Smouldering Wildfires in Peatlands, Forests and the Arctic

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

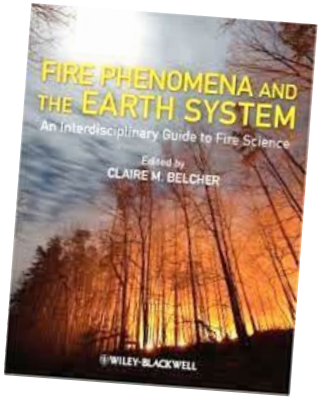
29 March 2022, zoom.

The content of this lecture is based on our work, 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,

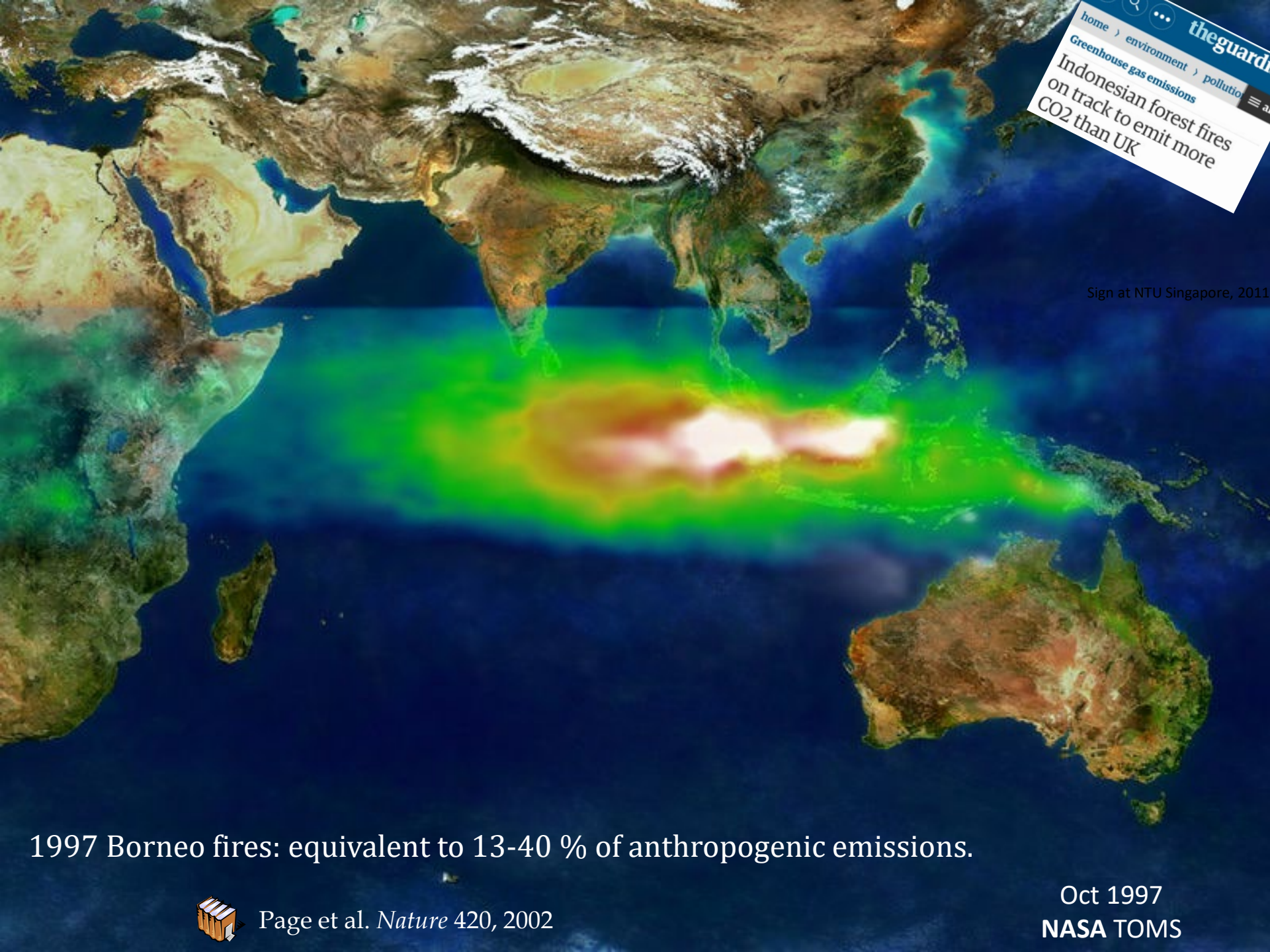
Chapter 2 in: *Fire Phenomena in the Earth System*, Wiley 2013. DOI:10.1002/9781118529539.ch2

IMPERIAL HAZE LAB

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
- Stopped by flooding and excavation
- $20 million suppression costs



Sign at NTU Singapore, 2011

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

Page et al. *Nature* 420, 2002

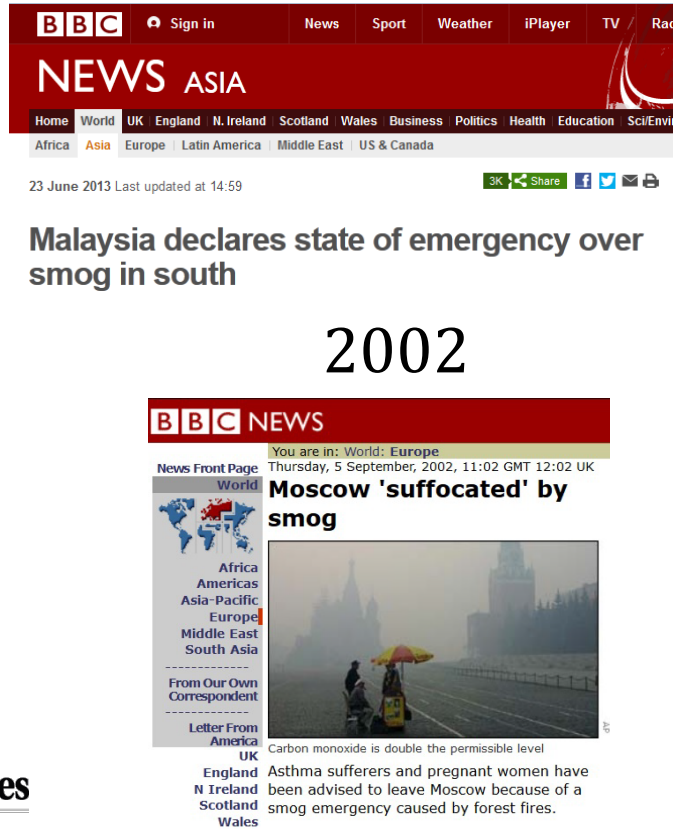
Oct 1997
NASA TOMS

Largest fires on Earth are smouldering peatlands

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

2015

2013



2010

2002

1999

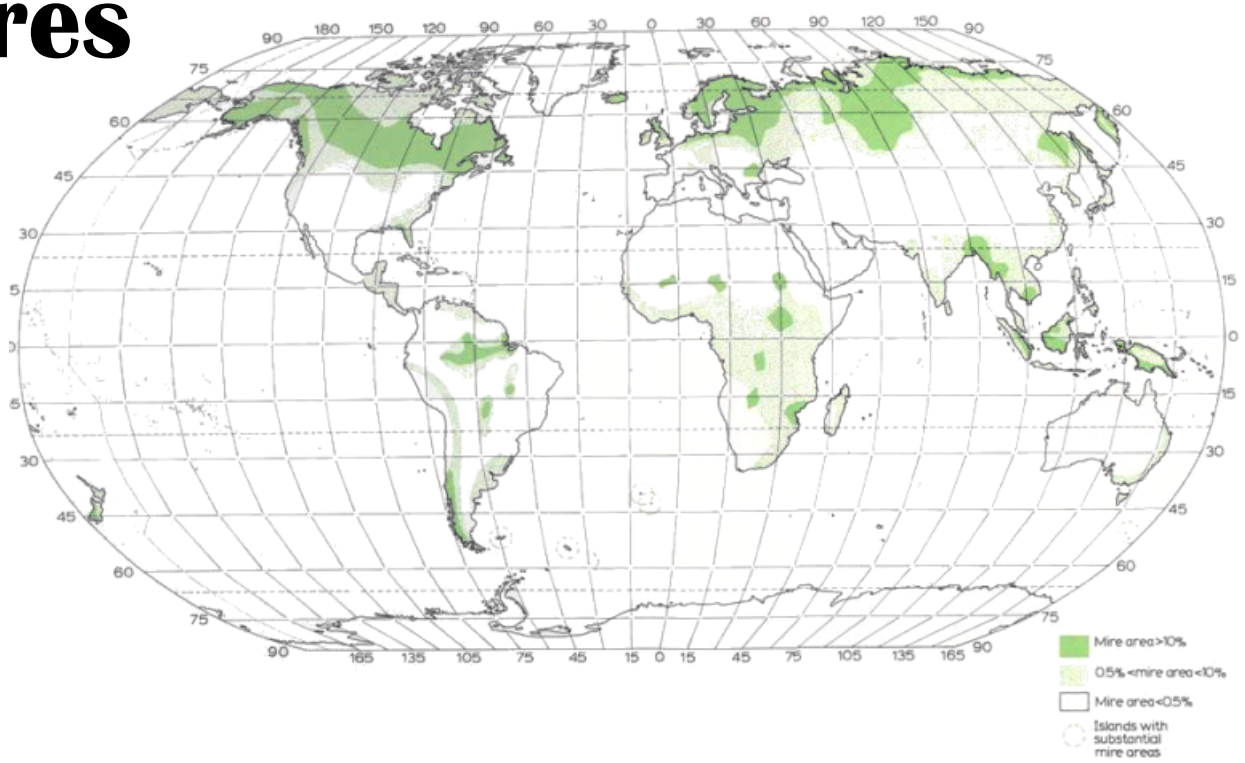
The St Petersburg Times

1972

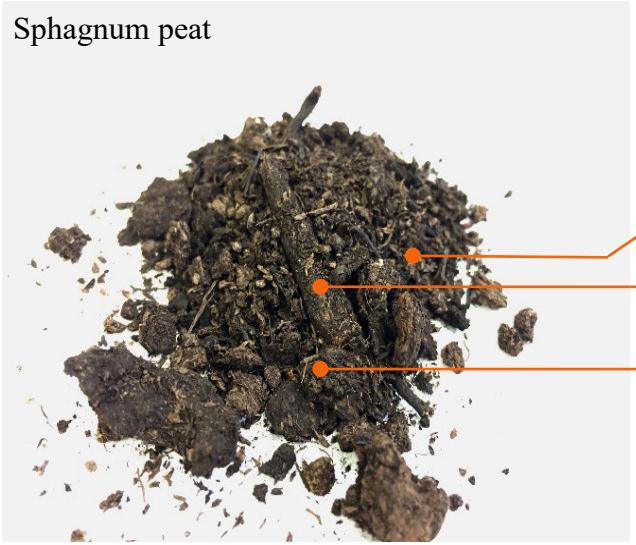
"Smoke Shrouds Moscow as Peat-bog fire rages" The New York Times

Peat Megafires

Smoldering is the dominant combustion phenomena in peat fires.



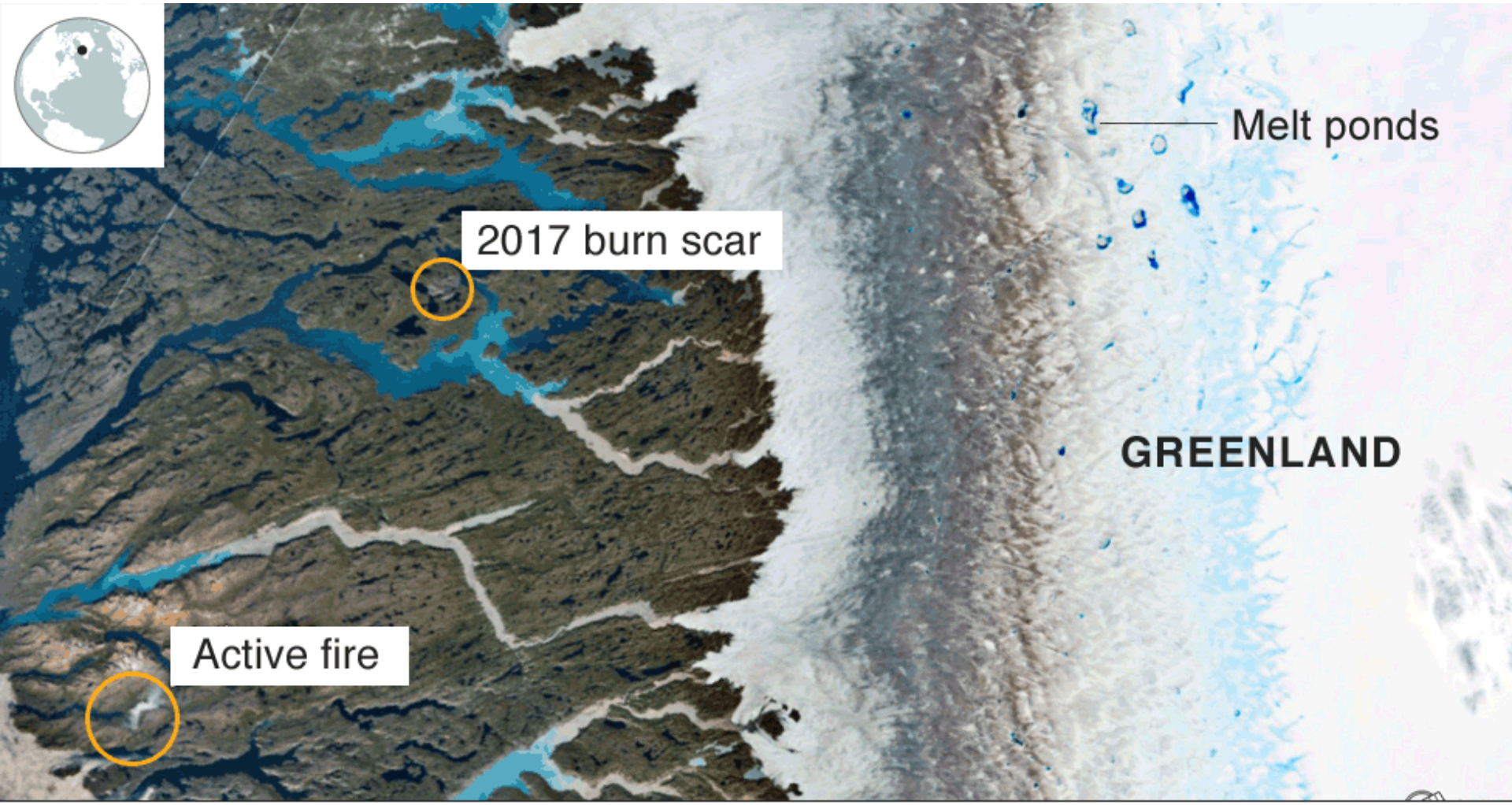
Sphagnum peat



Peat (natural carbon sink)

- **Carbon-rich** organic soil (**>12%** carbon).
- Composed of **partially decomposed plants.**
- Accumulated in **water-logging**, anaerobic conditions over centuries to millennia.

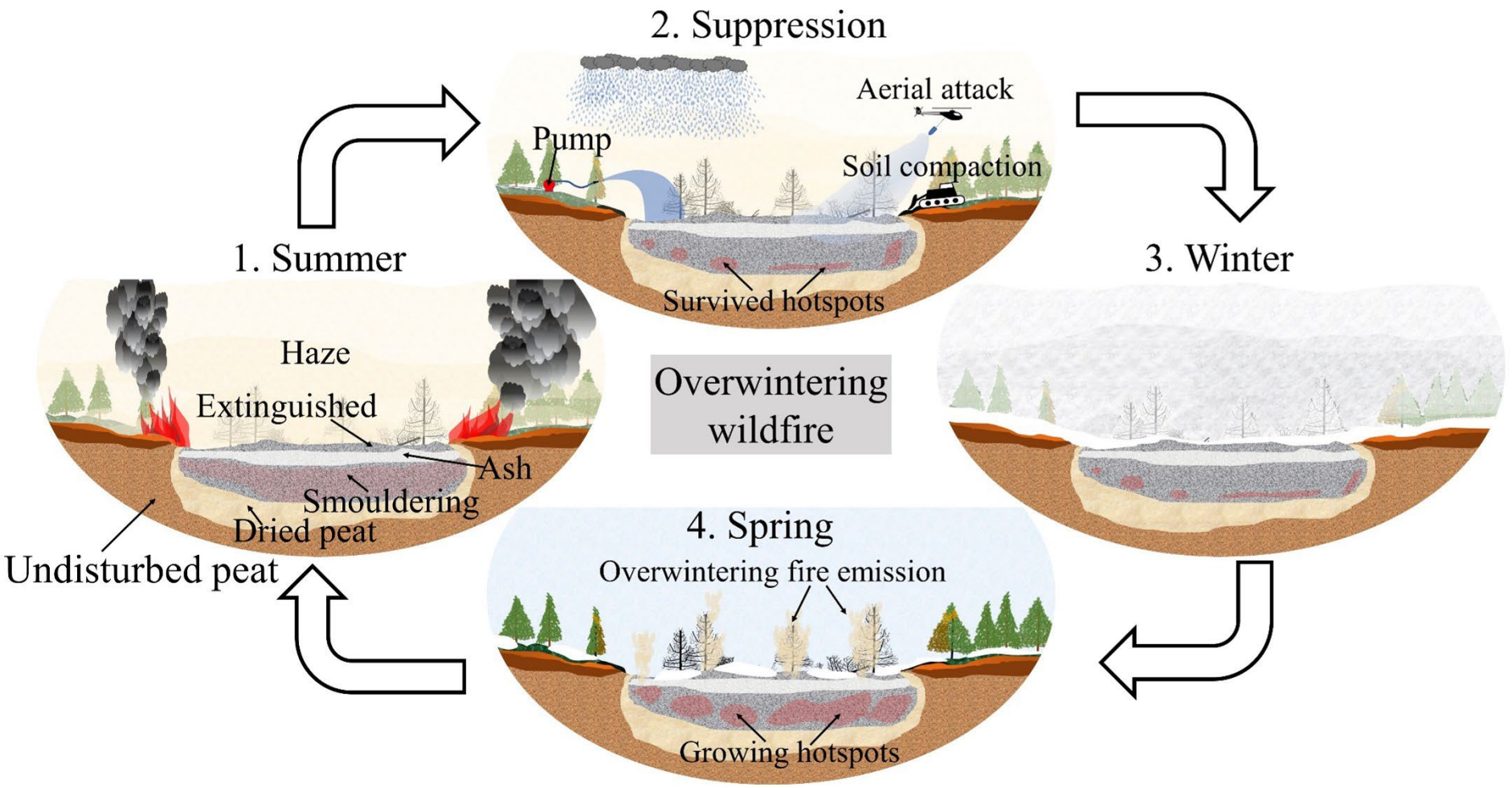
Arctic wildfires



Source: Copernicus Sentinel data, processed by Pierre Markuse

BBC

Arctic


2. Suppression
Aerial attack
Pump
Soil compaction
Survived hotspots
1. Summer
3. Winter
Haze
Extinguished
Ash
Smouldering
Dried peat
Undisturbed peat
Overwintering wildfire
4. Spring
Overwintering fire emission
Growing hotspots

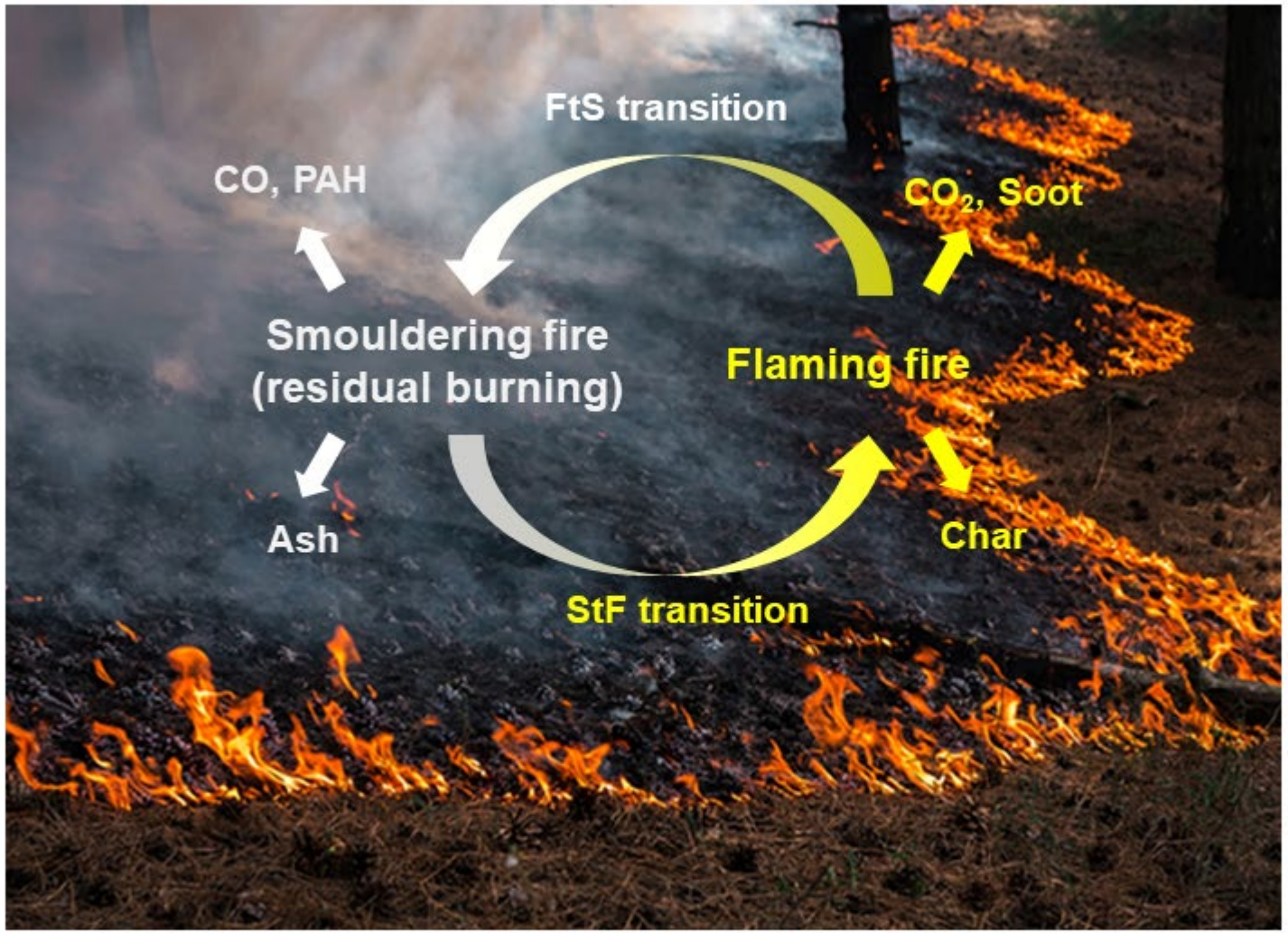
Smouldering and Wildfires

(a) Peat fire

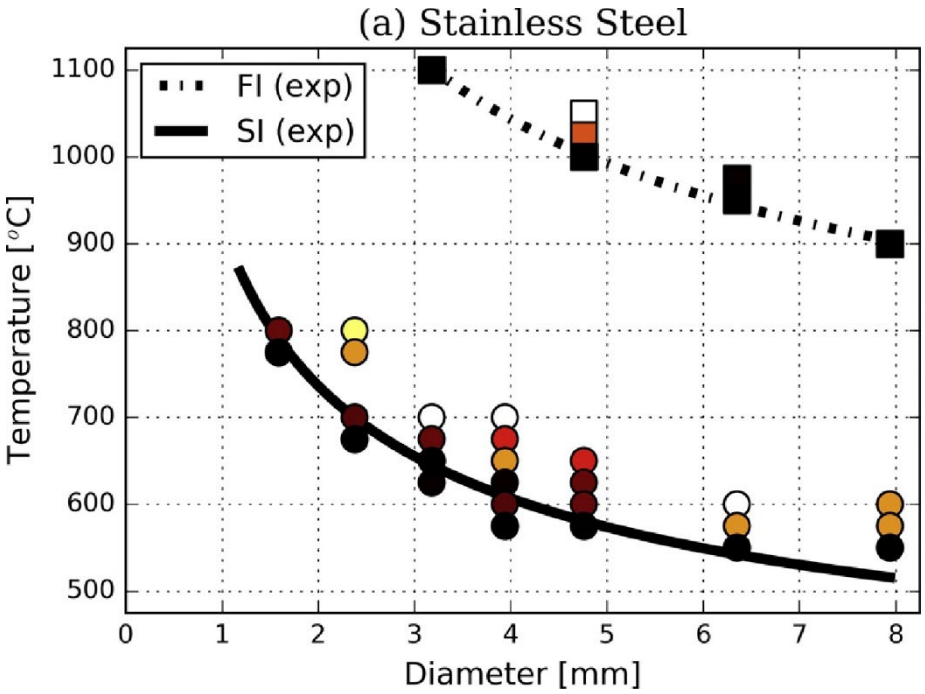
(b) Residual burning

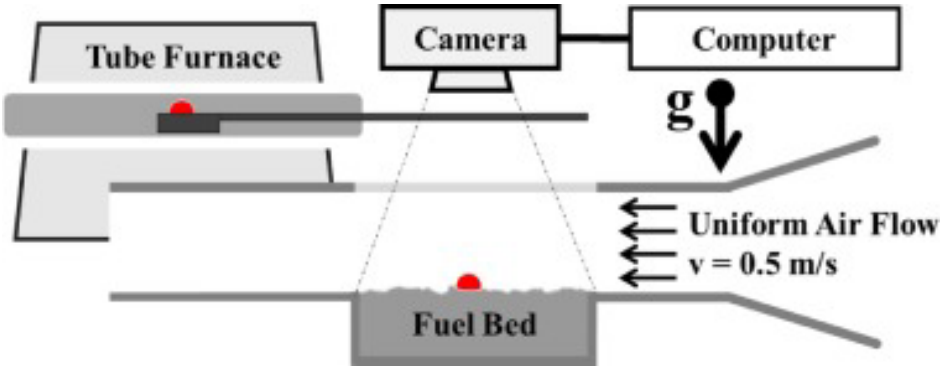
(c) Firebrands

Residual Burning



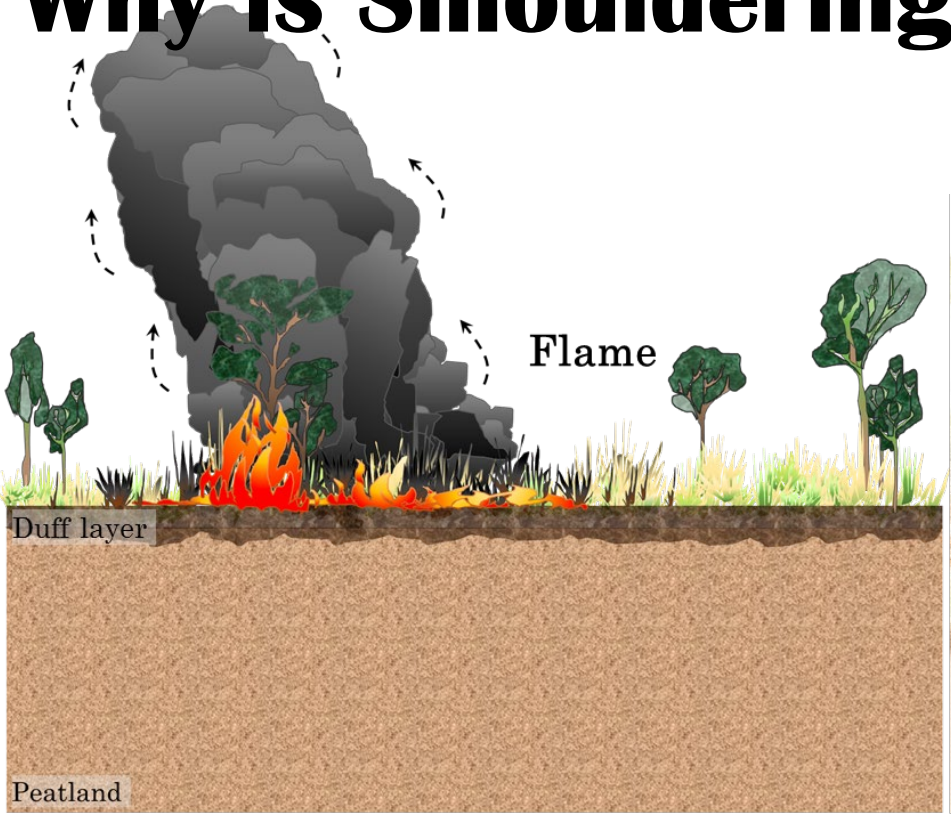
Firebrand ignition, landing on fuel bed

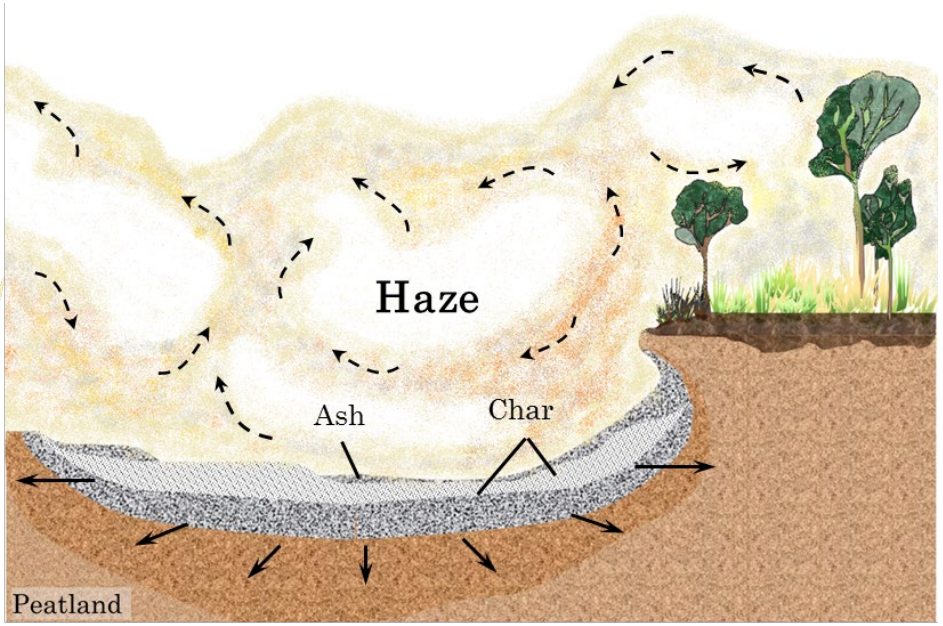




Urban et al, *Proceedings Combustion Inst* 2017

Why is Smouldering Different?





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)

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 g_{H2O}/g_{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 6k years ago.

What is smouldering combustion?

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

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

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

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

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

$$\text{Biomass (s)} \rightarrow \mathbf{Pyrolyzate\ (g)} + \text{Char (s)}$$
$$\text{Pyrolyzate (g)} + O_2\,(g) \rightarrow CO_2 + H_2O + \text{emissions}$$

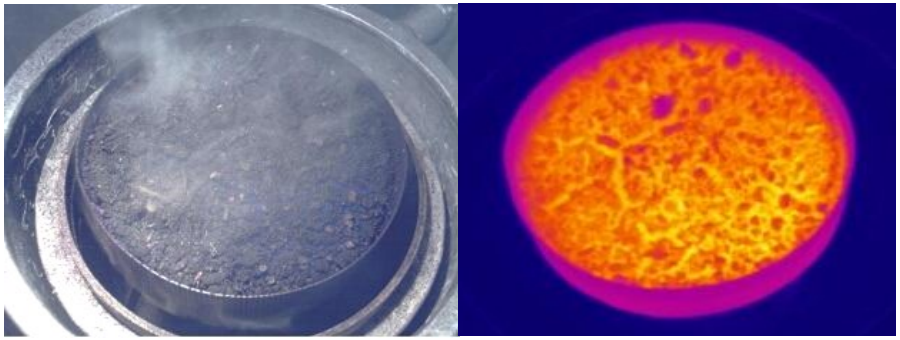
Rein et al., SFPE Handbook, 2015

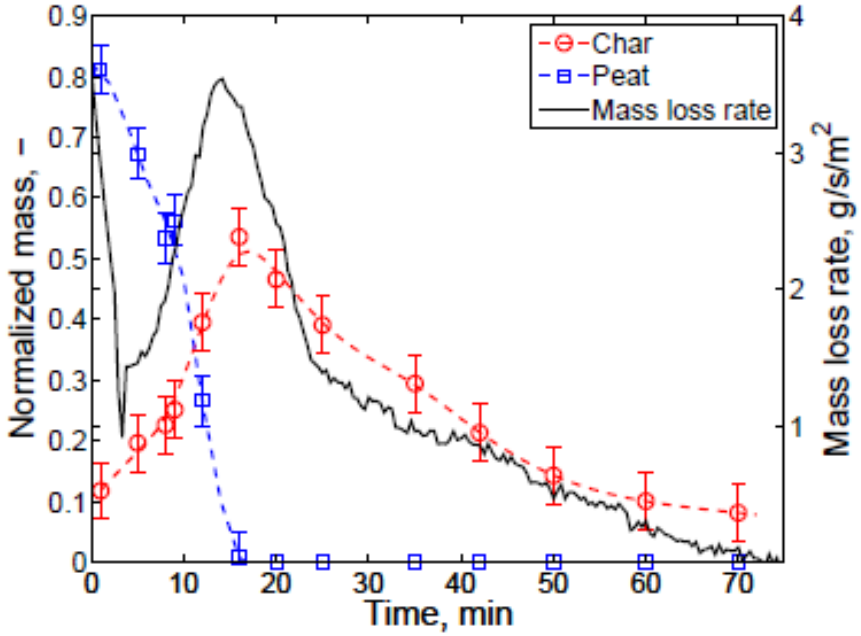
Char: intermediate product of smouldering

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

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

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

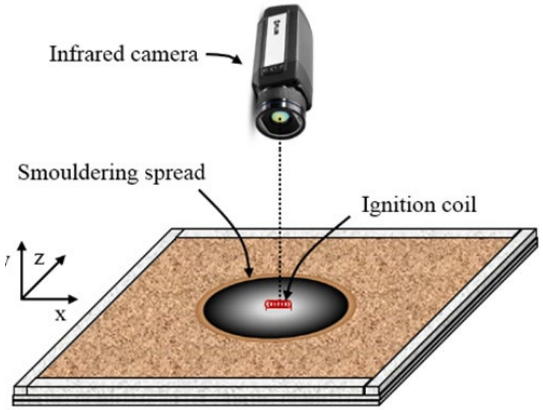




Hadden et al, *Proceedings of the Combustion Institute*, 2012

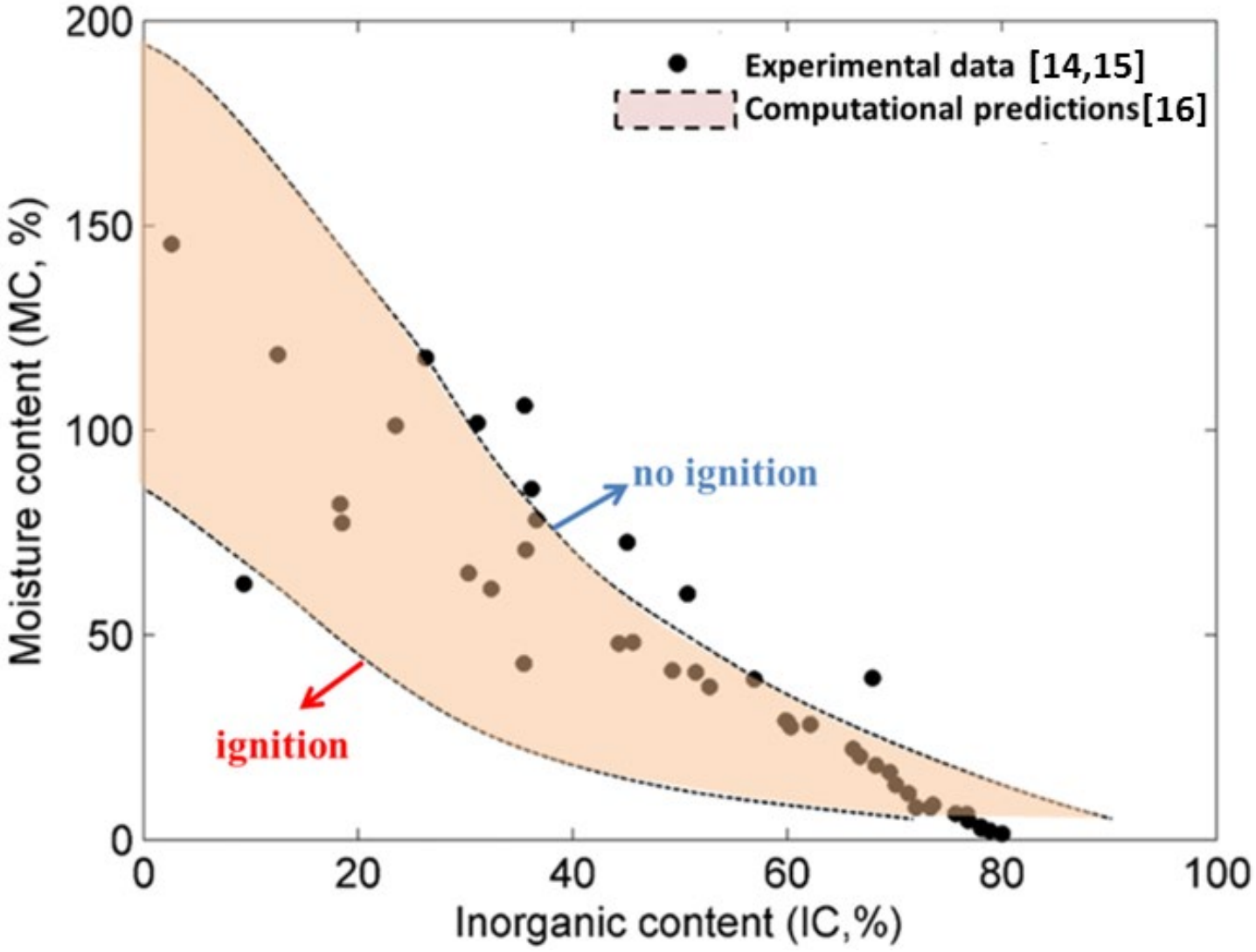
What is smouldering combustion?

speeded up 600 times



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

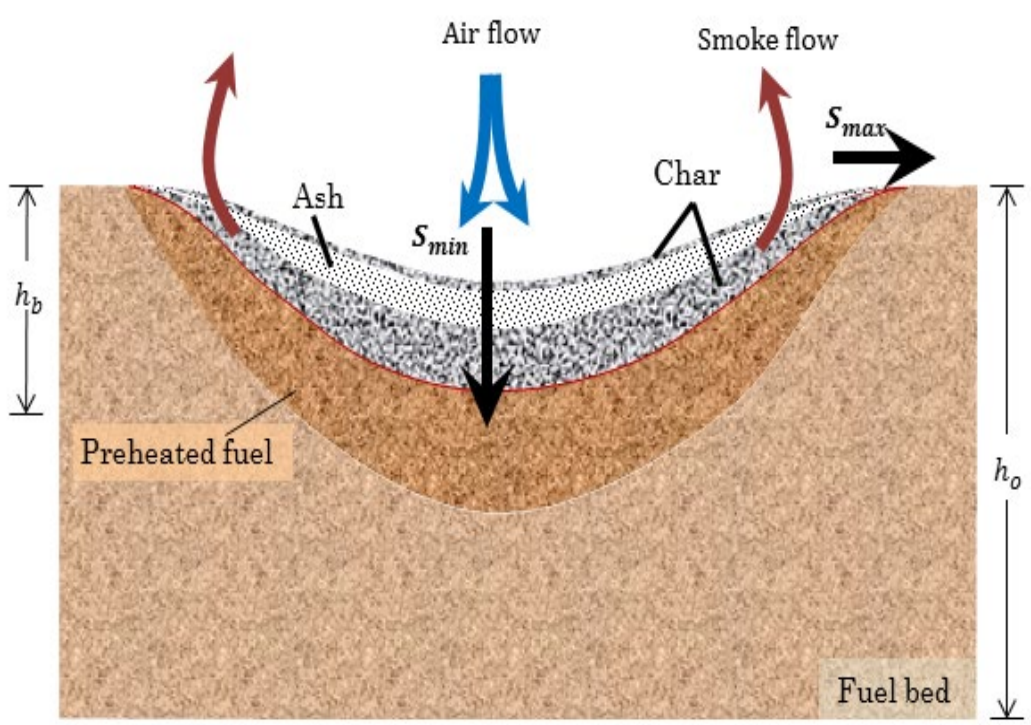
How does it ignite?

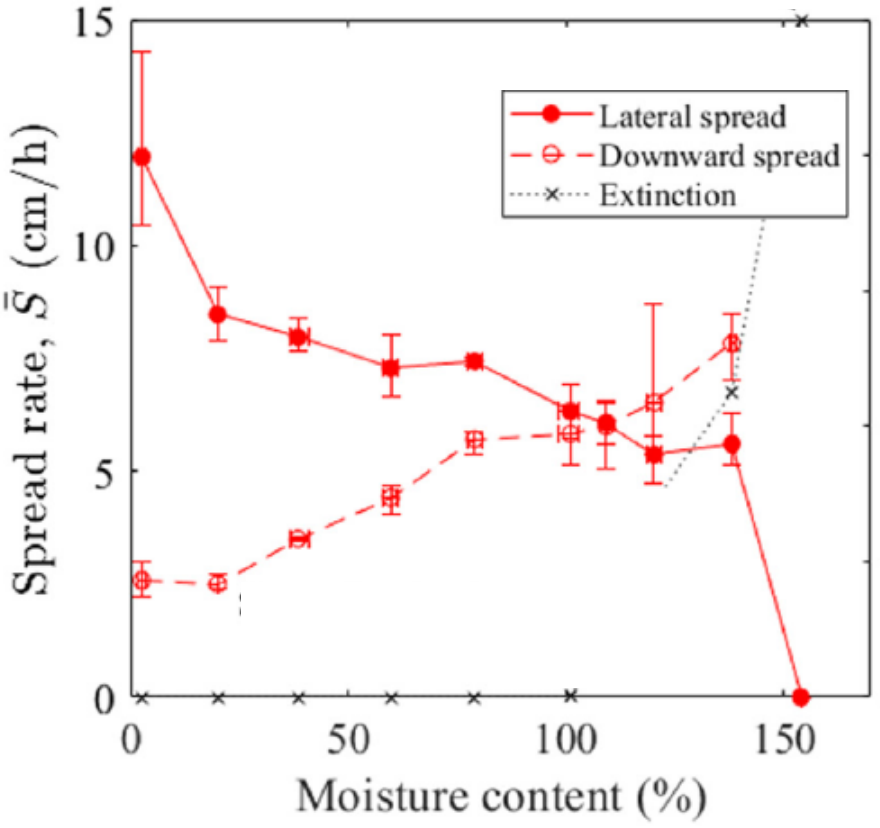


Frandsen, *Can. J. For. Res.* 1997

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

Challenge#1: Multidimensional Spread

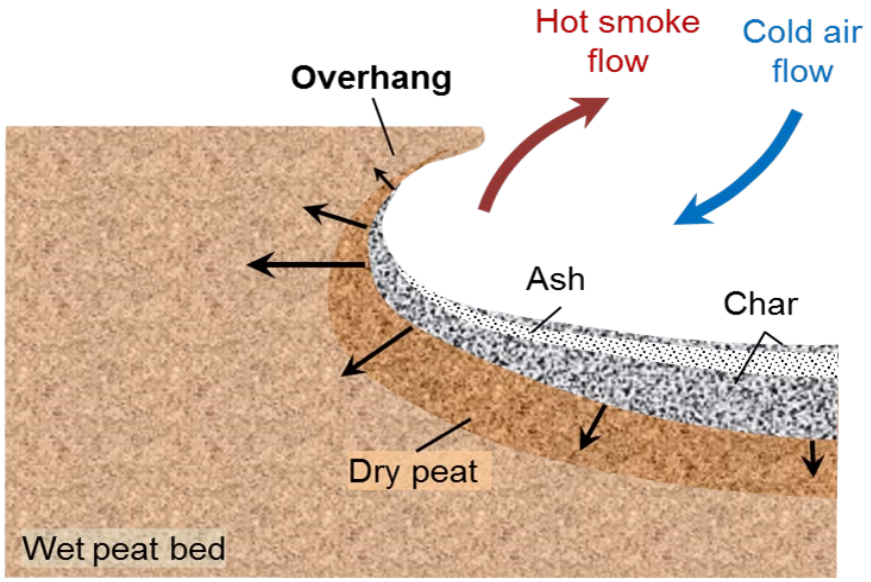


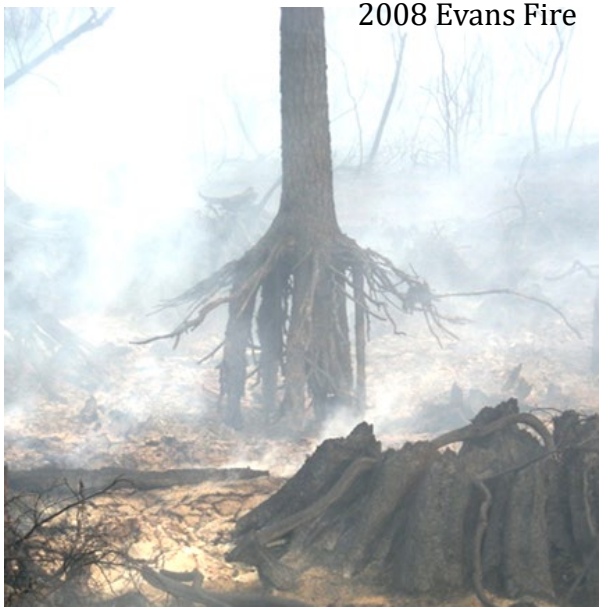


- Lateral spread decreases with moisture because of + heat sink.
- In-depth spread **increases** with moisture because of + porosity.

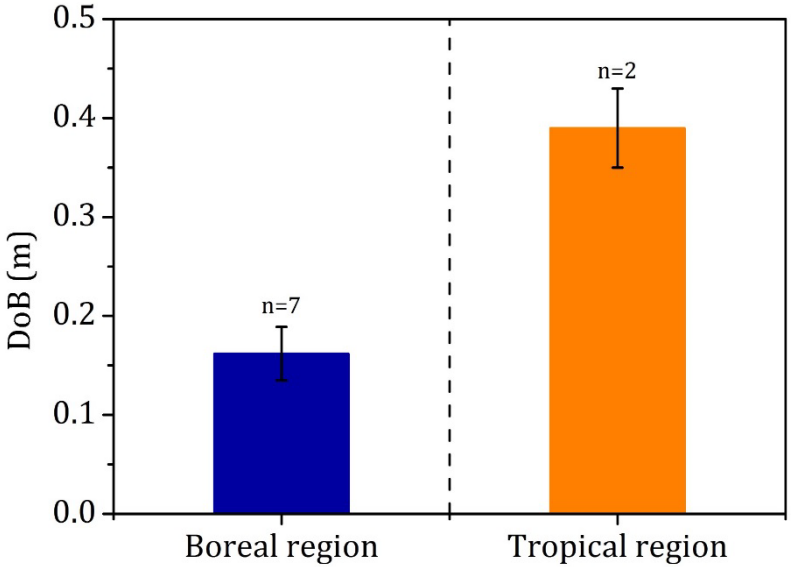
Christensen et al., *Combustion and Flame, 2020.*

Overhang vs. Depth of Burn

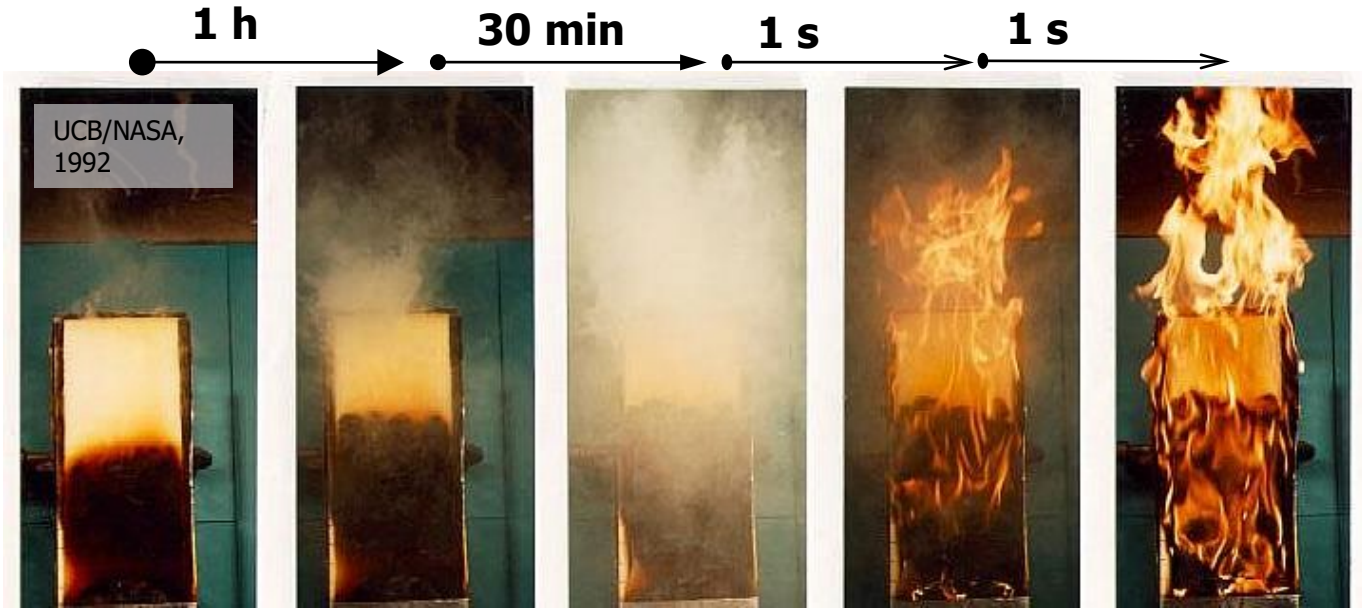




- Overhang is caused by the vertical gradient of the lateral spread rate.
- This in-depth spread leads to 50 to **100 times larger fuel consumption** per unit area than flaming fires.



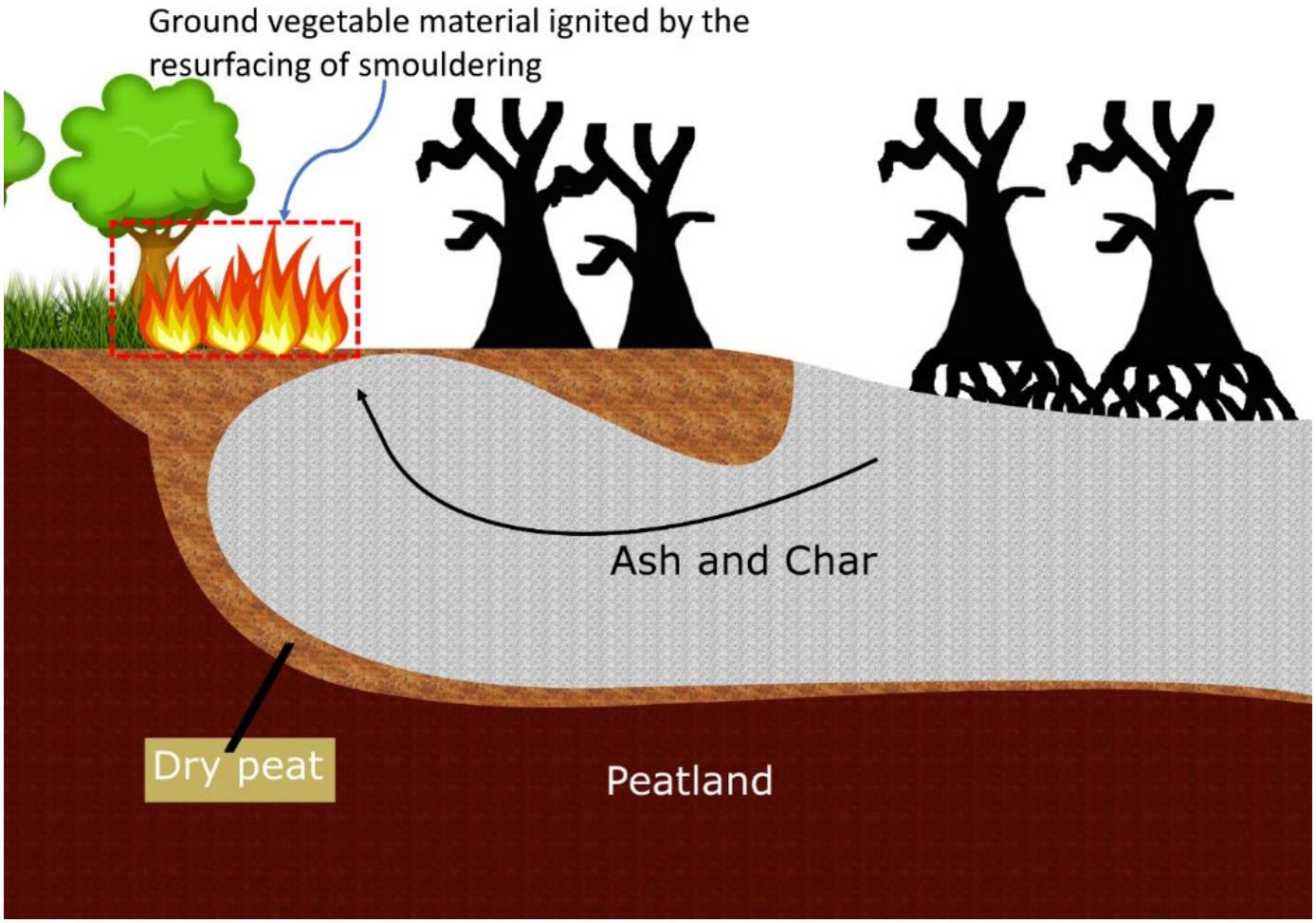
Challenge#2: Transition from Smouldering to Flaming Combustion



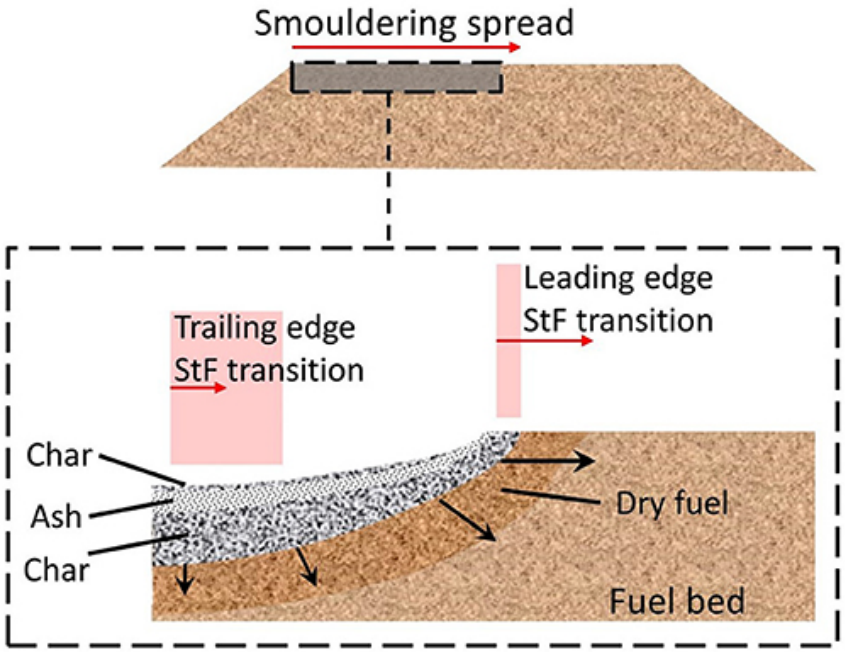
"The current understanding of the mechanisms leading to the transition is poor and mostly limited to small experiments.

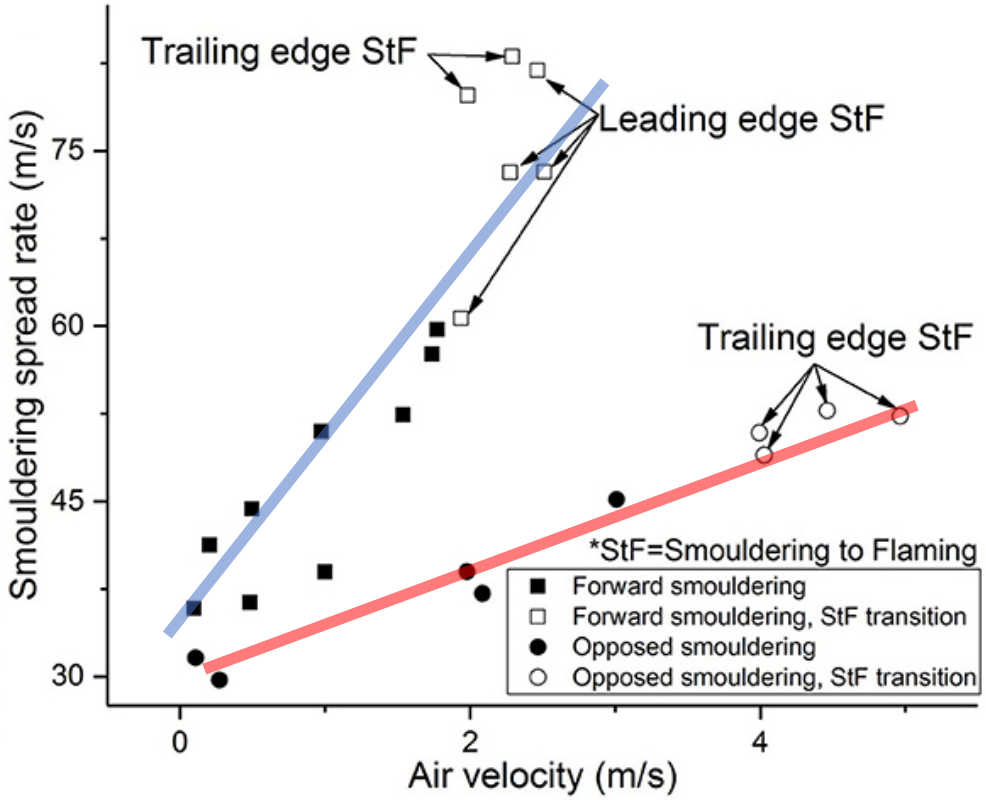
Santoso *et al., 2019.*

Transition from smouldering to flaming (StF)



Transition from smouldering to flaming (StF)





Ohlemiller 1990
Santoso et al. 2019.

Challenge#3: Smouldering Gas Emissions

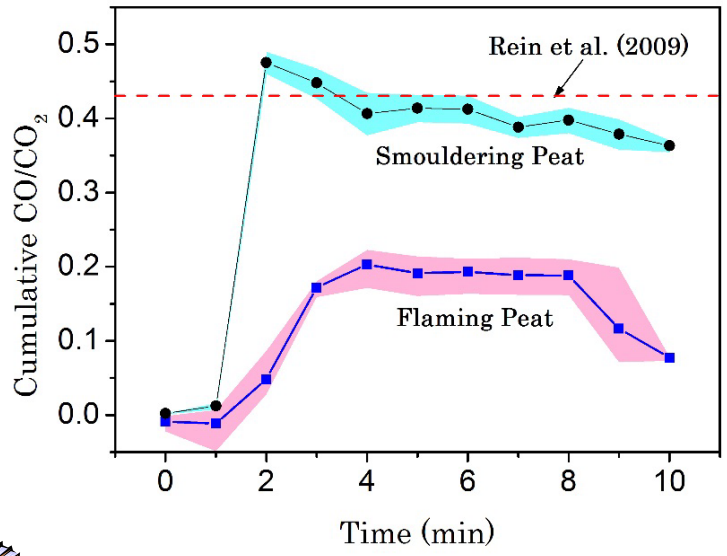
Emission factors (g/kg)

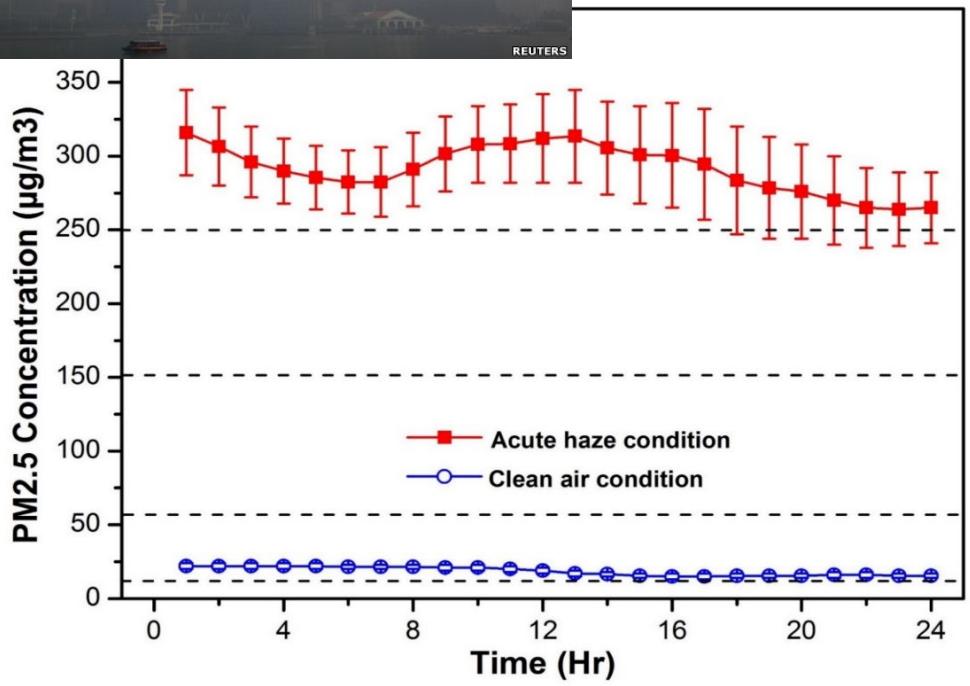
CO_2	**1703**	Phenol	4
CO	**210**	C_3H_6	4
$PM_{2.5}$	**44**	CH_3CHO	3
CH_4	**21**	Benzene	3
NH_3	**20**	Furan	2
CH_3COOH	9	Toluene	2
Methanol	9	HCHO	1
HCN	8	Acetone	1
CH_3CN	5	Isoprene	1
Acetol	4	NO	1

2015 SEA haze:

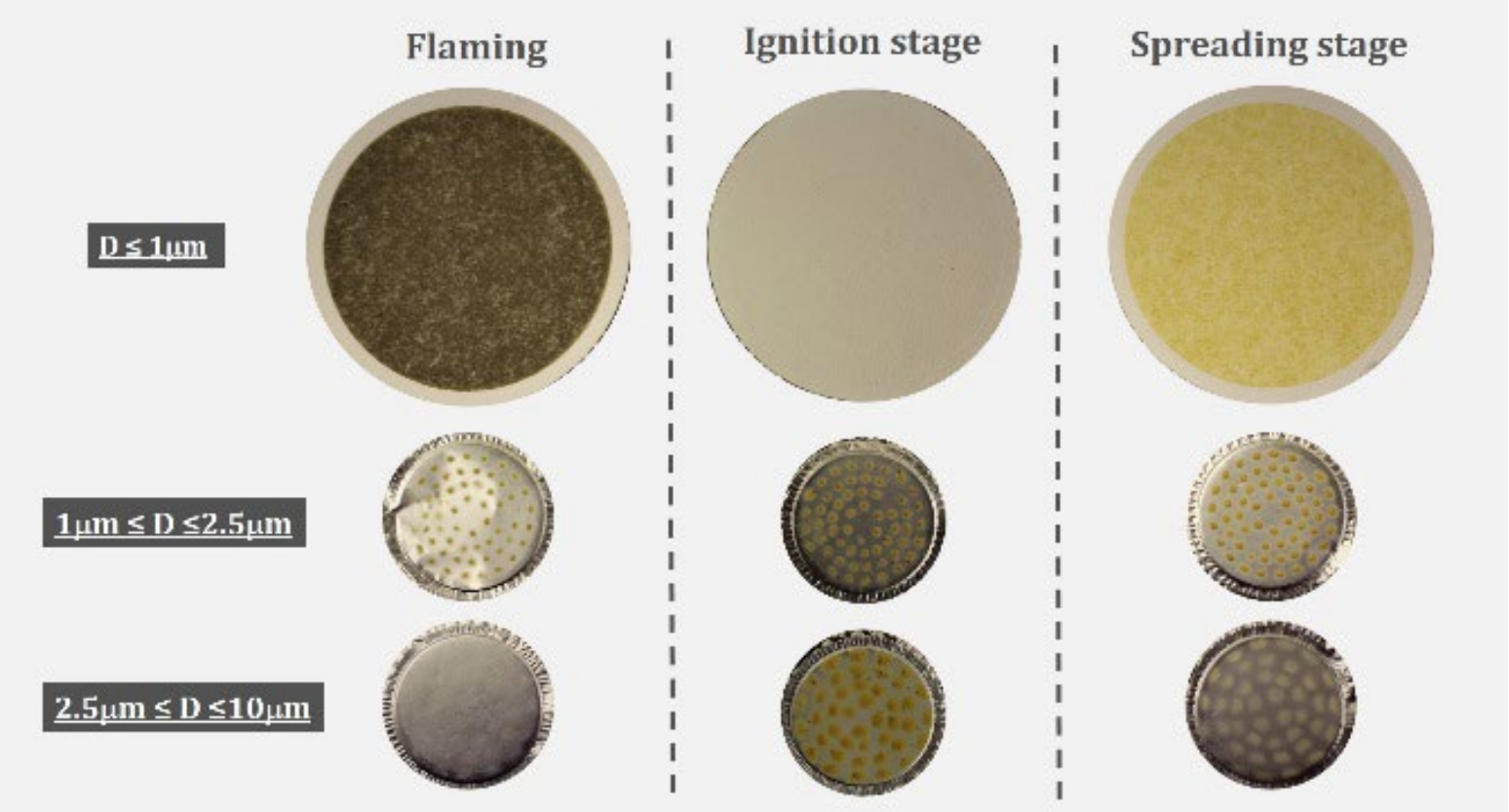
100k excess deaths.

140k respiratory illness.



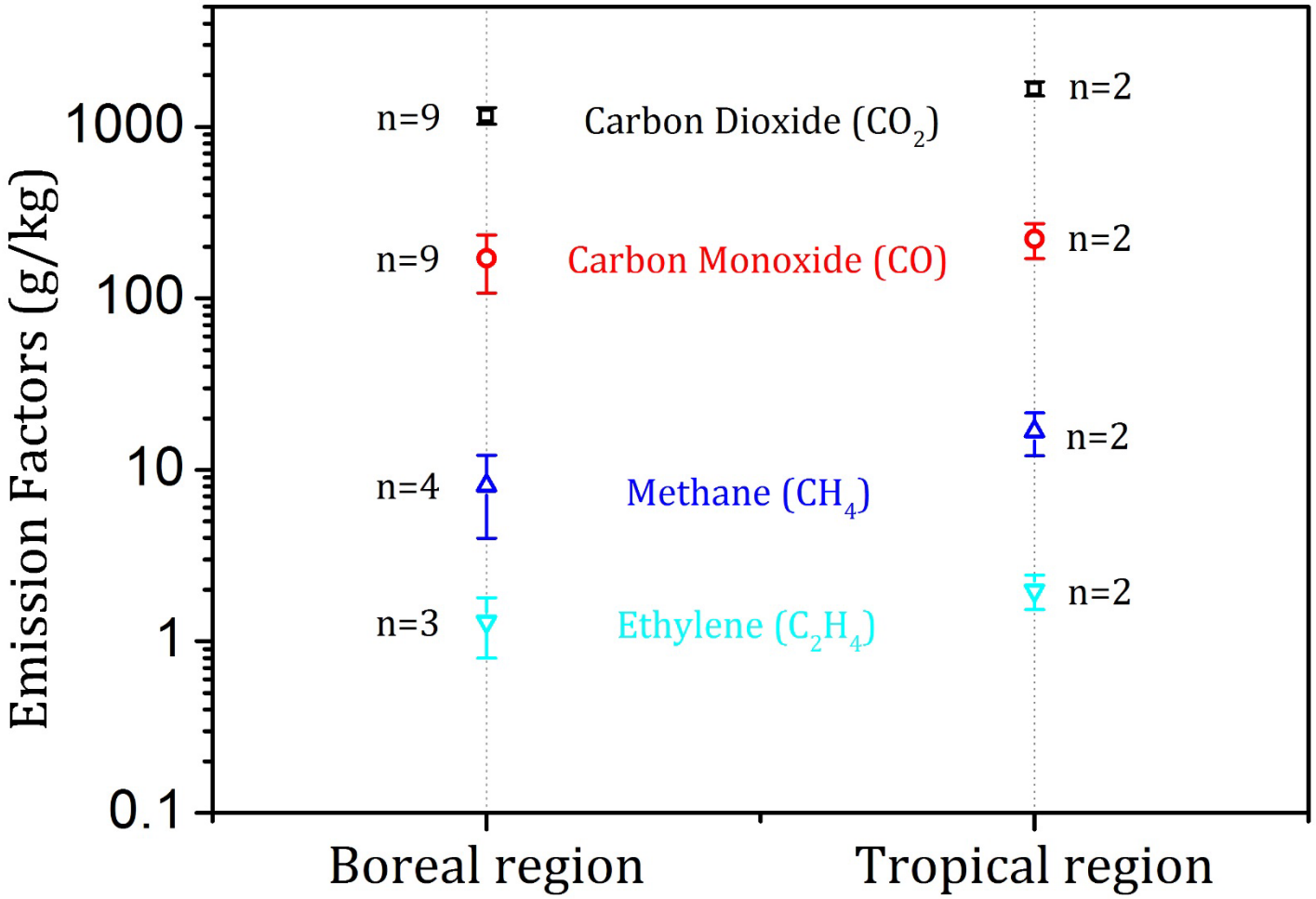


Hu *et al.*, Int J Wildland Fire, *2018*.



Hu *et al.*, Int J Wildland Fire, *2018*.

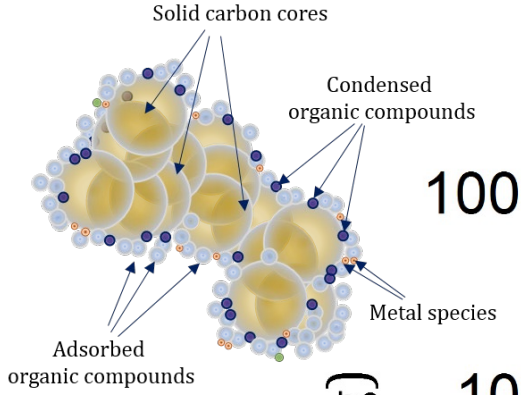
Gas emissions

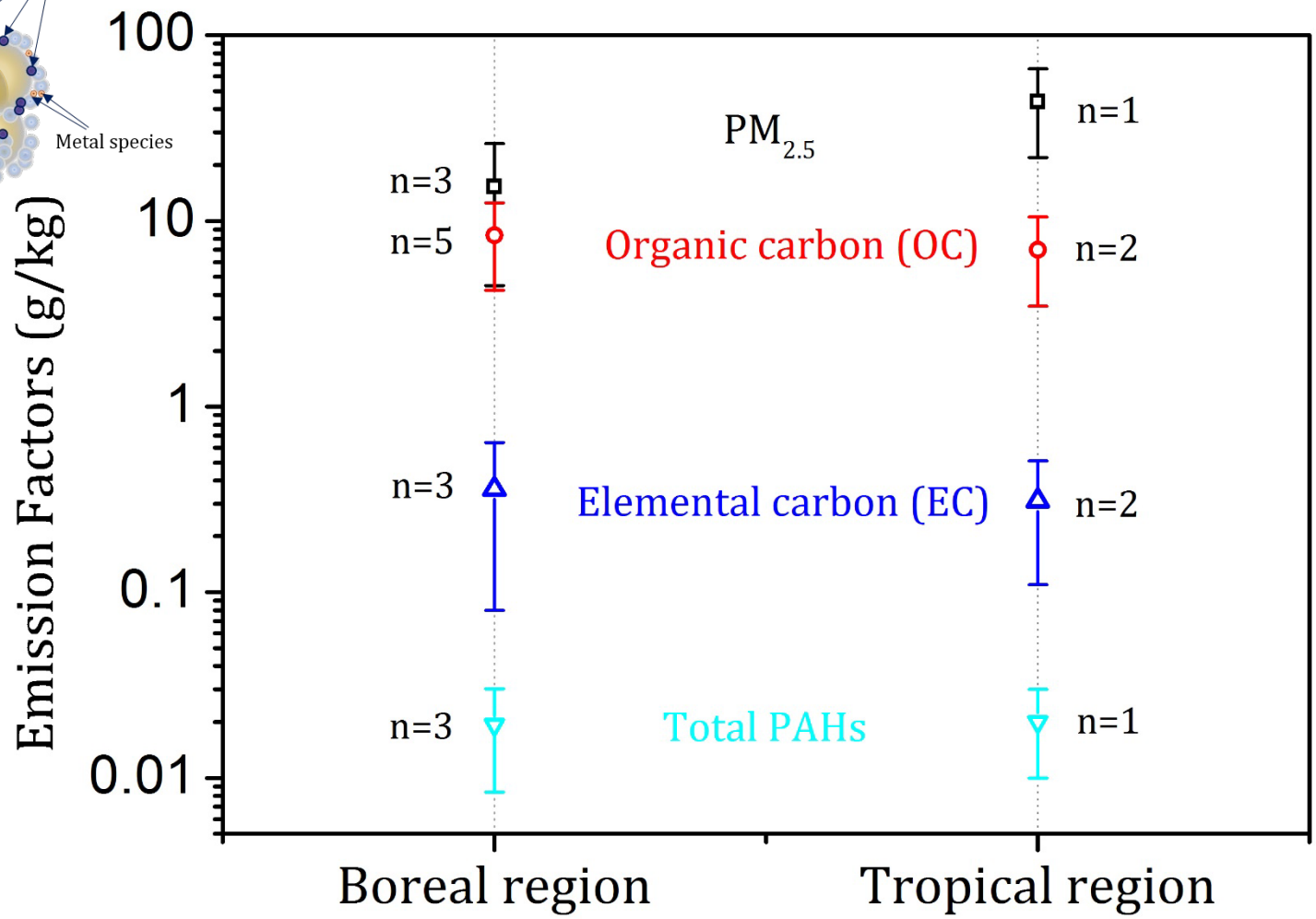


- **Most abundant gas emitted is CO_2, followed by CO and CH_4.**
- **Gas emissions are significantly different between boreal and tropical peats.**

Hu *et al.*, Int J Wildland Fire, *2018.*

Particle Matter Emissions

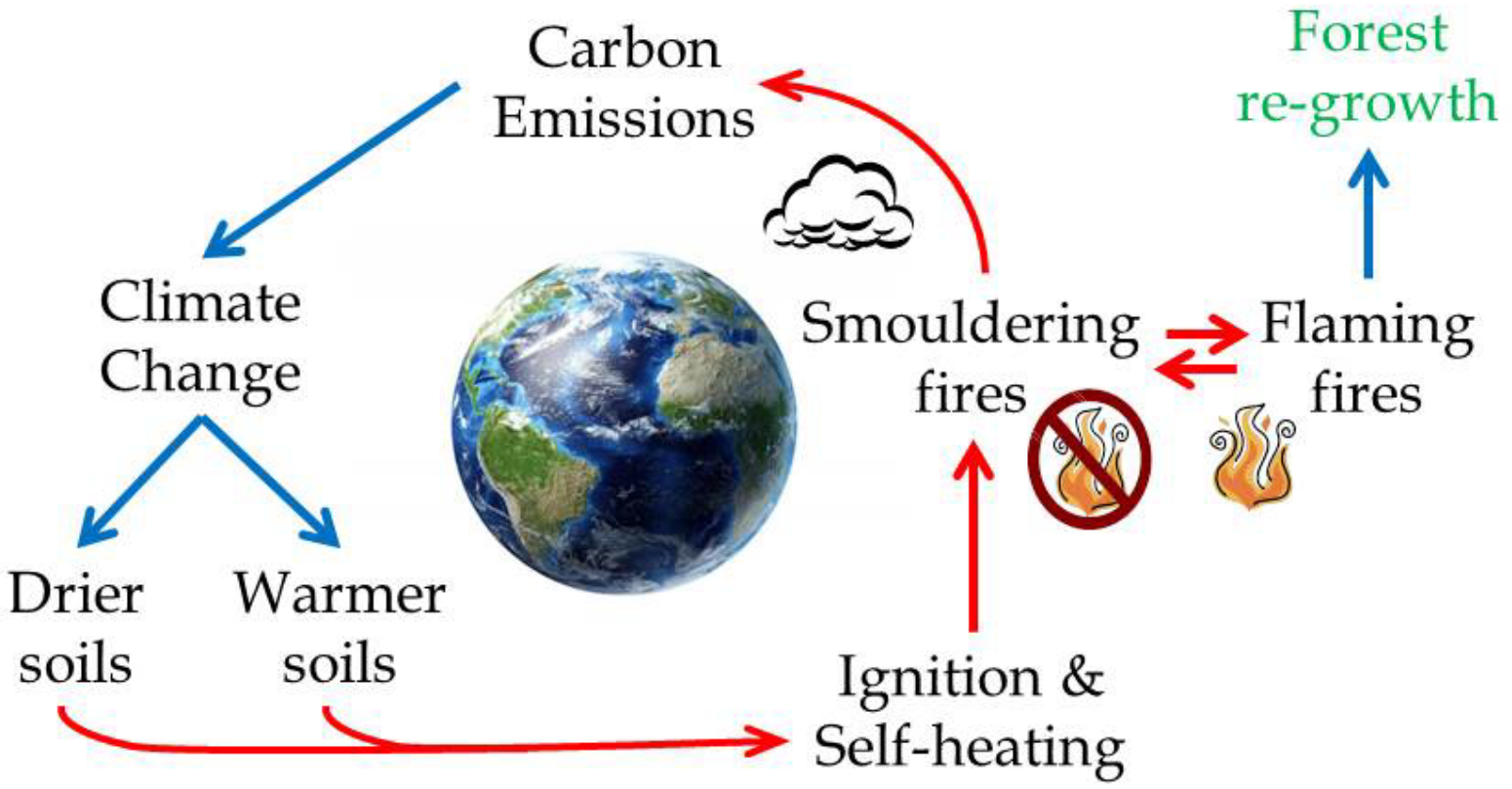




- OC constitutes the main components in $PM_{2.5}$ aerosols
- PM2.5 significantly different between boreal and tropical peats.
- Information of PM EFs is limited

Hu *et al.*, Int J Wildland Fire, *2018.*

Challenge#4: Positive feedback mechanism to climate change



Rein, *Wiley, 2013.*

What we found about smouldering:

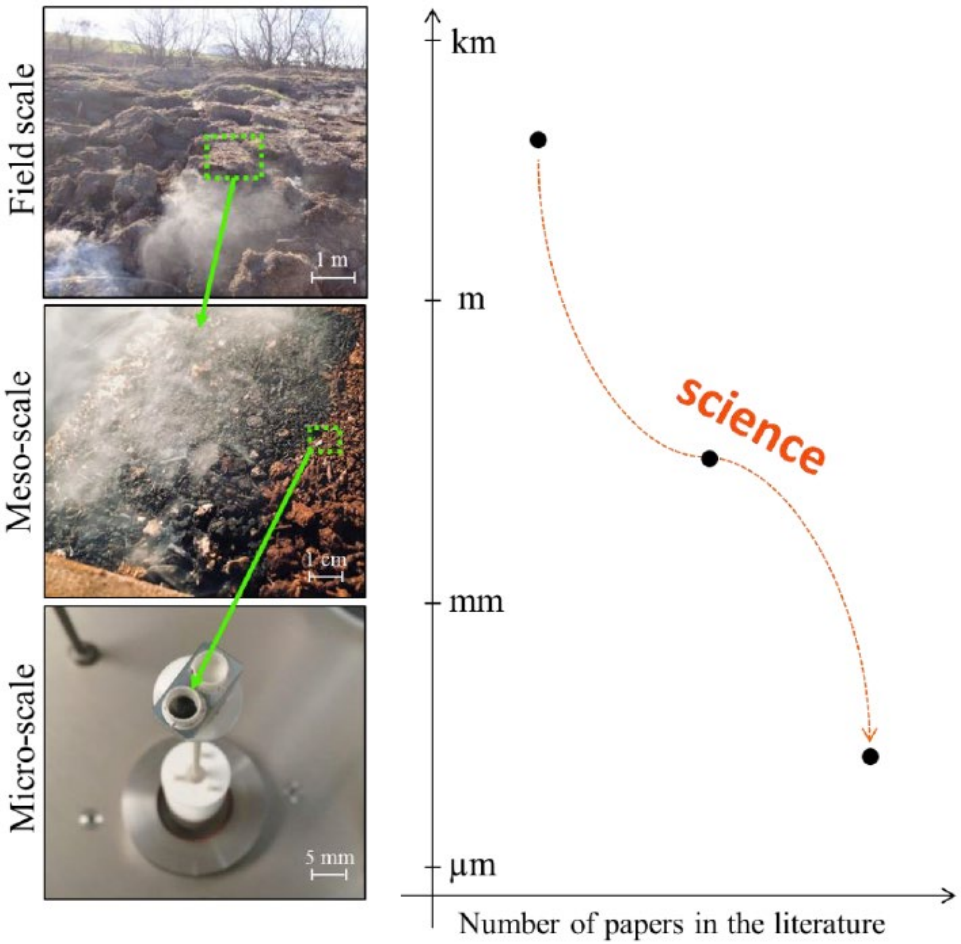
- In forest, peatlands and Arctic, as burning of the soil, residual burning of thick fuels, and firebrand ignition.

- **Top Challenges**:
  1. Multidimensional spread.
  2. Transition to flaming.
  3. Gas emissions.
  4. Feedback to climate change.

- Emerging scientific topic of global interest.

@GuillermoRein

GAMBUT: Novel Field Experiments on Peat Fires



Scale Matters

Meso-scale laboratory peat fire emission experiments

Field-scale peat fire emission experiments

2018 GAMBUT Field Measurement Of Life Cycle Emissions From Peatland Fire

E. Christensen et al. Experimental Methods and Scales in Smouldering Wildfires. 2018