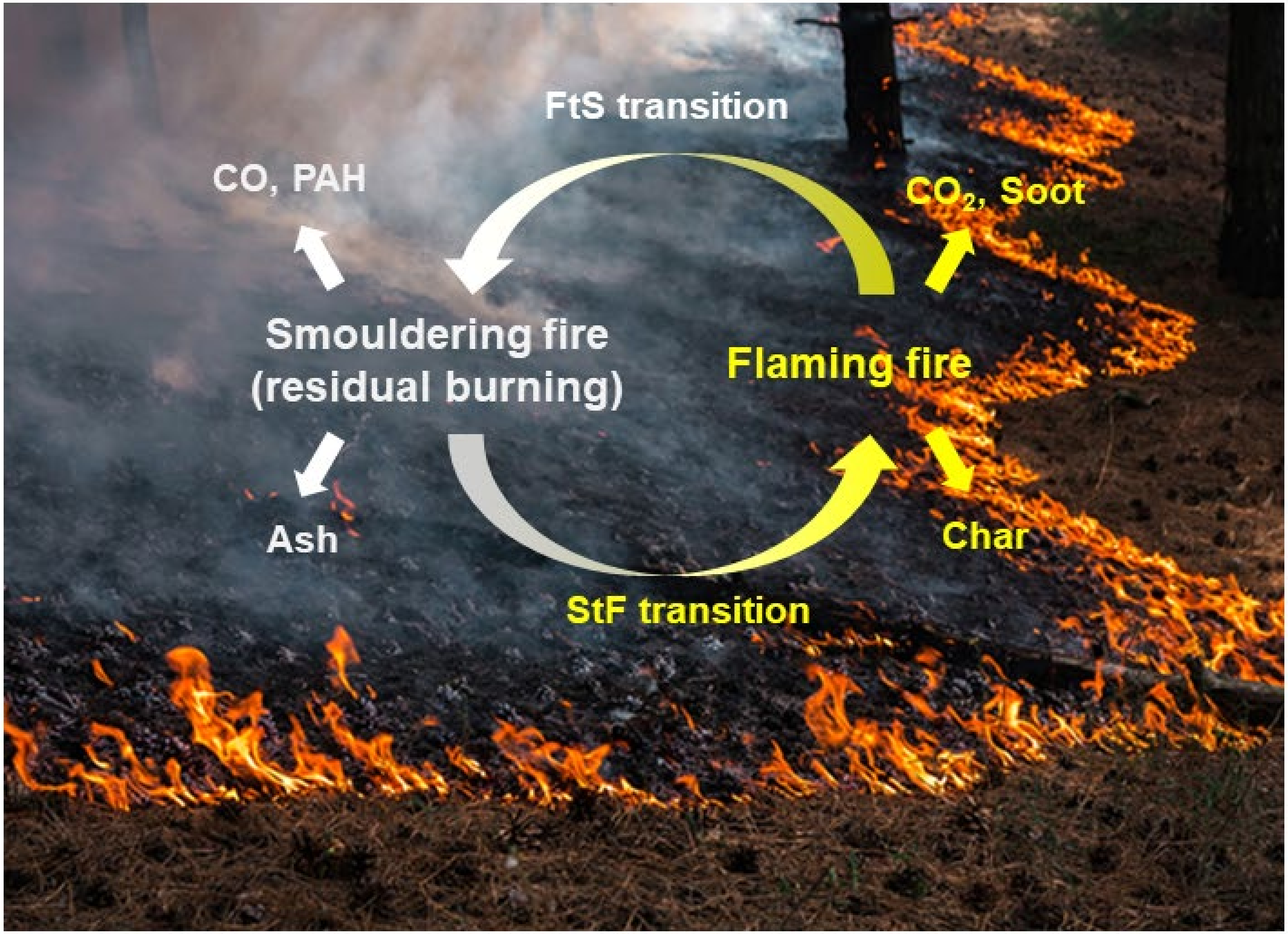

Rein et al., SFPE Handbook, 2016

# Transition from smouldering to flaming (StF)


Ember shower during the 2018 Delta Fire in California. It shows flaming fires of grass due to embers, representing a smouldering-to-flaming transition.

# Transition from to flaming to smouldering (FtS)

(aka) Residual burning

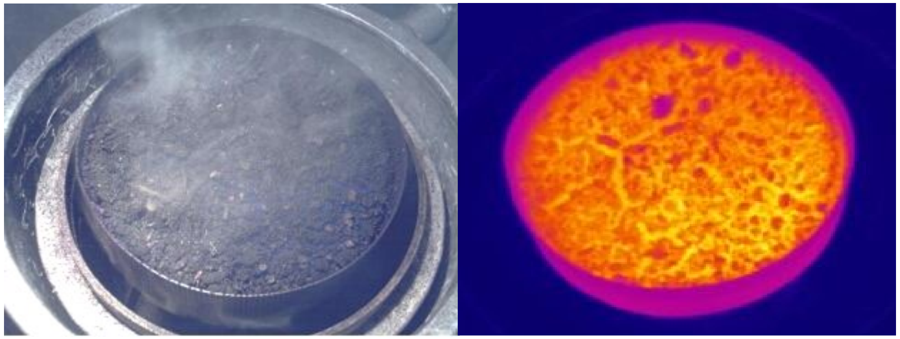


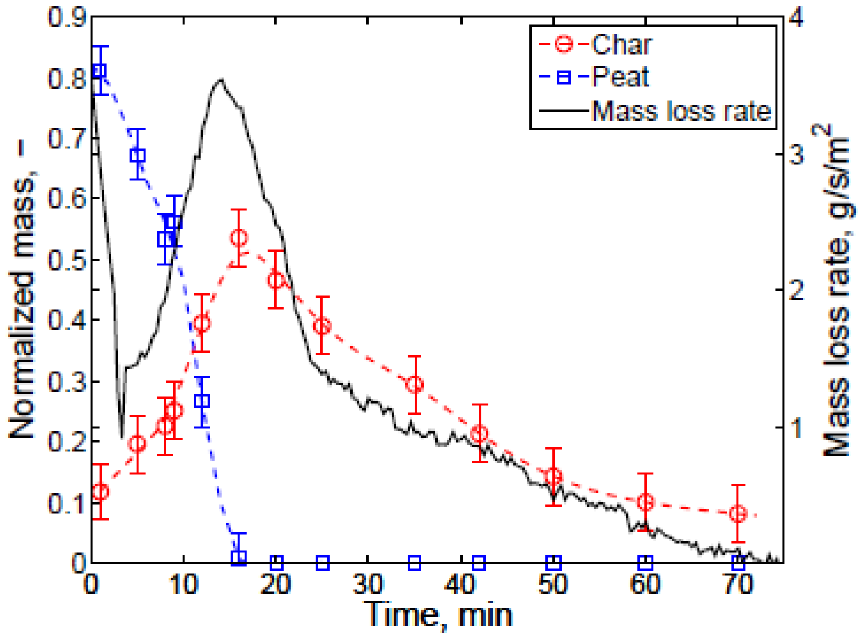
# Char: intermediate product of smouldering

$$\text{Biomass (s)} \rightarrow \text{Pyrolyzate (g)} + \text{Char (s)}$$

$$\text{Char (s)} + O_2\text{ (g)} \rightarrow CO_2 + H_2O + \text{emissions} + \text{Ash (s)}$$

**Char** is simultaneously **produced by pyrolysis** and **consumed by oxidation**, which initially results in net char production and later becomes net char consumption.



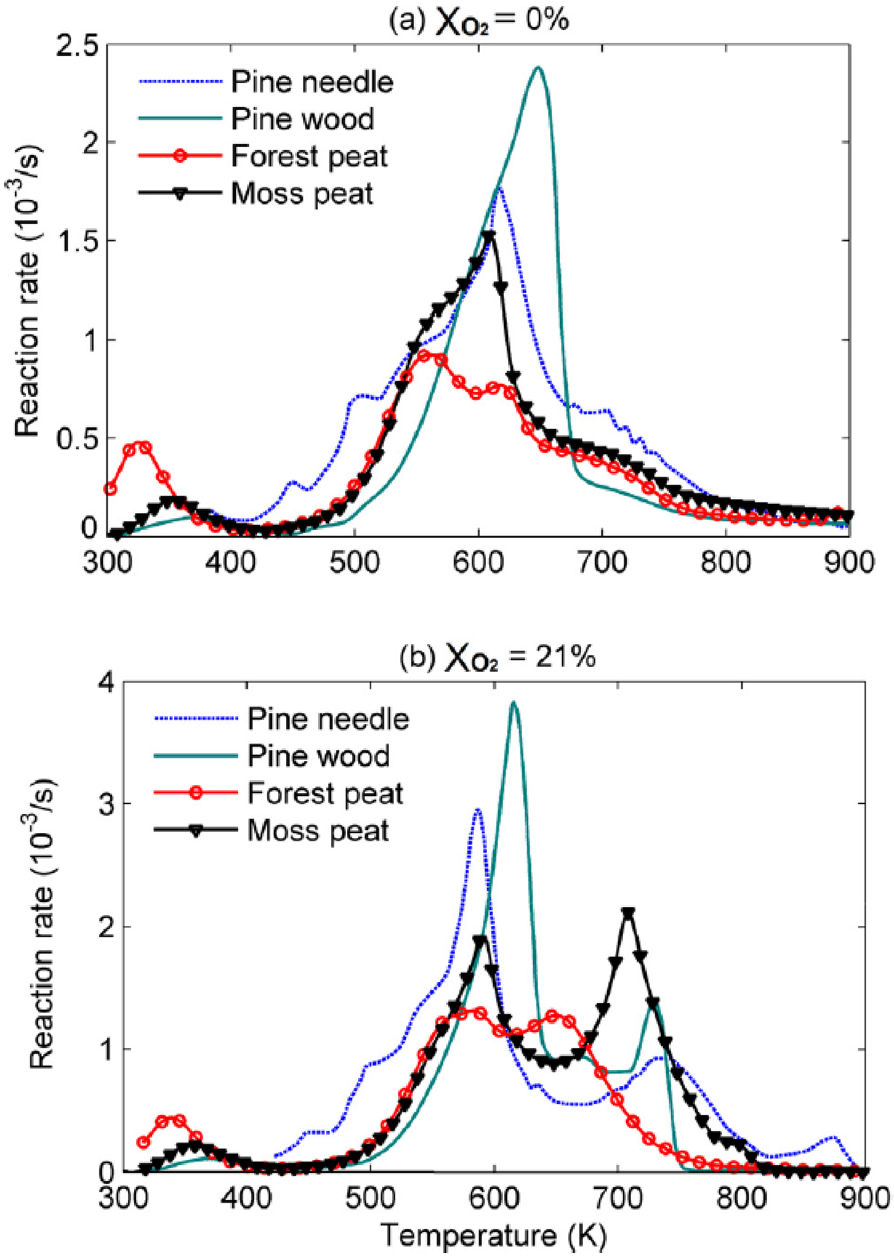



Hadden et al, *Proceedings of the Combustion Institute*, 2012

# Smouldering Chemistry – TGA Kinetics

$$\text{Biomass} \rightarrow \text{Gas} + \text{Char}$$

$$\text{Char} + O_2 \rightarrow \text{Smoke} + \text{Ash}$$

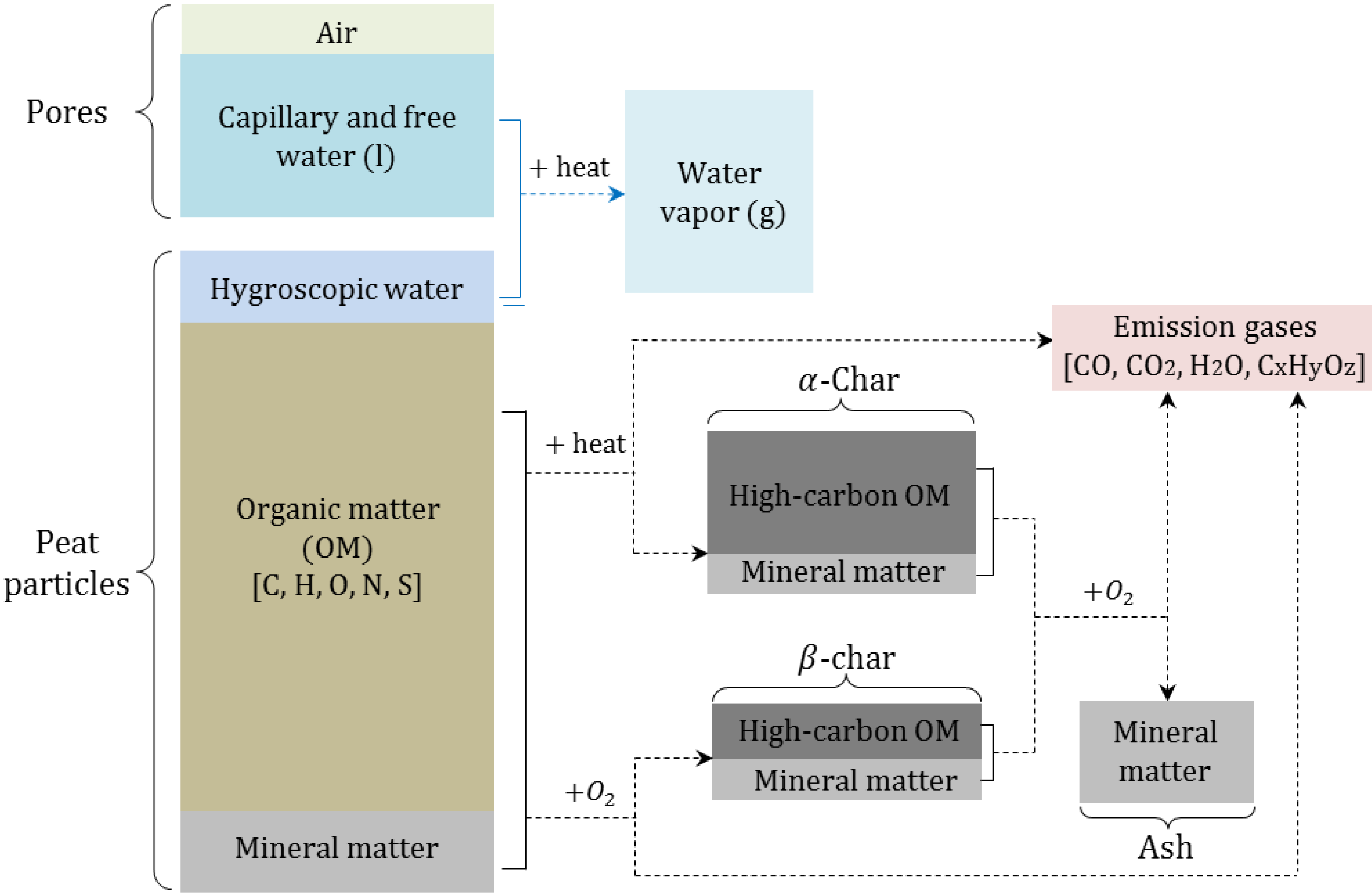



Chen et al,
*Energy & Fuels*, 2011

Huang and Rein,
*Combustion & Flame*, 2013

Huang and Rein,
*Bioresource Technology*, 2016

# Smouldering Chemistry




Huang and Rein, *Combustion and Flame* 2013

# Quantify Reaction Rates

$$\dot{\omega}_i = A_i e^{-E_i/RT} m_i^{n_i} y_{O_2}^{\delta}$$

$$\begin{cases} \text{biomass} \cdot \nu_{w,dr}\mathrm{H_2O} \rightarrow \text{biomass} + \nu_{w,dr}\mathrm{H_2O(g)} & (dr) \\ \text{biomass} \rightarrow \nu_{\alpha,pp}\alpha\text{-char} + \nu_{g,pp}\text{gas} & (bp) \\ \text{biomass} + \nu_{O_2,po}\mathrm{O_2} \rightarrow \nu_{\beta,po}\beta\text{-char} + \nu_{g,po}\text{gas} & (bo) \\ \beta\text{-char} + \nu_{O_2,\beta o}\mathrm{O_2} \rightarrow \nu_{a,\beta o}\text{ash} + \nu_{g,\beta o}\text{gas} & (\beta o) \\ \alpha\text{-char} + \nu_{O_2,\alpha o}\mathrm{O_2} \rightarrow \nu_{a,\alpha o}\text{ash} + \nu_{g,\alpha o}\text{gas} & (\alpha o) \end{cases}$$

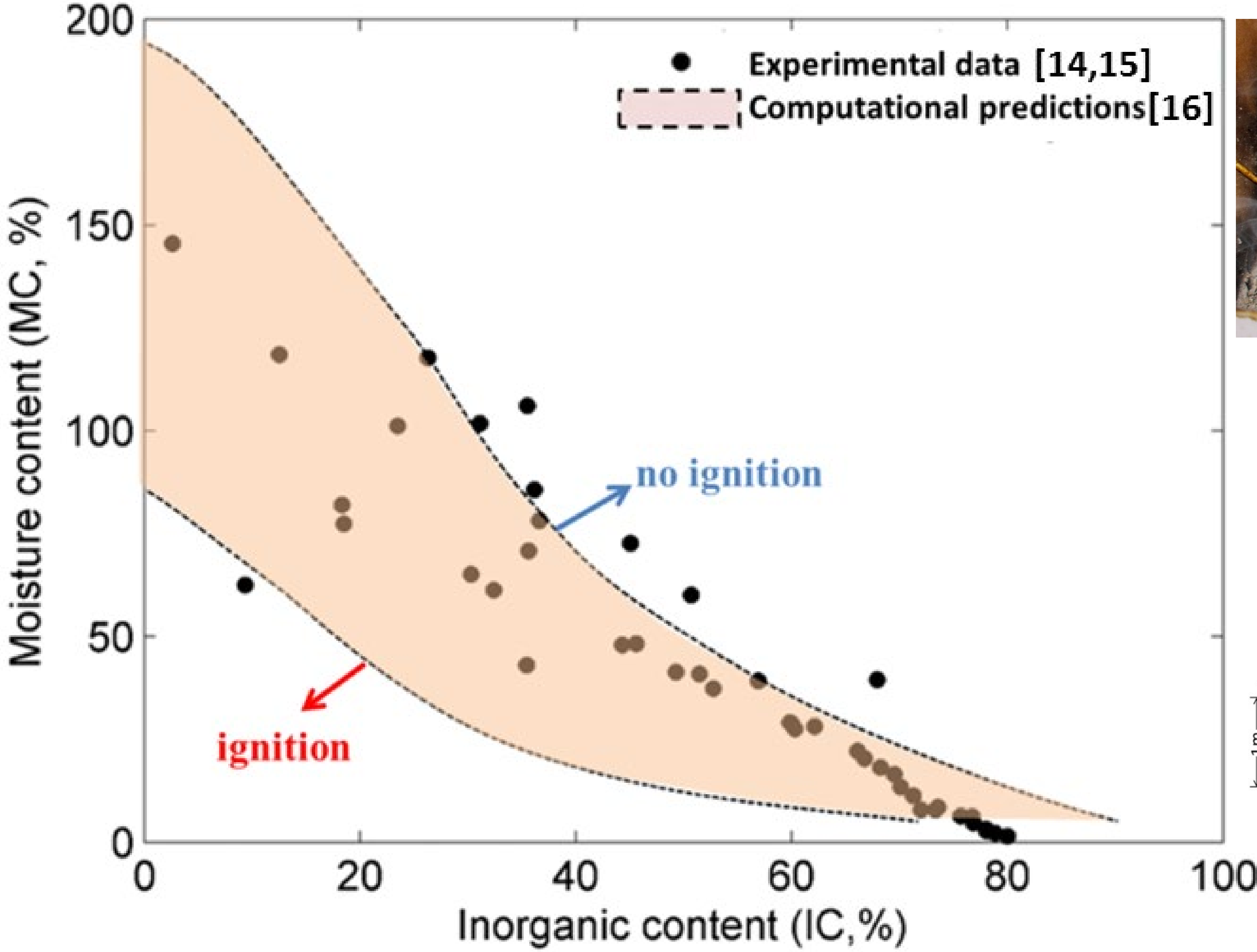
Reaction parameters and gaseous yields of 5-step reactions for SC peat sample [12].

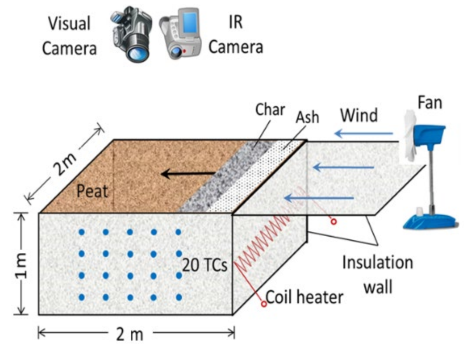
| Parameter/$k$ | $dr$ | $pp$ | $po$ | $\alpha o$ | $\beta o$ |
|---|---|---|---|---|---|
| $\lg A_k$ ($\lg(s^{-1})$) | 8.12 | 5.92 | 6.51 | 1.65 | 7.04 |
| $E_k$ (kJ/mol) | 67.8 | 93.3 | 89.8 | 54.4 | 112 |
| $n_k$ (–) | 2.37 | 1.01 | 1.03 | 0.54 | 1.85 |
| $\nu_{B,k}$ (kg/kg) | 0 | 0.75 | 0.65 | 0.03 | 0.02 |
| $\Delta H_k$ (MJ/kg) | 2.26 | 0.5 | −3.54 | −19.5 | −19.5 |
| $\nu_{O_2,k}$ (kg/kg) | 0 | 0 | 0.27 | 1.48 | 1.49 |

Huang and Rein, *Combustion and Flame* 2013

# Ignition

# Ignition/Spread Thresholds

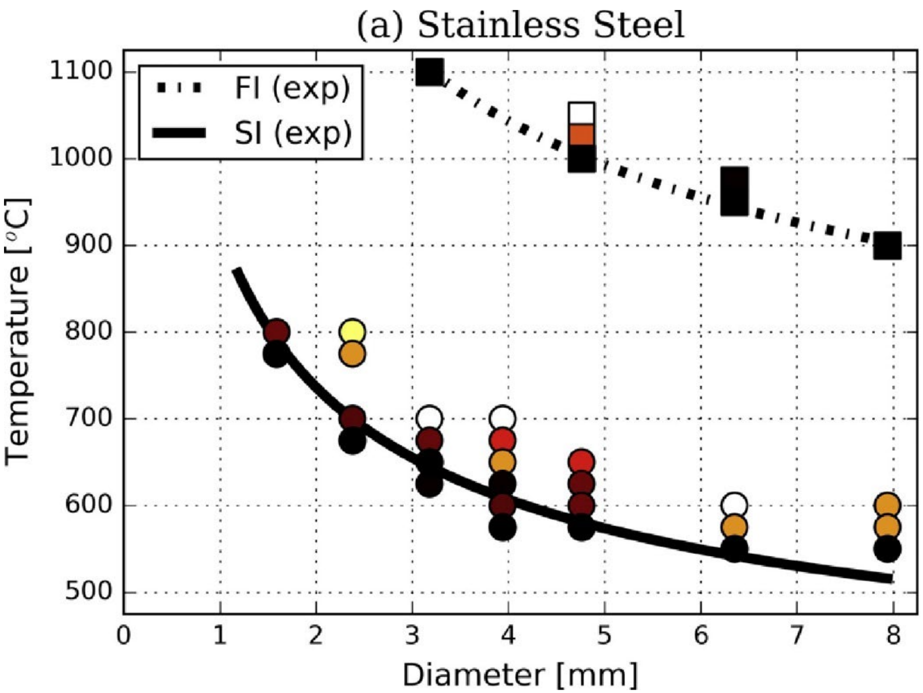


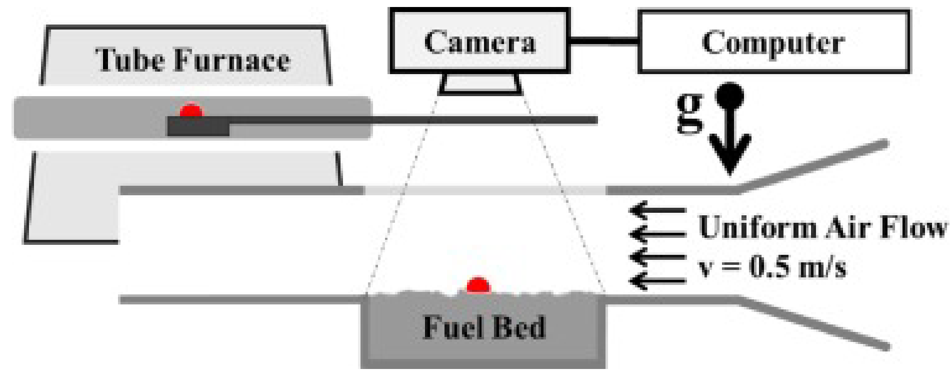




Frandsen, *Can. J. For. Res.* 1997

Huang et al, *Proc. Comb. Inst.* 2015

# Firebrand landing on fuel bed



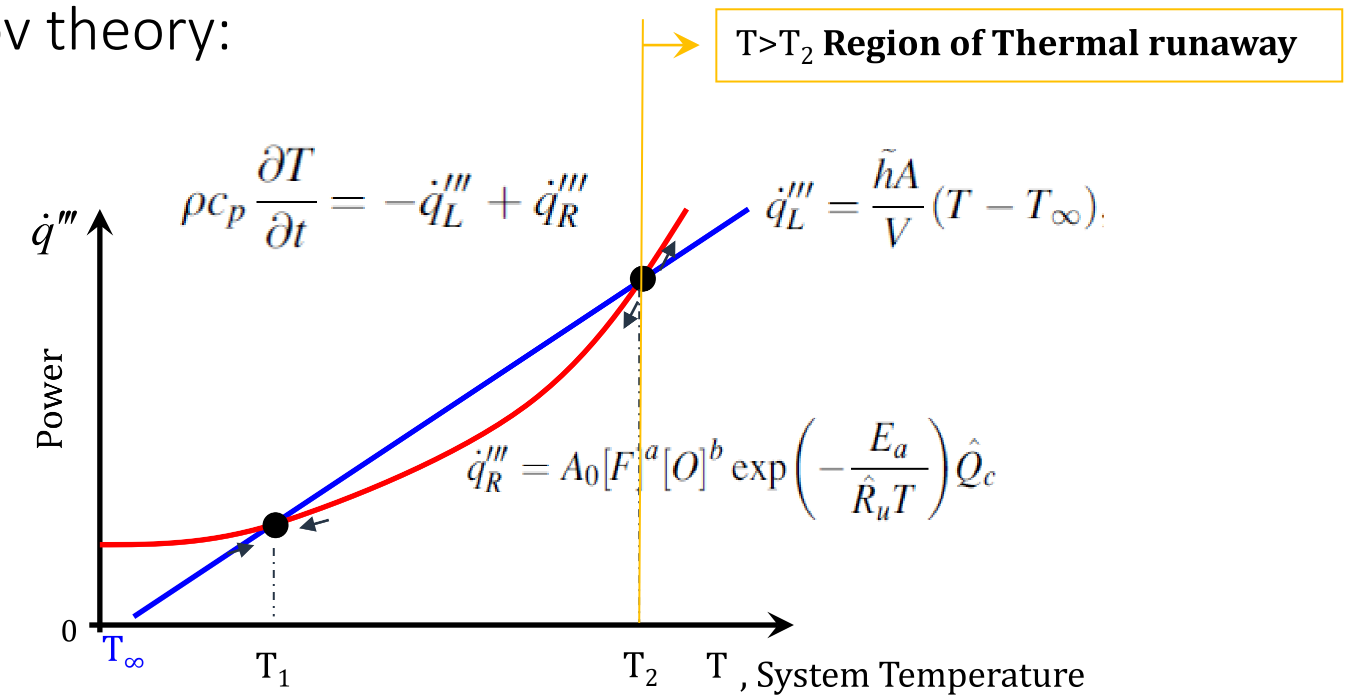

- Smouldering ignition with the **smallest and lowest temperature** embers (1 mm and 500°C).
- Flame ignition with larger and much hotter embers (3 mm and 900°C).

Urban et al, *Proceedings Combustion Inst* 2017

# Self-heating Ignition inside Natural Fuels

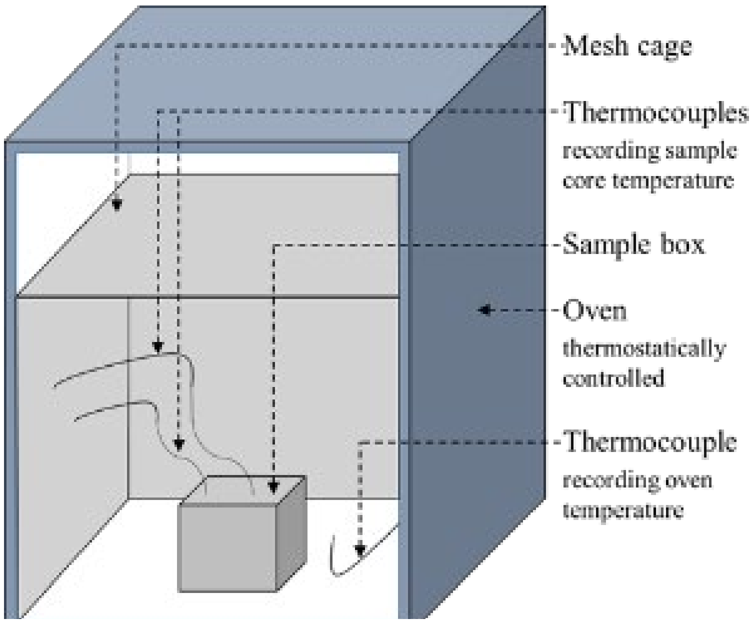
**Self-heating** is to the tendency of certain reactive systems to spontaneous exothermic reactions at low ambient temperatures.

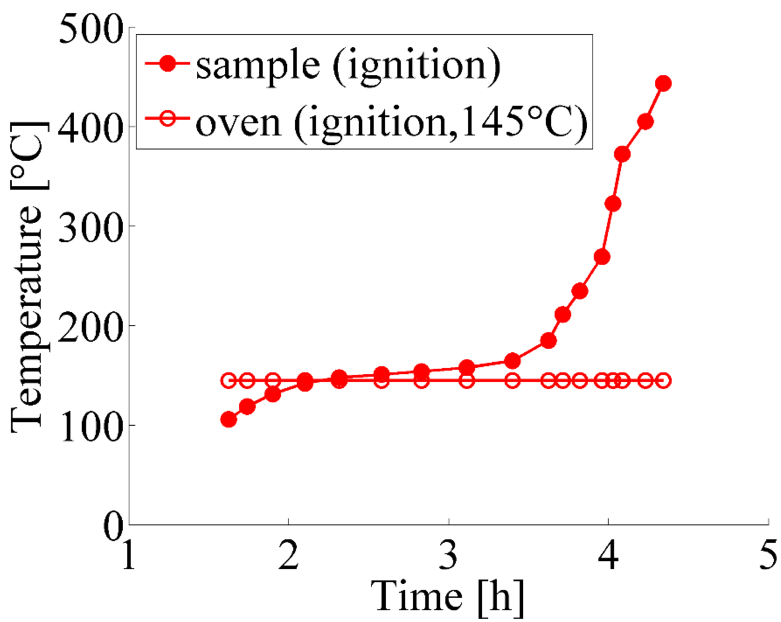
Semenov theory:

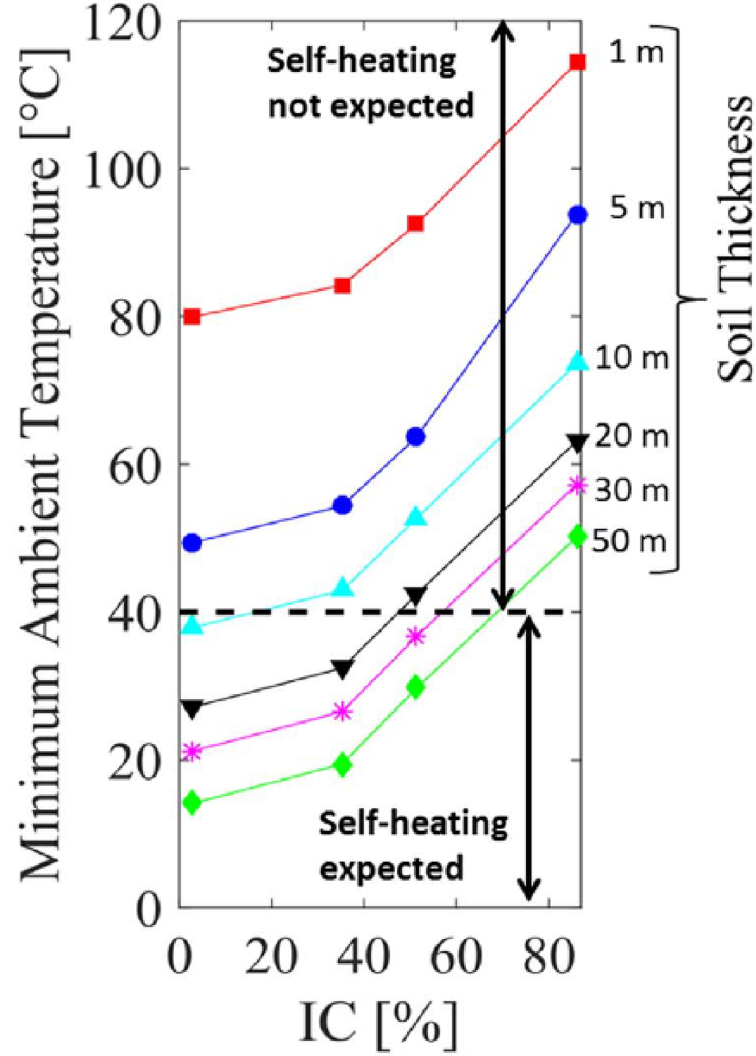



Frank-Kamenetskii: $$ln\left[\frac{\delta_c T_{a,c}^2}{L_c{}^2}\right] = \ln\left[\frac{QEf}{Rk}\right] - \frac{E}{R\ T_{a,c}}$$

# Self-heating Ignition of Natural Fuels

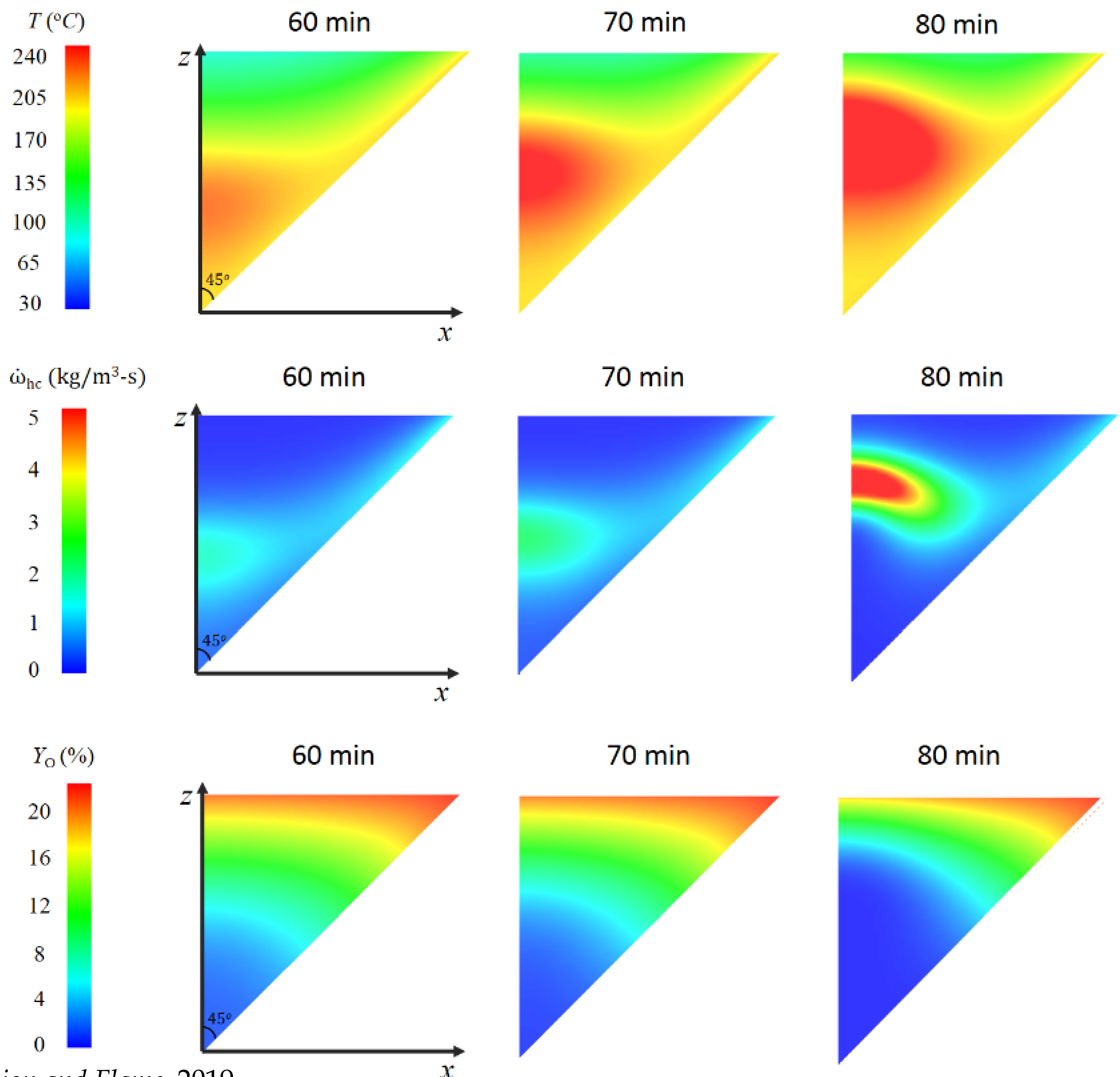



Restuccia *et al.*, Fire Safety Journal 2017

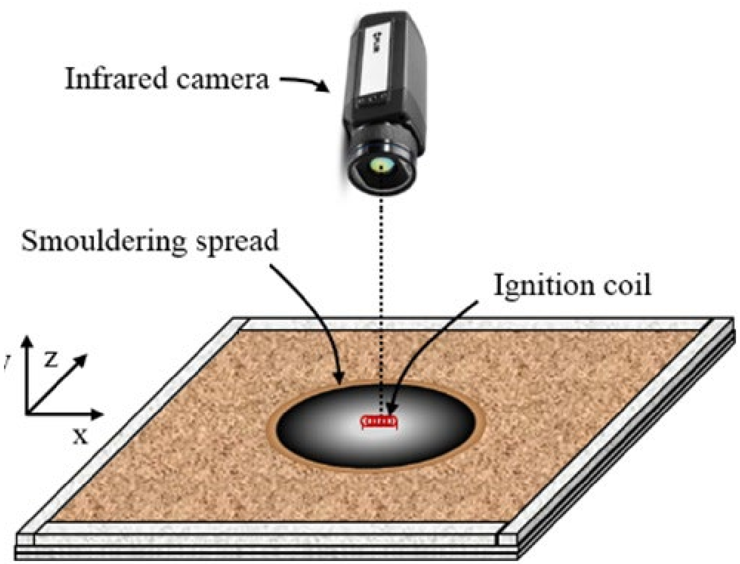
# Self-heating Ignition and Smouldering




Han et al., *Combustion and Flame*, 2019

# Spread

# Spread over dry/wet patterns




5 cm deep layer of peat
20 x 20 cm square open-top reactor.

Videos by
Hadden, 2010

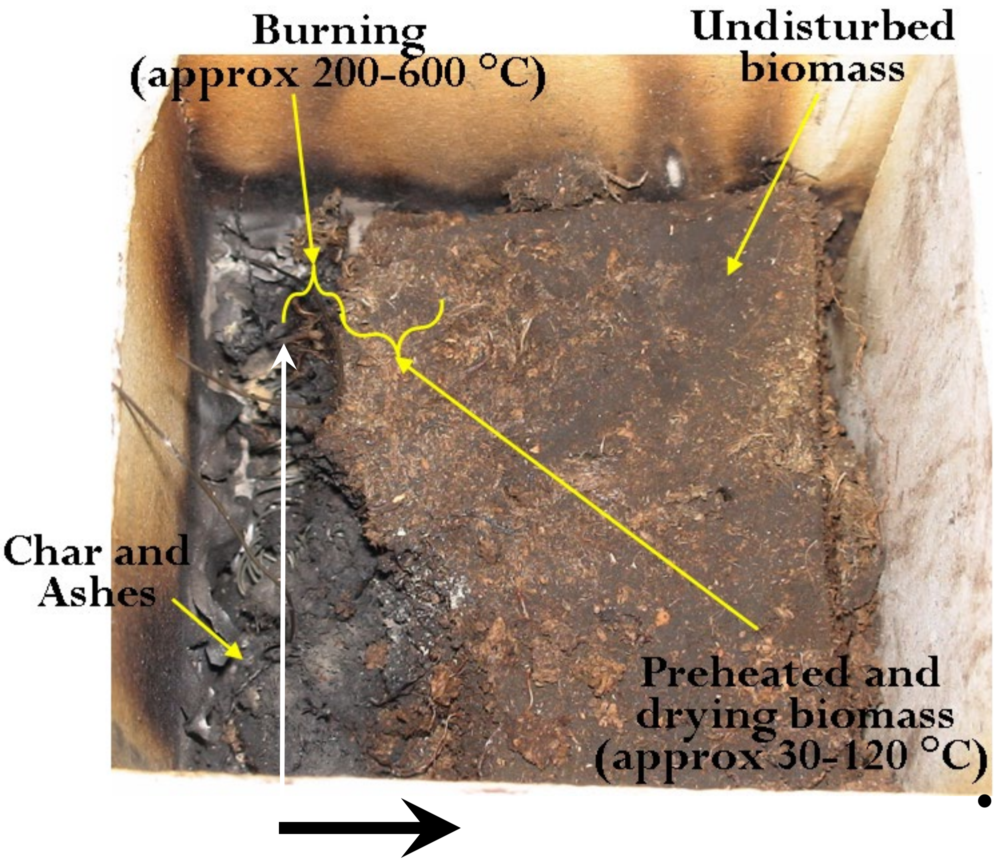


Longitudinal split

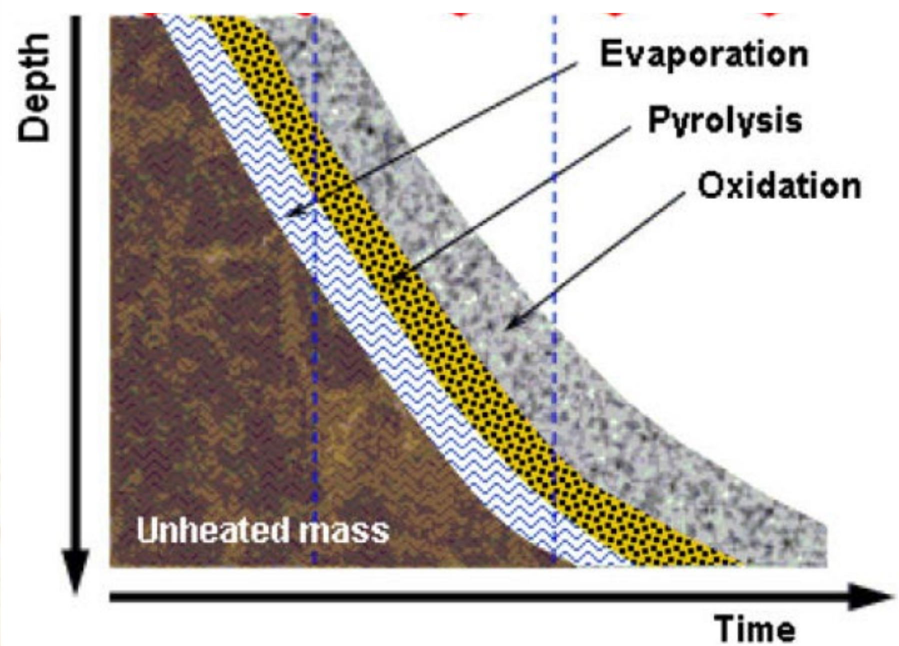


Checker board

# Structures of the Reaction Front




Direction of spread




- Preheating
- Drying (<100 °C)
- Pyrolysis (threshold ~200 °C)
- Oxidation

Rein et al., Catena, 2009

# Cellular automata model of Smouldering

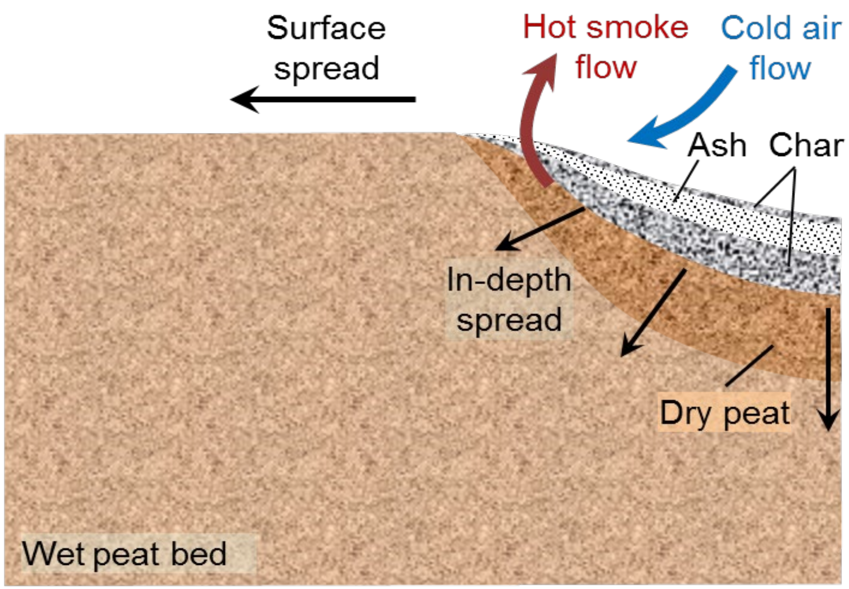
- Multi-layer cellular automata: **Fuel**, **Heat** and **Oxygen**.
- Simple model captures **complex behaviour.**

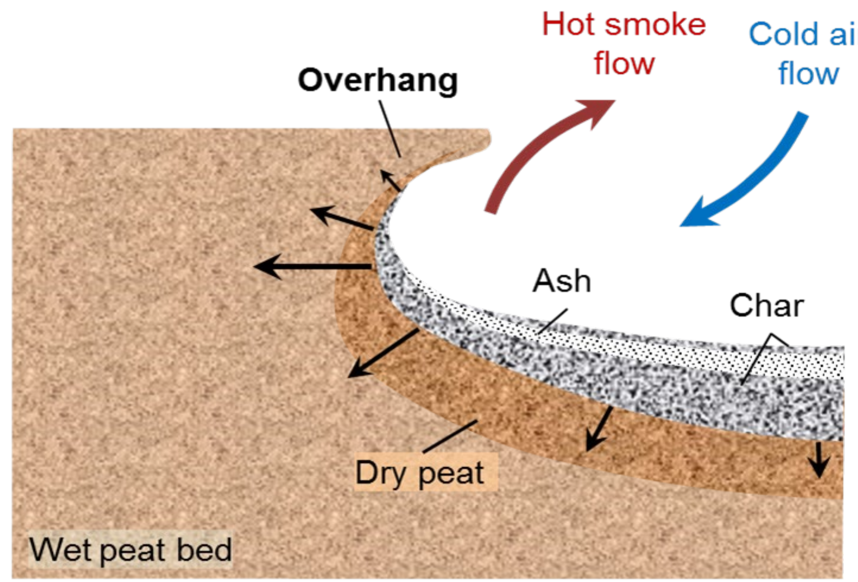
Line front

Hotspot

Fernandez-Anez et al., *Fire Safety Journal*, 2017.

# Lateral Spread



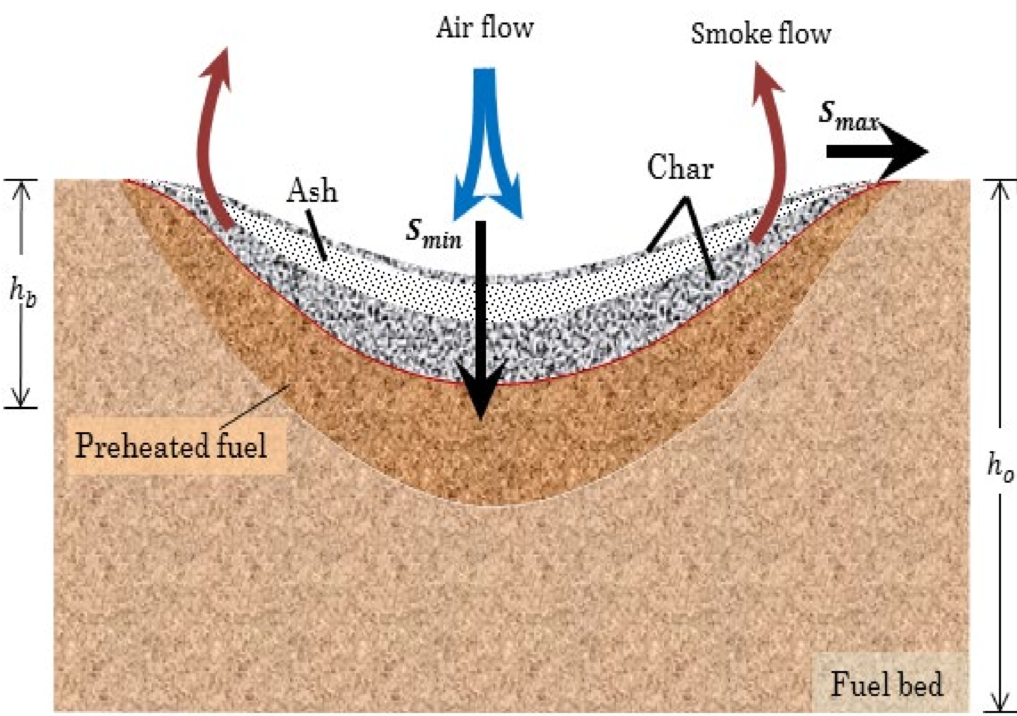




- Controlling mechanisms: **oxygen supply** vs. **heat losses.**
- Peat fire leads to the formation of **overhang** caused by the vertical gradient of the lateral spread rate.

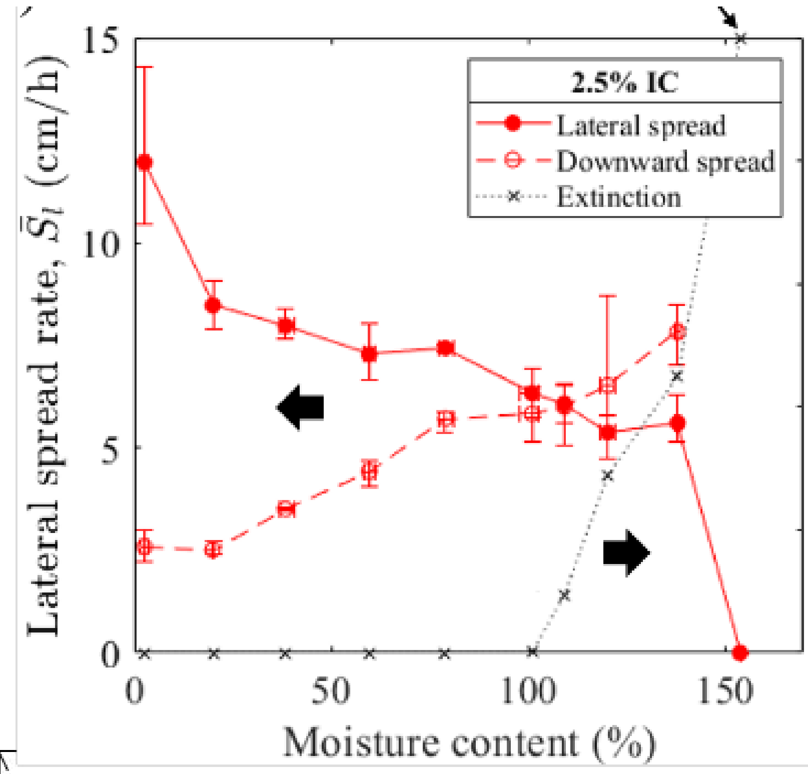
Huang et al, *Comb Flame*, 2016

# Downward Spread

- Two spread components: lateral and in-depth (or downward).



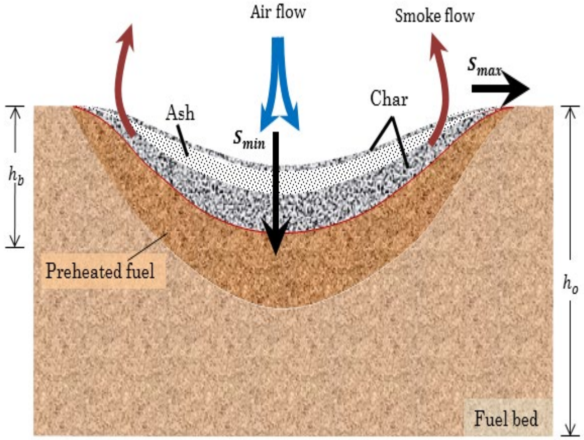

Christensen et al., *Combustion and Flame, 2019*

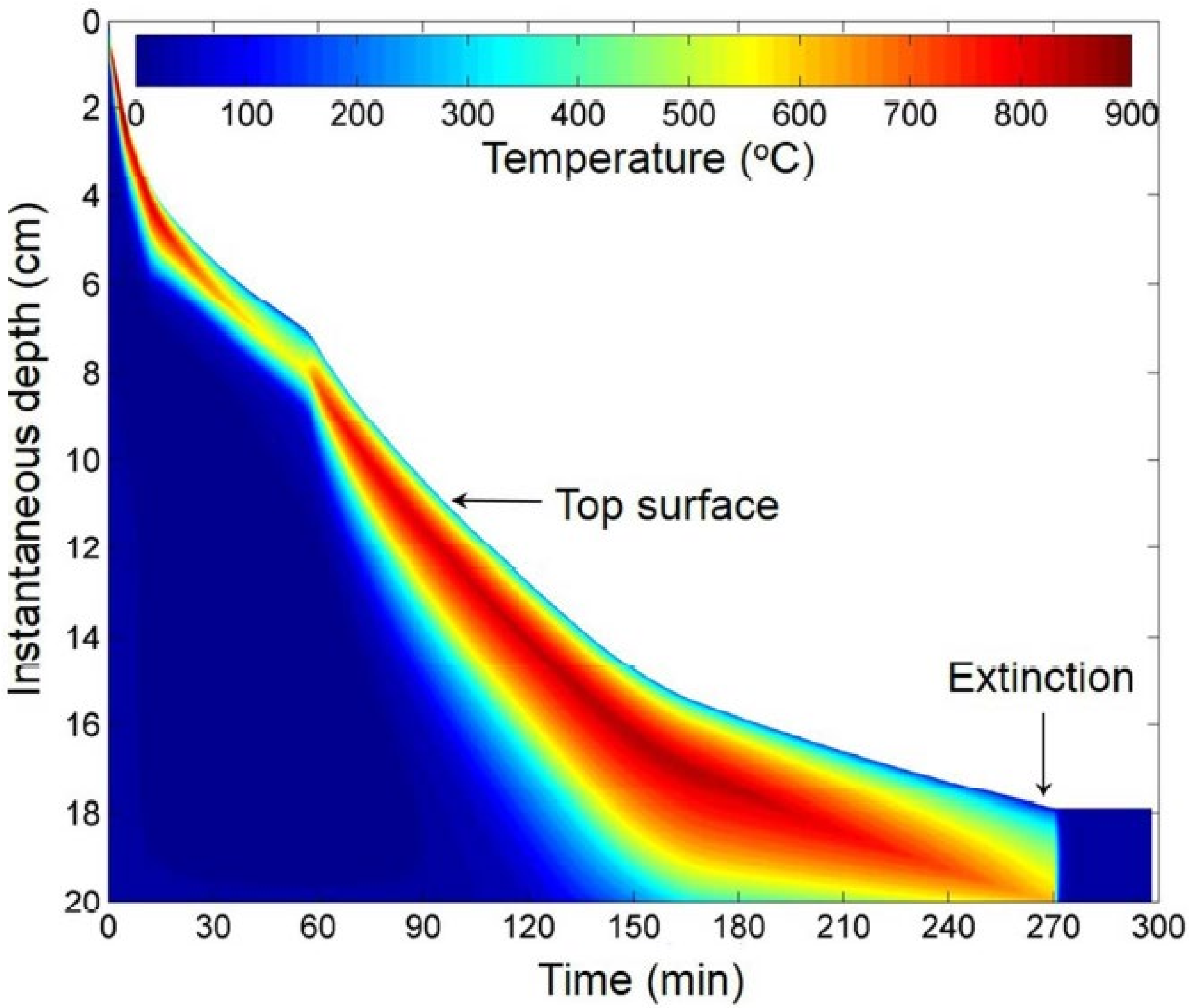



- For dryer peat: lateral spread is faster than in-depth spread.
- For wetter peat: lateral spread is slower than in-depth spread.

# Computational Smouldering

Controlling mechanisms: **oxygen supply** and **heat losses**.



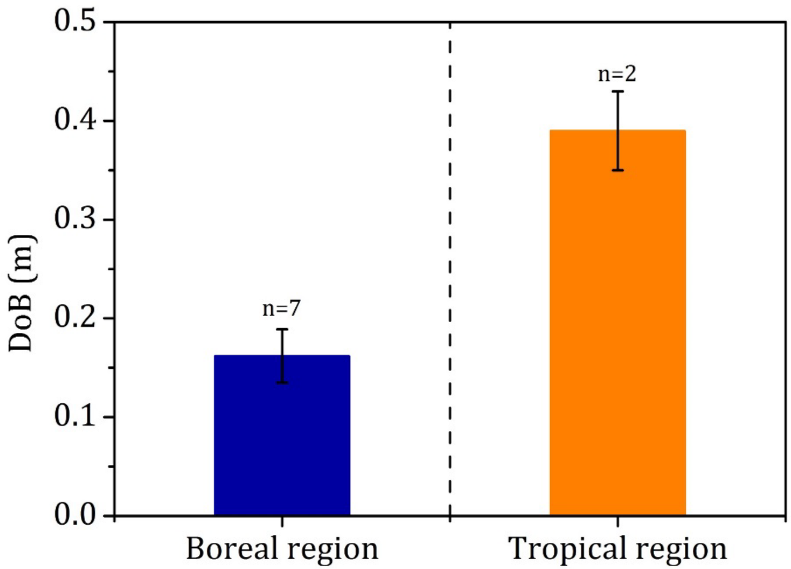

Huang et al, *Proc Combustion Institute* 2015

# Smouldering Depth of Burn (DOB)

2008 Evans Fire

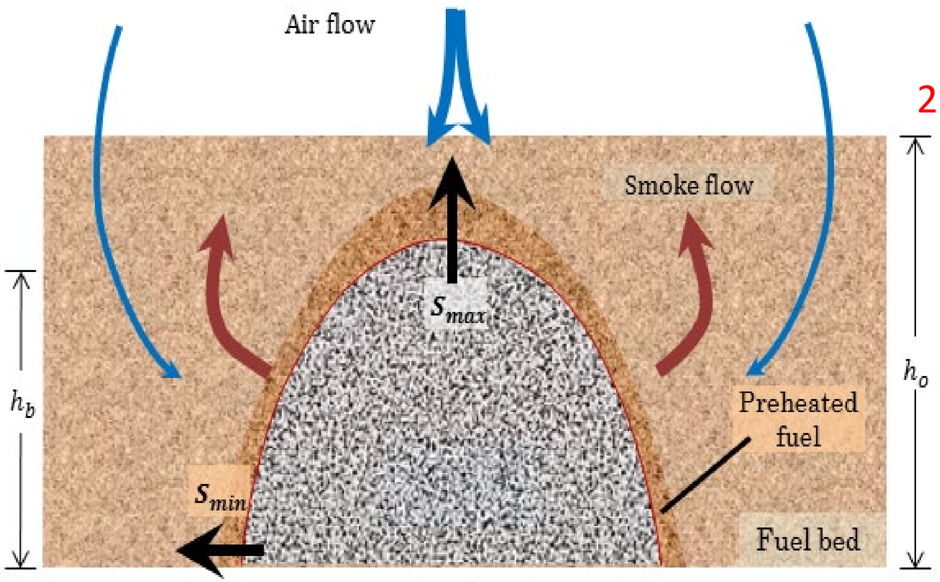
- Observed DOB range between 0.05 to 3 m, with tropical average at 0.45 m.

- This in-depth spread leads to 50 to **100 times larger fuel consumption** per unit area than flaming fires.

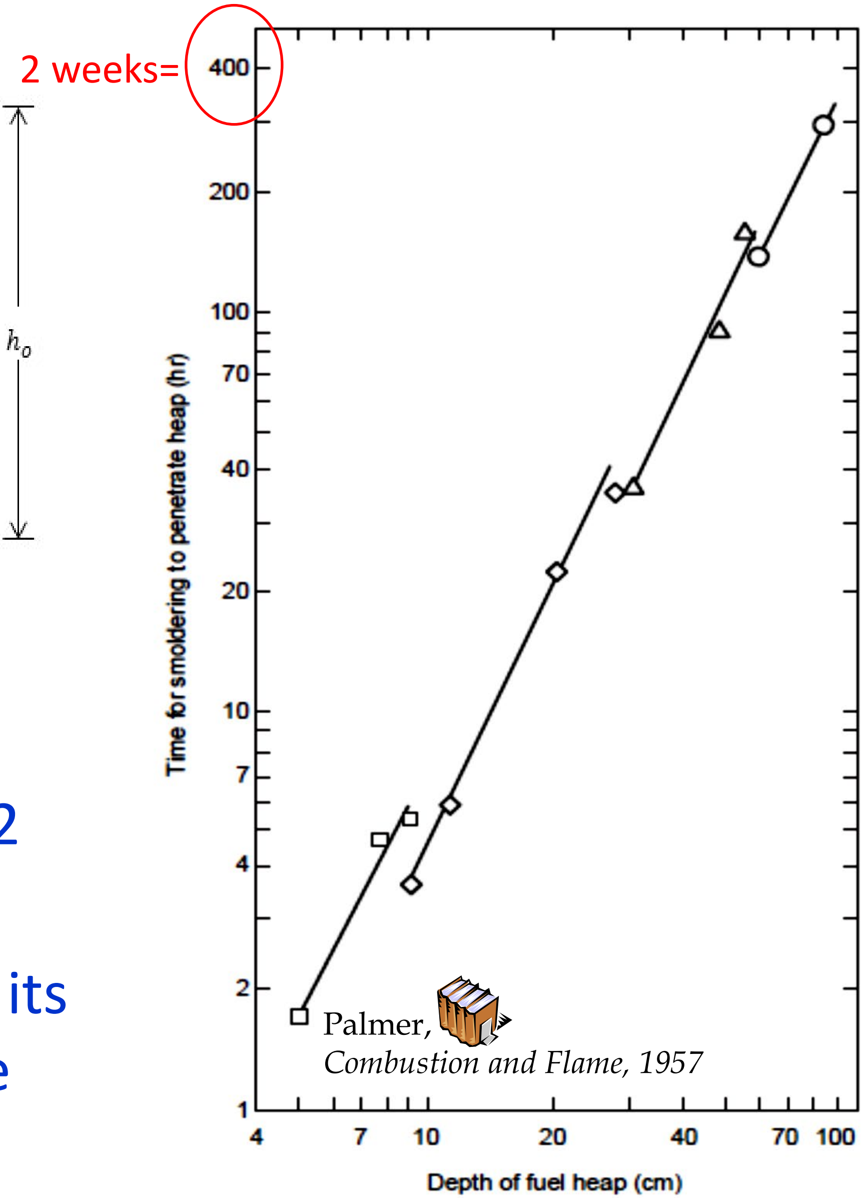


# Upward Spread thought a fuel bed

Controlling mechanisms: **oxygen supply** and **heat losses**.



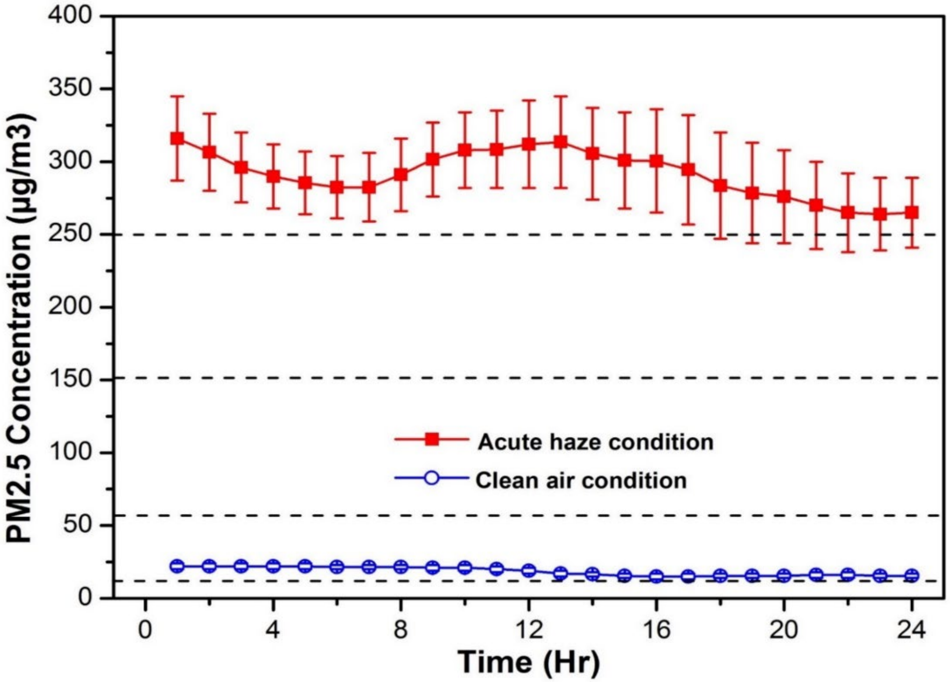

- Seeks $O_2$ supply
- Time to smoulder upwards through a layer 1 m deep is ~ 2 weeks
- The process give little hints of its presence until it is close to the surface of the fuel layer.



# Emissions

# Emissions

**Haze leads to severe pollution events and reduced visibility.** During 1997 SEA Haze, local land, air and marine traffic were disrupted, the total damages amounted to £**4 billion**.

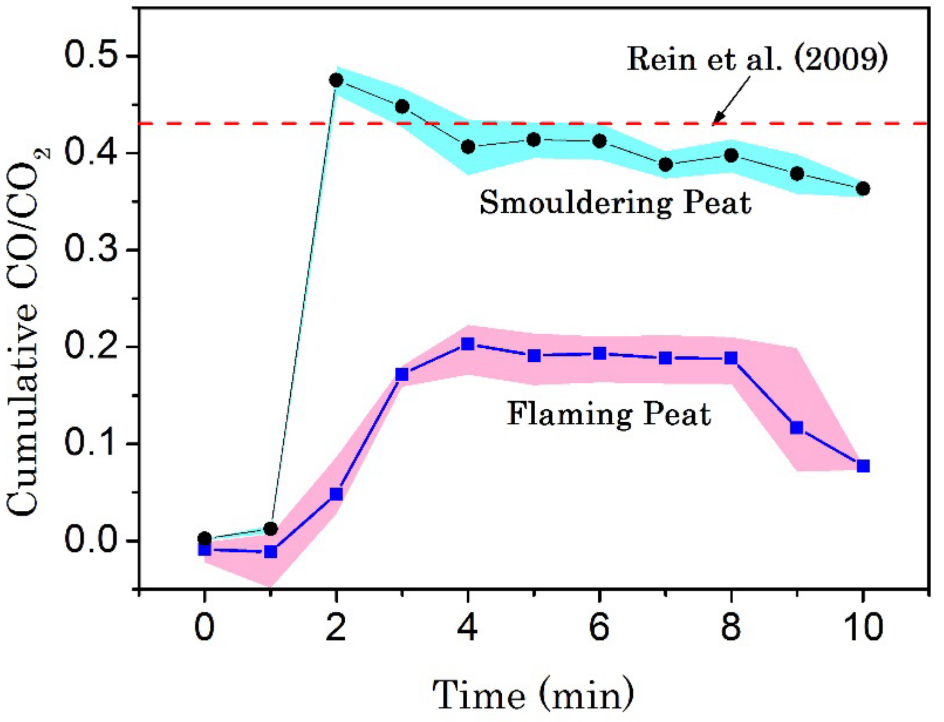



# Gas Emissions

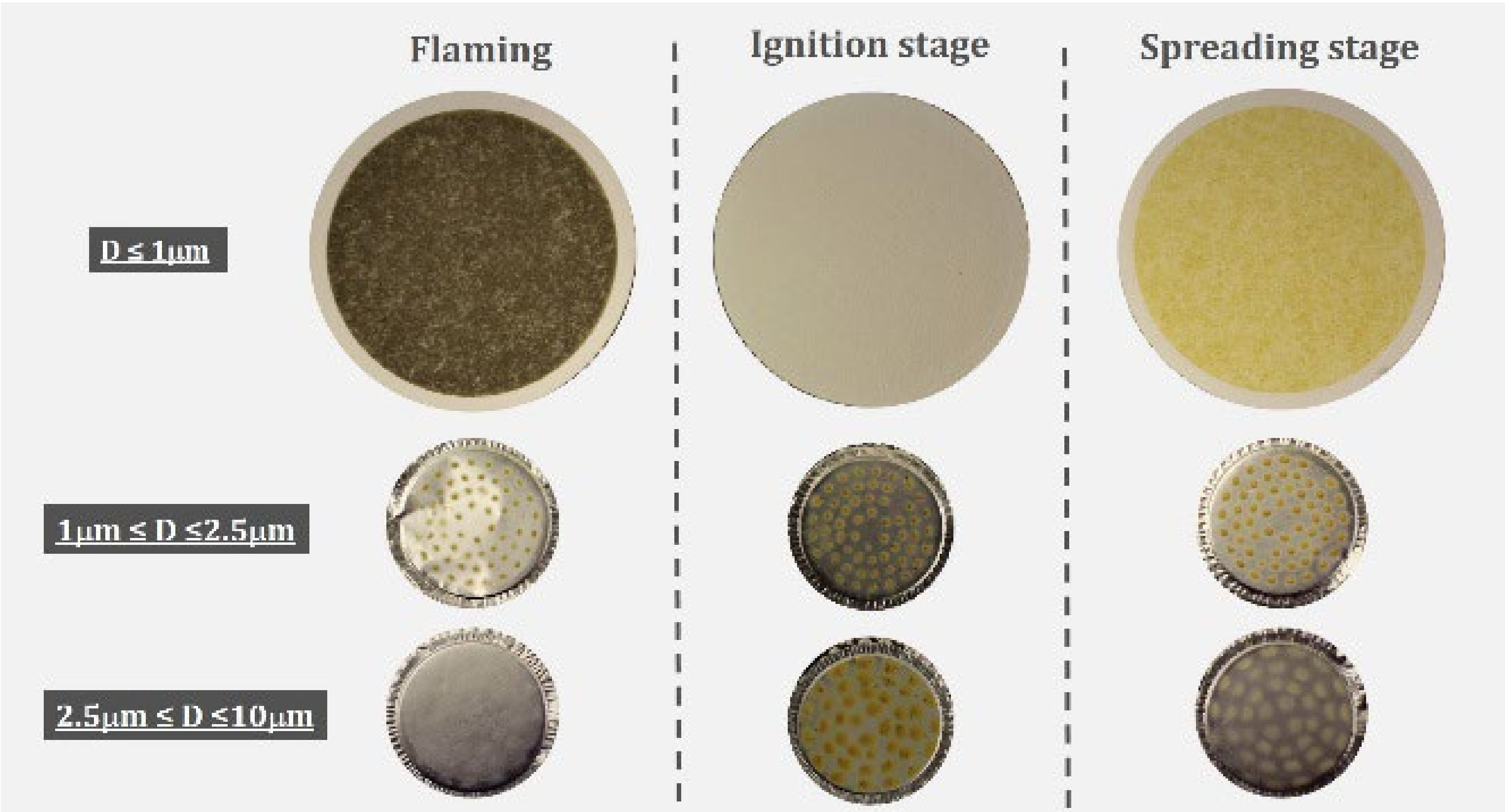
- Carbon gaseous emissions mostly as $CO_2$ and CO, but also $CH_4$ and PAH
- $CO/CO_2$ smouldering is ~0.4 vs. typical values for flaming combustion ~0.1

Average emission factors of peat fires (g/kg, dry fuel base)

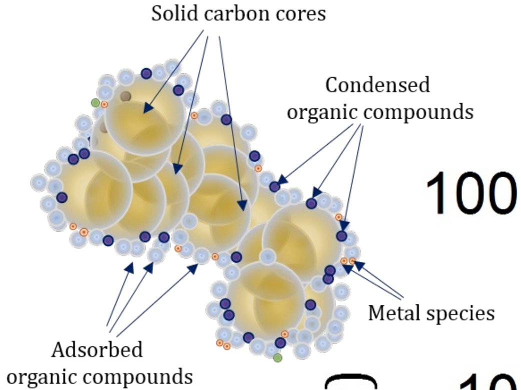
| | | | |
|---|---|---|---|
| $CO_2$ | **1703** | Phenol | 4 |
| CO | **210** | $C_3H_6$ | 4 |
| $PM_{2.5}$ | **44** | $CH_3CHO$ | 3 |
| $CH_4$ | **21** | Benzene | 3 |
| $NH_3$ | **20** | Furan | 2 |
| $CH_3COOH$ | 9 | Toluene | 2 |
| Methanol | 9 | HCHO | 1 |
| HCN | 8 | Acetone | 1 |
| $CH_3CN$ | 5 | Isoprene | 1 |
| Acetol | 4 | NO | 1 |

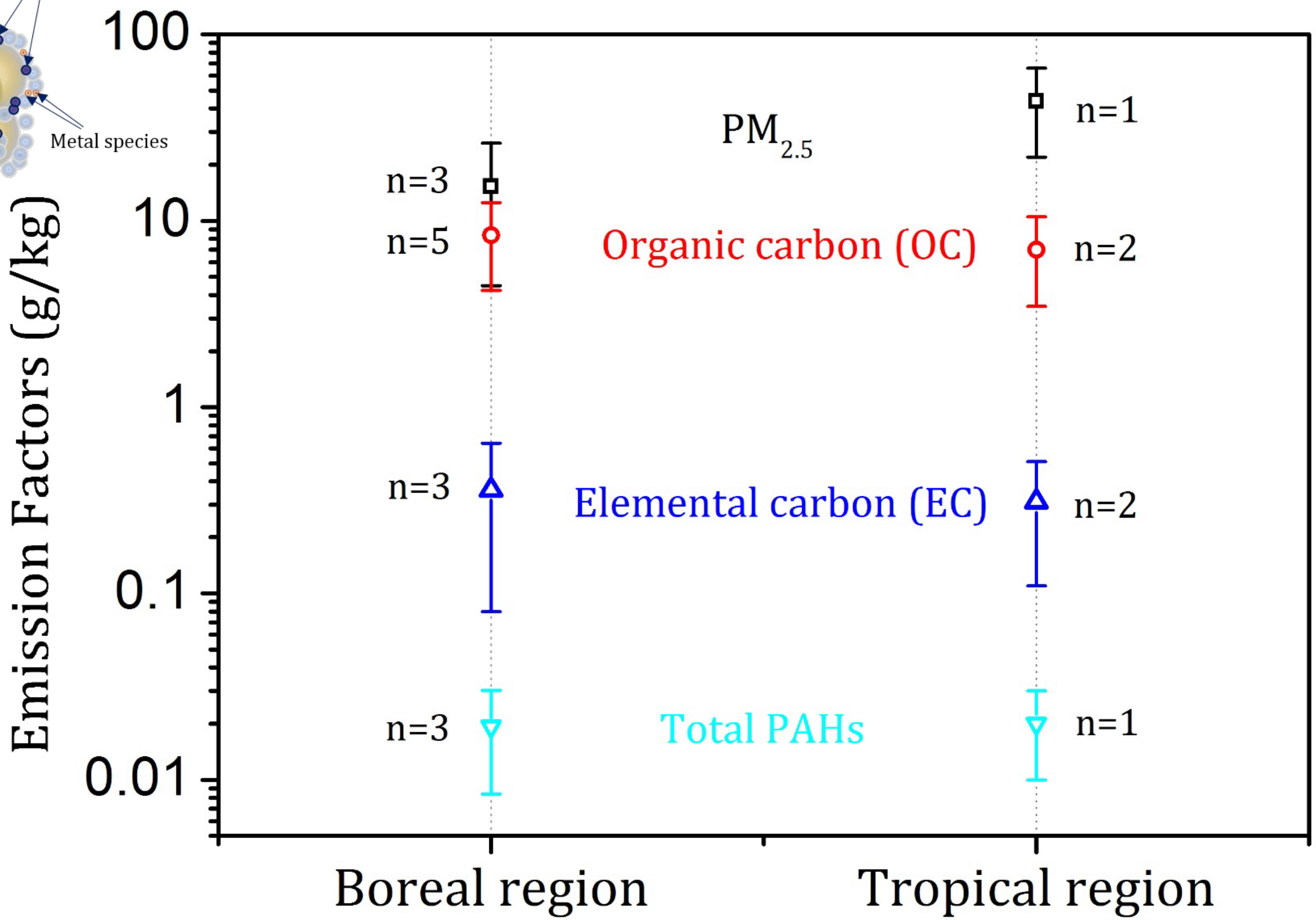



# Particle Matter Emissions



# Particle Matter Emissions




- OC constitutes the main components in $PM_{2.5}$ aerosols
- PM2.5 significantly different between boreal and tropical peats.
- Information of PM EFs is limited

# Suppression

# Means for Suppression

The most important objective is to **detect early,** then **locate** the hotspots, and deliver **suppression**.

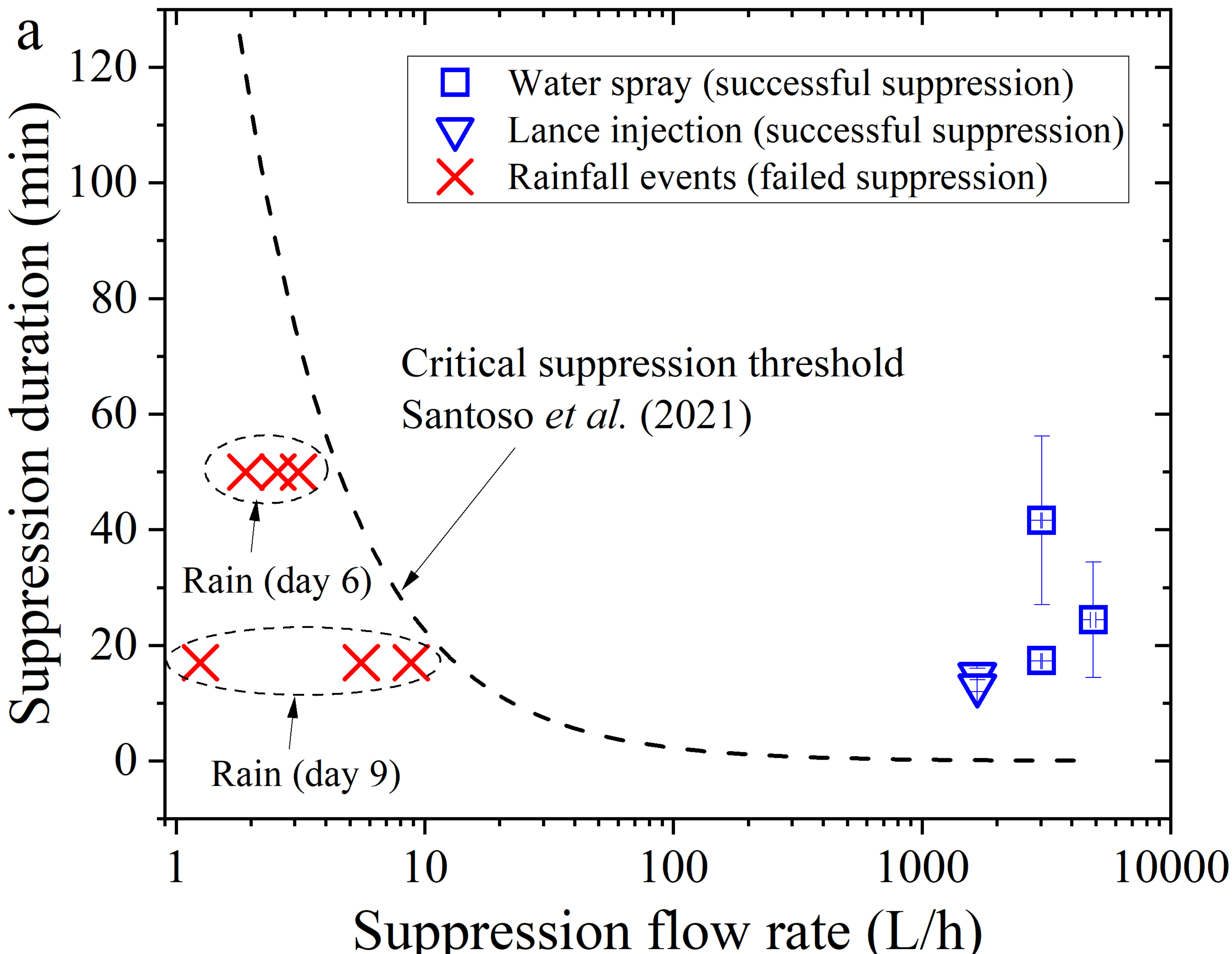
If detection is late, and smouldering fire is large:

1. **Flooding.**
2. **Compartmentation via fire breaks.**

3. Wetting fuel (with additives) - reduces spread rate.
4. Injection with lances
5. Foams
6. Making fuel inert (eg, sand) - reduces spread rate.
7. Compacting – reduces spread rate.

8. Sealing – t ~ 100 days.
9. Smothering – $[O_2]<10\%$.

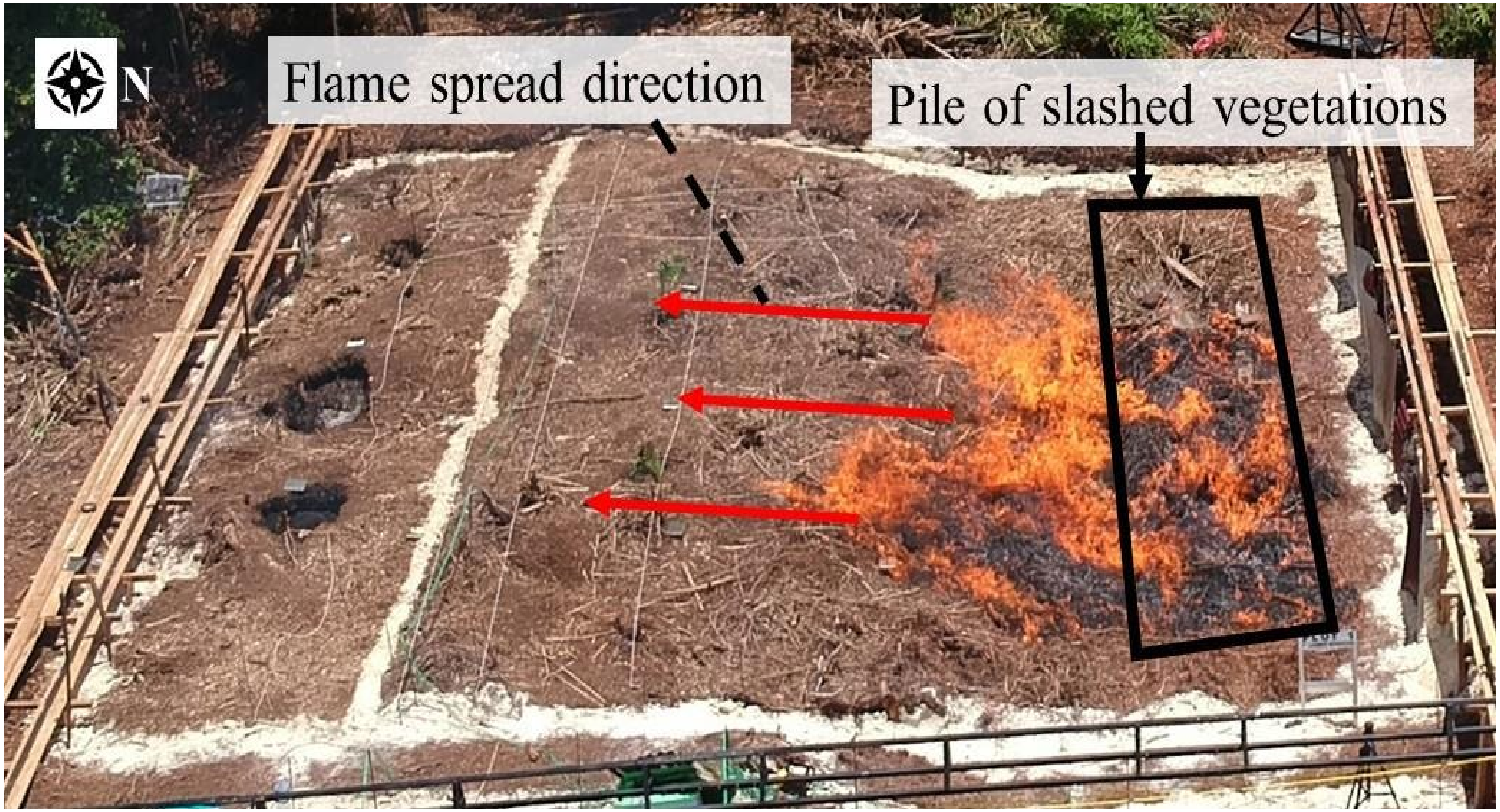
# Water suppression in the lab




Santoso et al, IJWF 2022

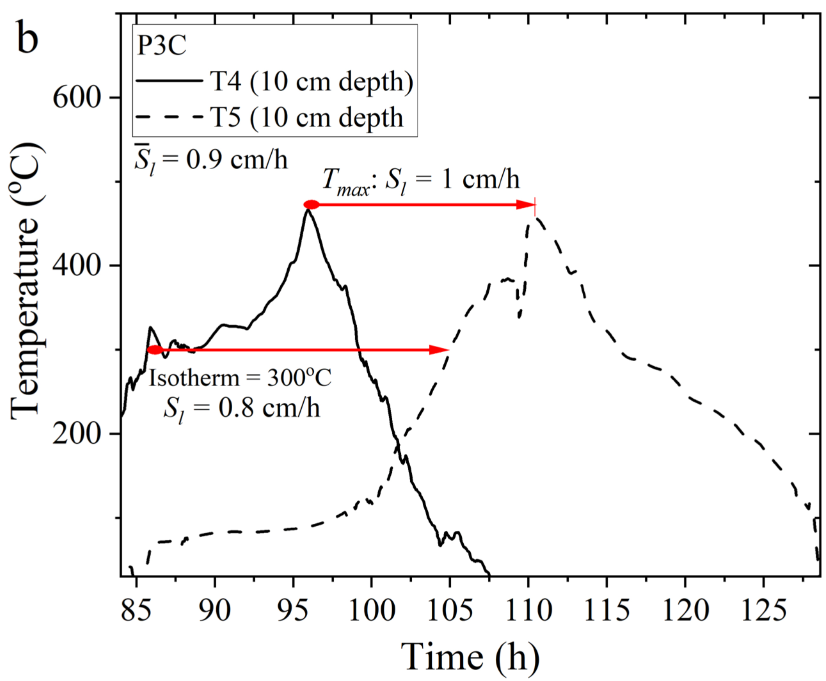
# GAMBUT: Novel Field Experiments on Peat Fires

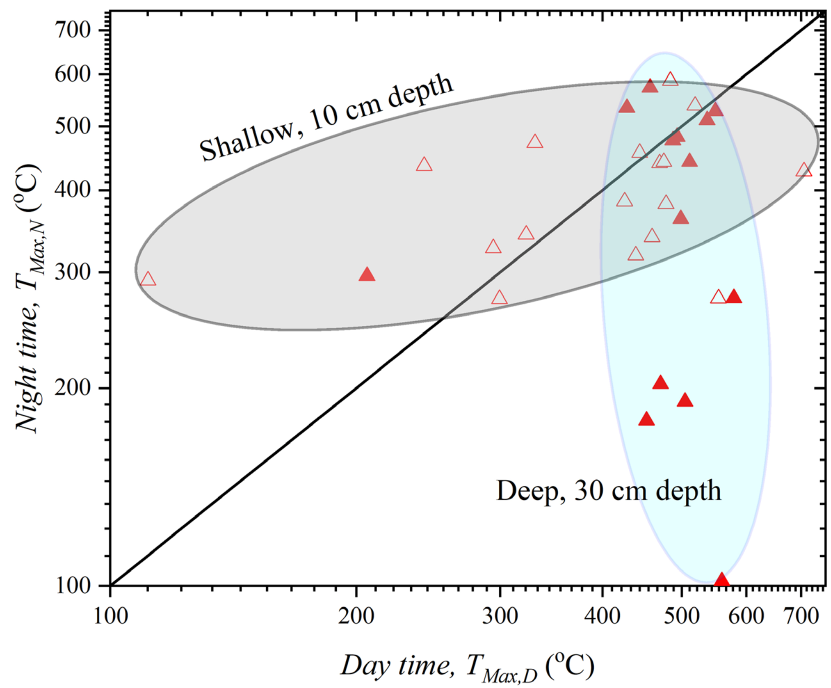
# GAMBUT 2018: Sumatra




Santoso et al, IJWF 2022

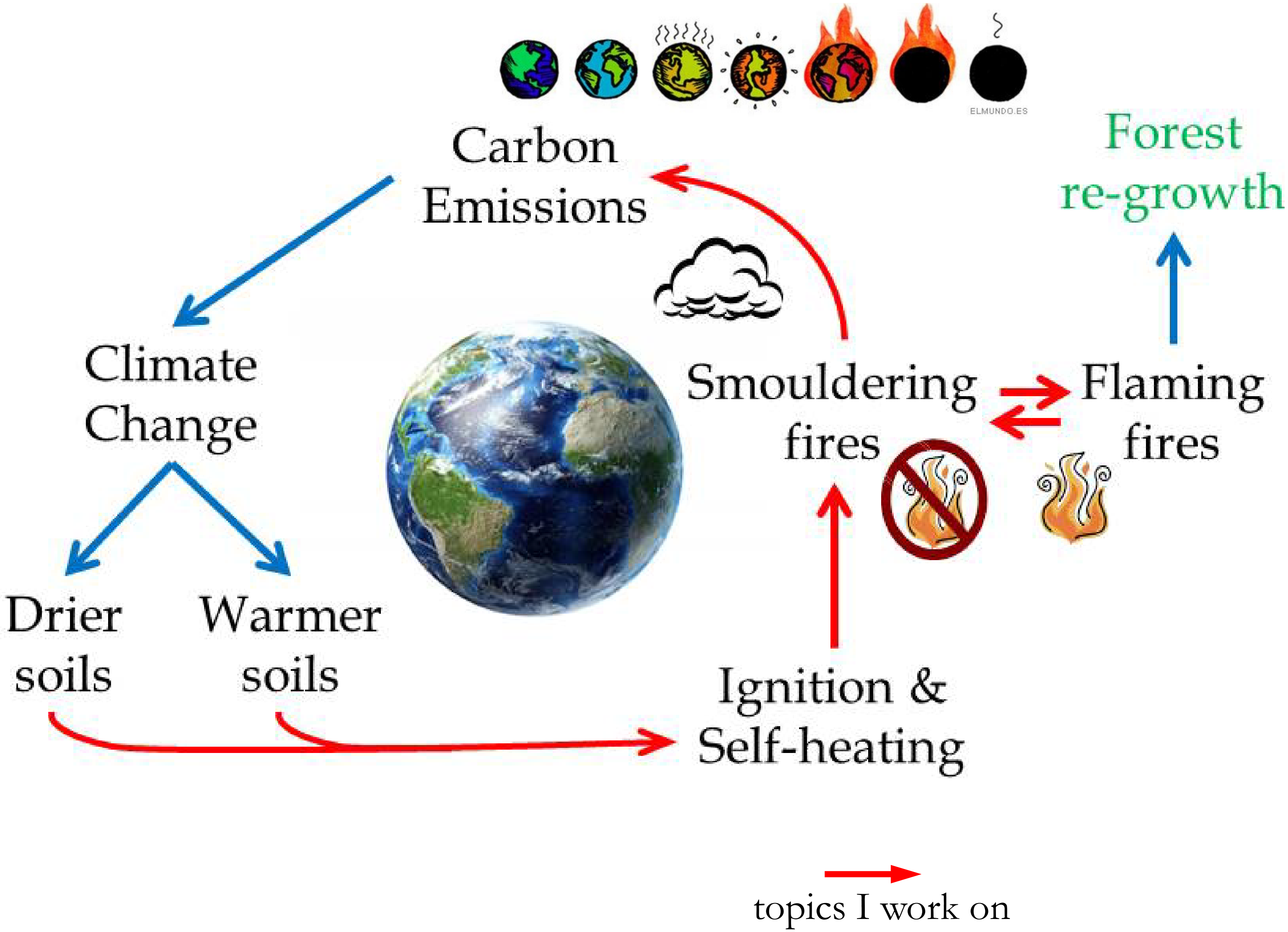
# GAMBUT 2018: Sumatra




Santoso et al, IJWF 2022

# **Earth Scale:** Positive feedback in climate change




Rein & Huang, *Current Op. Environ. Science & Health*, 2021

# Concluding Remarks

- Smouldering is a wildfire threat to life safety, property and the environment.
- The **most persistent** mode of combustion, related to peat fires, residual burning and firebrands.
- Simplest chemistry is **two-step**: pyrolysis of fuel followed by char oxidation.
- **Largest fires on Earth:** C footprint ~ worldwide fleet of vehicles.
- **Emerging scientific topic** of global interest.
- Regrettably, the state of the art is **fragmented** and this lack of integration hinders scientific progress on the topic.