Temporal variability of greenhouse gas and reactive gas emission factors during a two-week-long tropical peatland experimental burn

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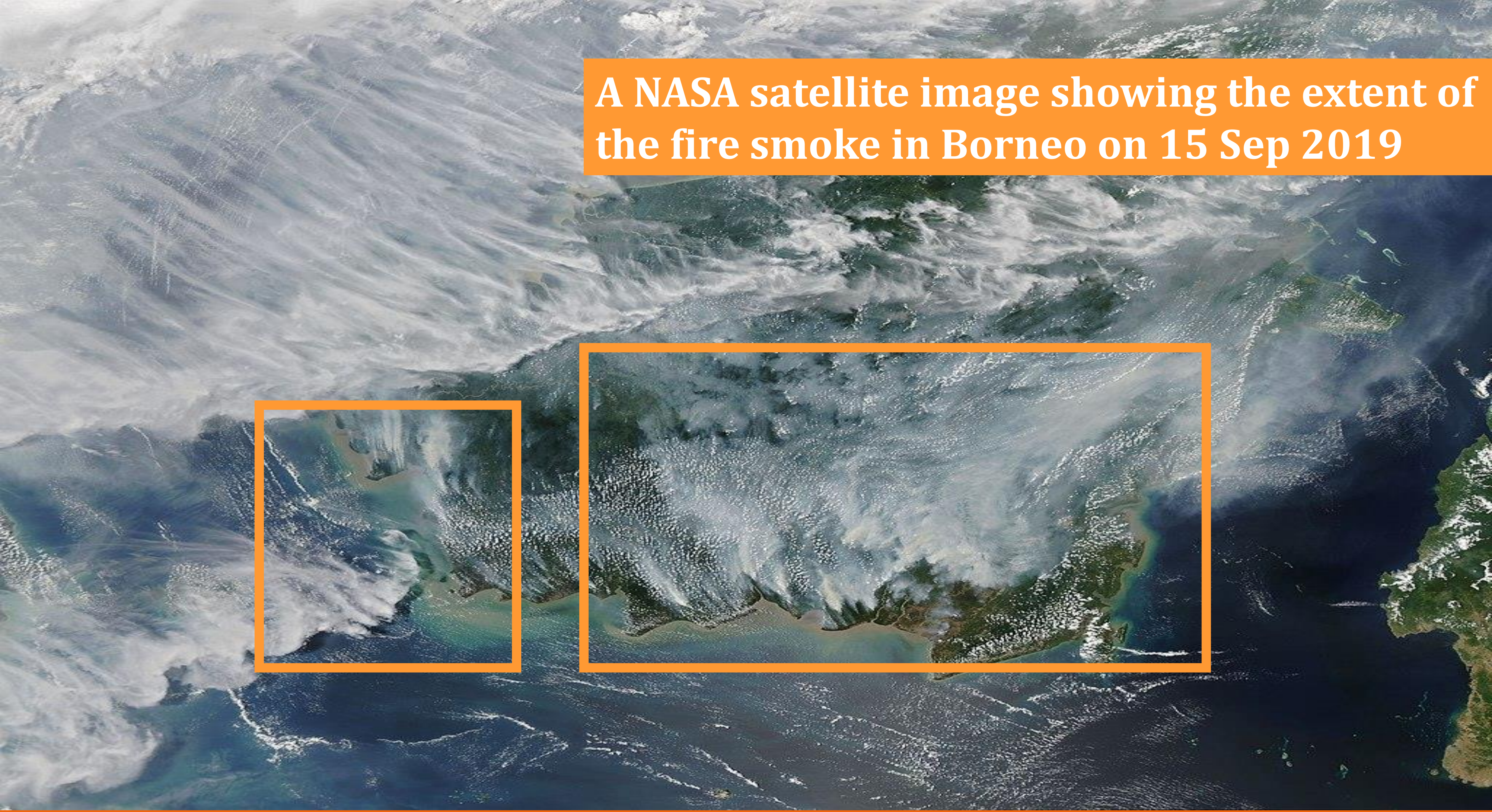
Imperial College London

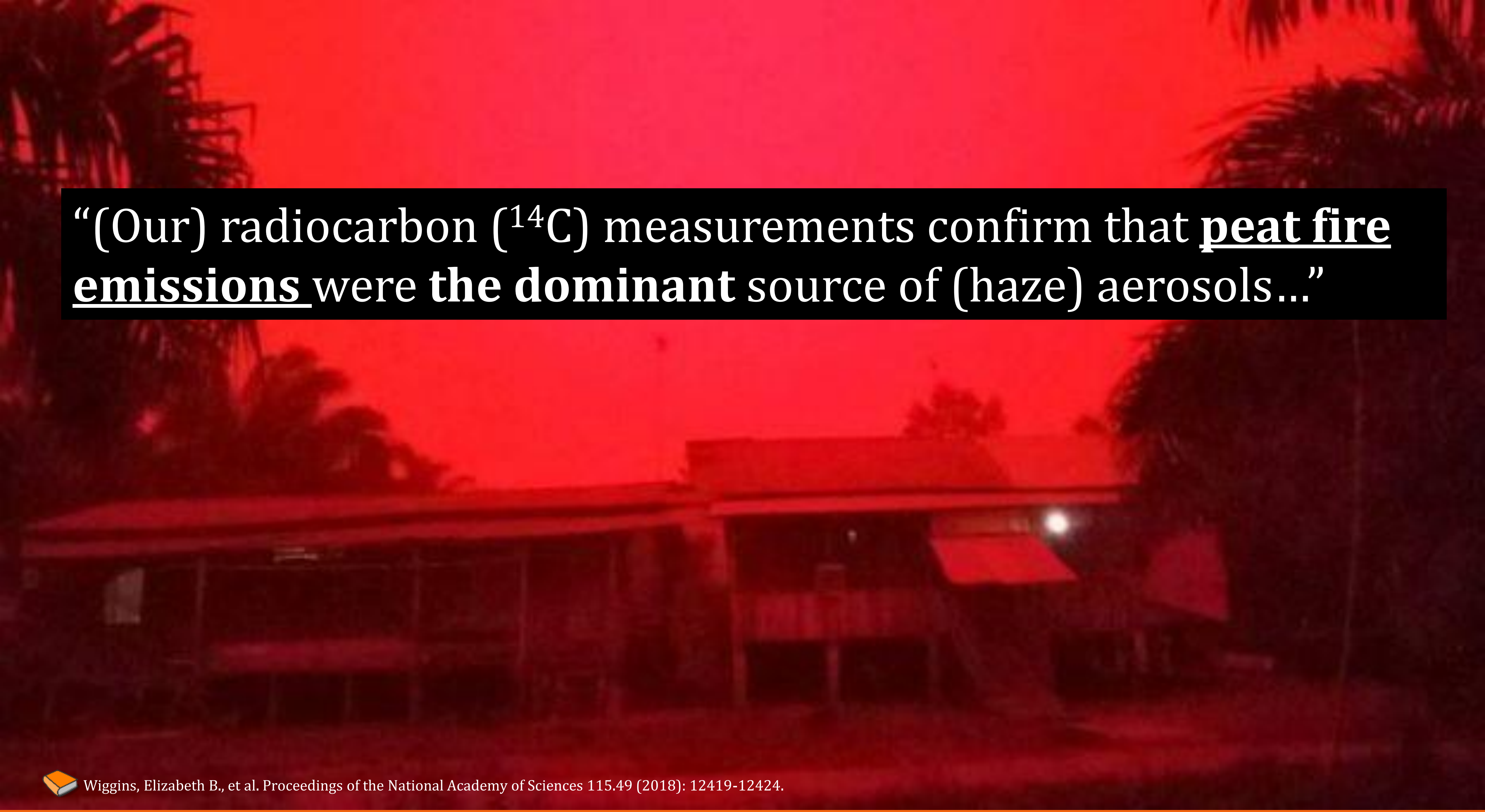
A NASA satellite image showing the extent of the fire smoke in Borneo on 15 Sep 2019



Toxic Haze

(Rayleigh scattering--
high concentration of aerosol scattering red light)

EKA WULANDARI



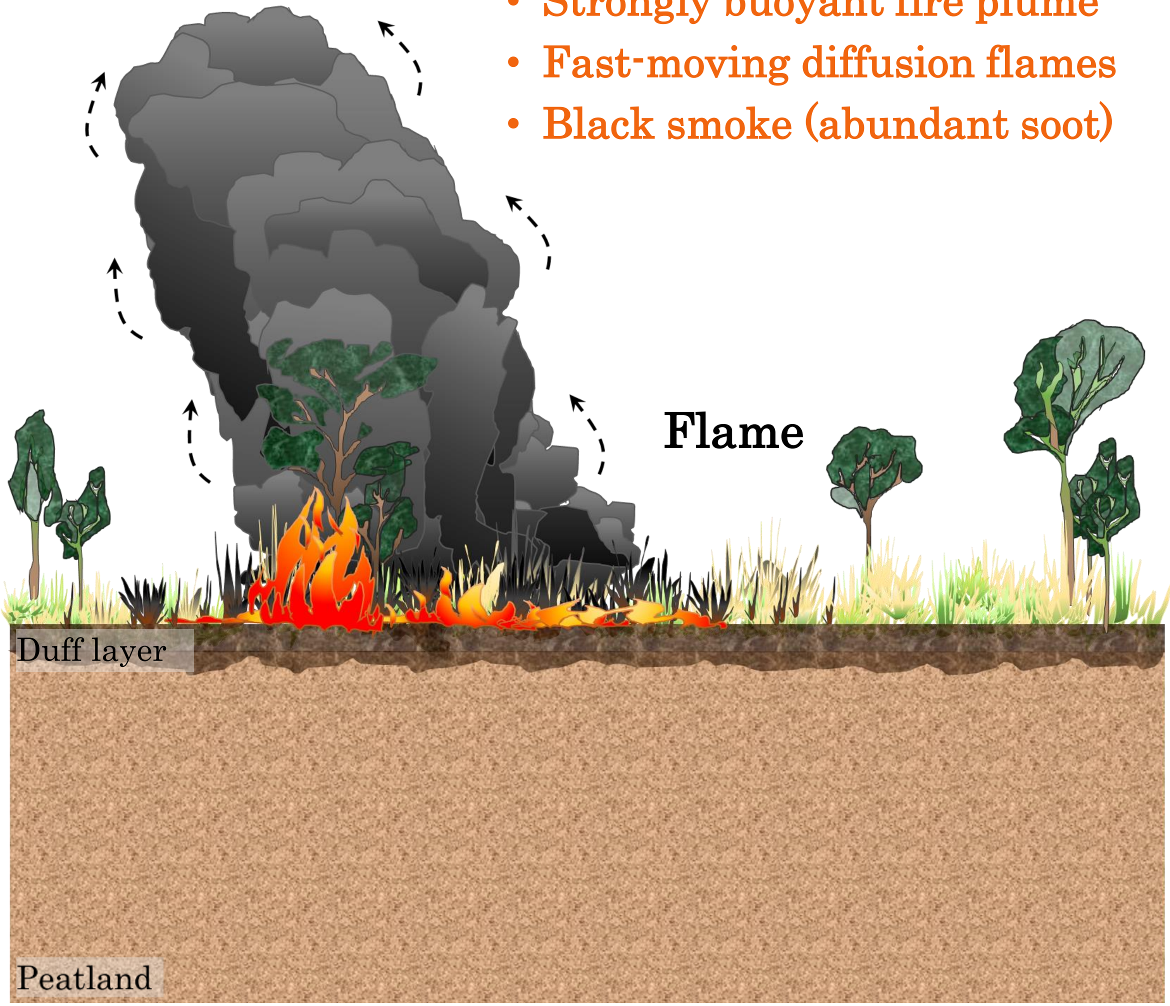
"(Our) radiocarbon (^{14}C) measurements confirm that **peat fire emissions** were **the dominant** source of (haze) aerosols…"

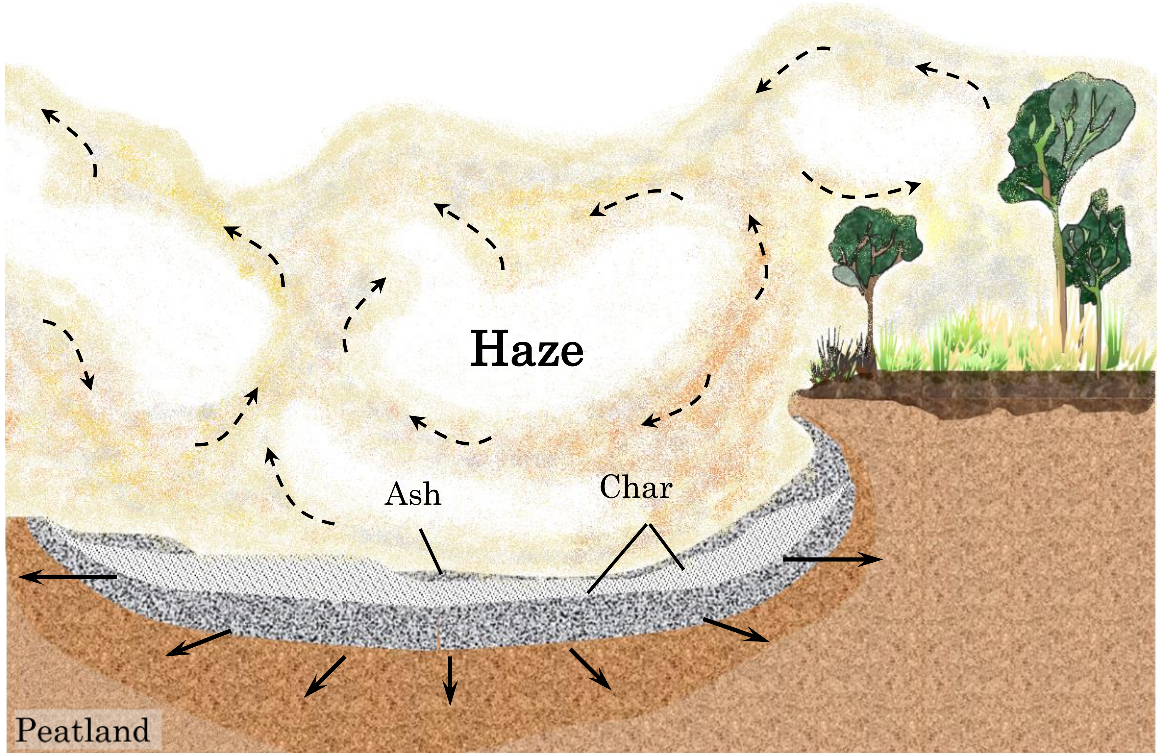
Wiggins, Elizabeth B., et al. Proceedings of the National Academy of Sciences 115.49 (2018): 12419-12424.

Flaming Forest Fire vs. Smouldering Peat Fire

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

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





Hu, Fernandez-Anez, Smith, Rein (2018, IJWF)

Fire Emission Quantification

GFED3.1 (Global Fire Emission Database) *(van der Werf et al. 2010)*

"Conventional" Burned Area Approach *(Seiler and Crutzen, 1980)*

$$E_i\,[g] = A\,[m^2] * B\,[kg/m^2] * C\,[kg/kg] * EF_i\,[g/kg]$$

E_i: Emission of trace species I
A: Area burned (MODIS burn scars)
B: Biomass density (Fuel load) (CASA biogeochemical model with satellite fAPAR data)
C: Combustion Completeness (CASA biogeochemical model with GPCP precipitation)
EF_i: Emission Factor for species i

GFAS1.1 (Global Fire Assimilation System) *(Kaiser et al., 2012)*

FRE-based Combustion Factor (CF) Approach *(Wooster et al., 2005))*

$$E_i\,[g] = FRE\,[J] * CF\,[kg/J] * EF_i\,[g/kg]$$

FRE: Fire Radiative Energy [J] (MODIS FRP)
(Time Integrated Fire Radiative Power (FRP) [W])
CF: Combustion Factor (fuel type dependent CF)
EF_i: Emission Factor for species i

Fire Emission Quantification

GFED3.1 (Glo

"Conventional" Bu

E_i [g] = A [m²

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GFAS1.1 (Glob

FRE-based Comb

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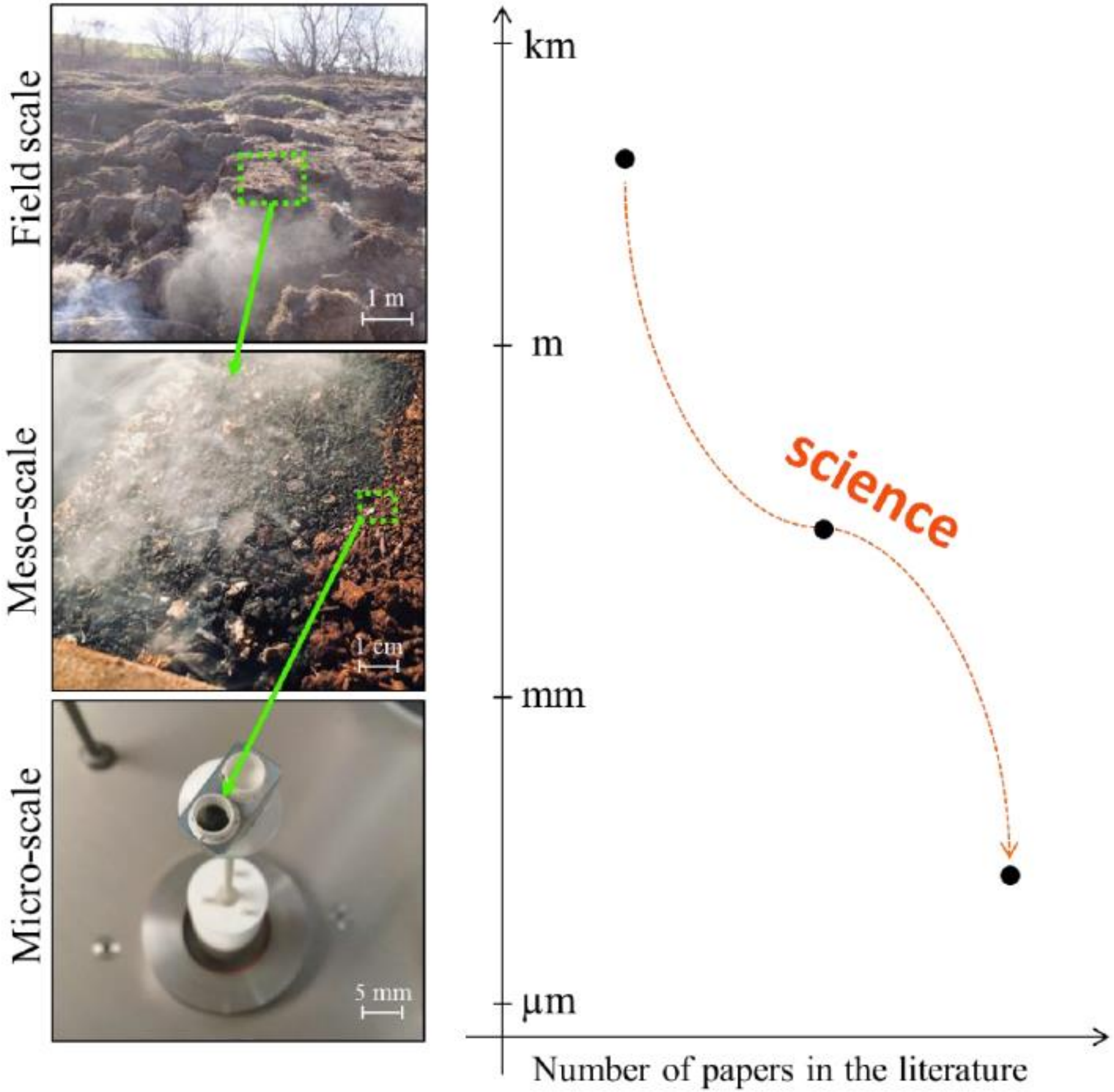
FRE: Fire Radiative Ene
(Time Integrated Fi
CF: Combustion Factor
EF_i: Emission Factor f

Emission Factor (EF, g·kg⁻¹)

$$\frac{\text{mass of species emitted}}{\text{mass of dry fuel consumed}}$$

Atmospheric chemistry modelling

Carbon budget calculations



Scale Matters

Field measurements gather emission information from fires in situ, and provide valuable insight in natural conditions

However, no controlled field-scale peat fire experiment has been conducted so far

2018 Tropical Peatland Wildfire Experiment (2 weeks+)

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

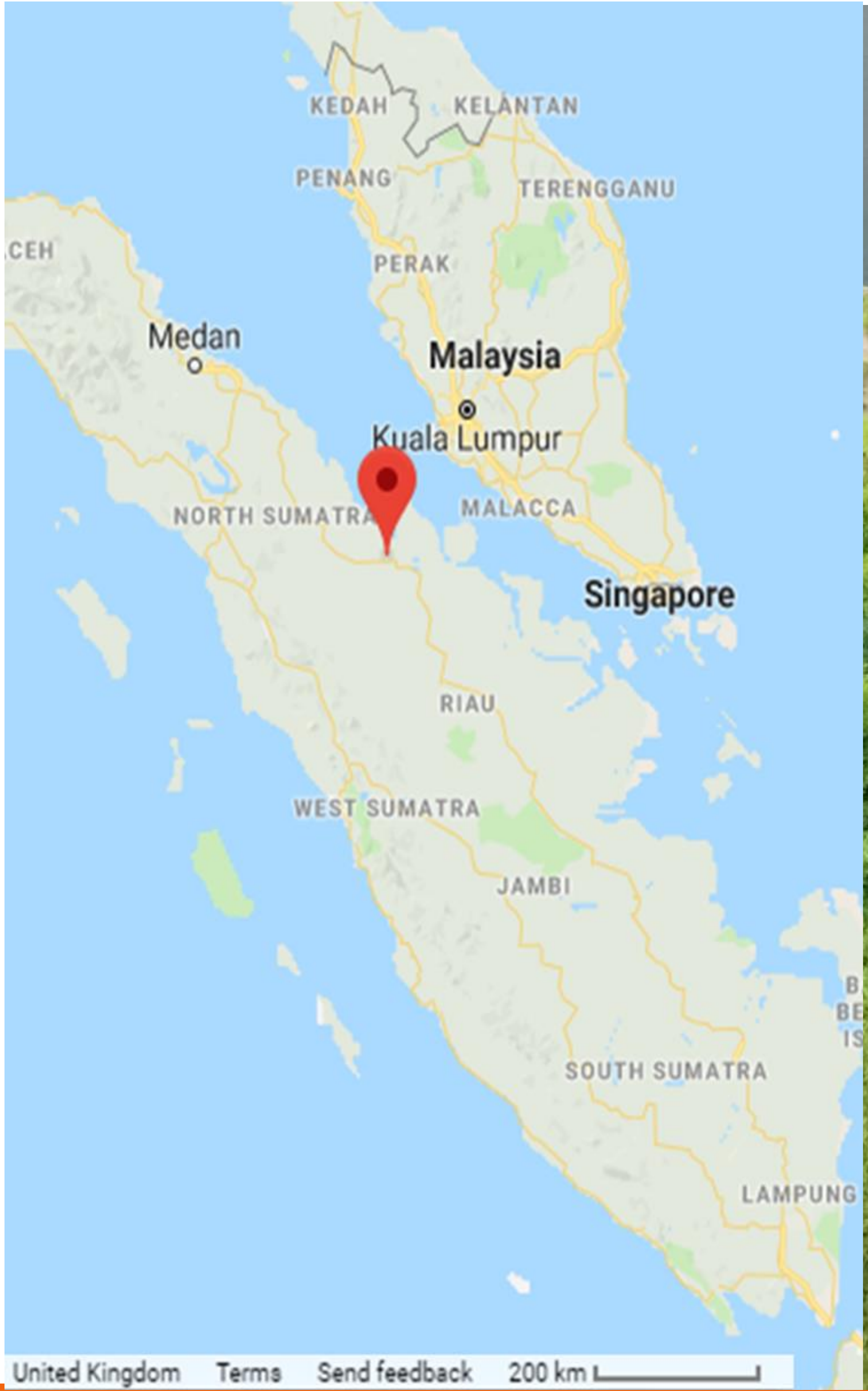
Hu, Fernandez-Anez, Smith, Rein, IJWF. 2018

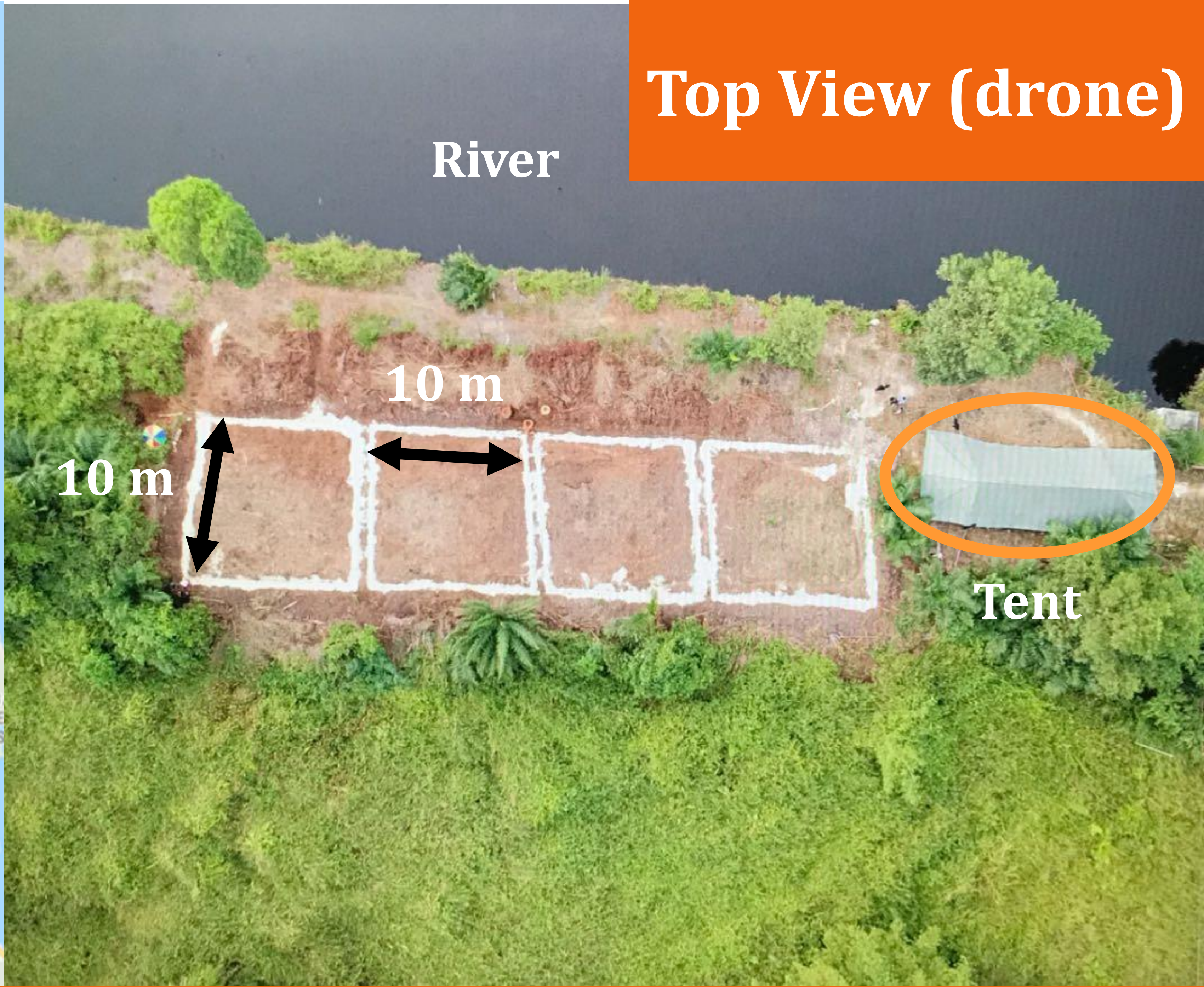
The Largest **Controlled** Tropical Peatland Wildfire Experiment

The 1st Gambut Workshop:
UK-Indonesia Collaboration for Mitigation of Peat Fires

13th August to 3rd September, 2018

Top View (drone)

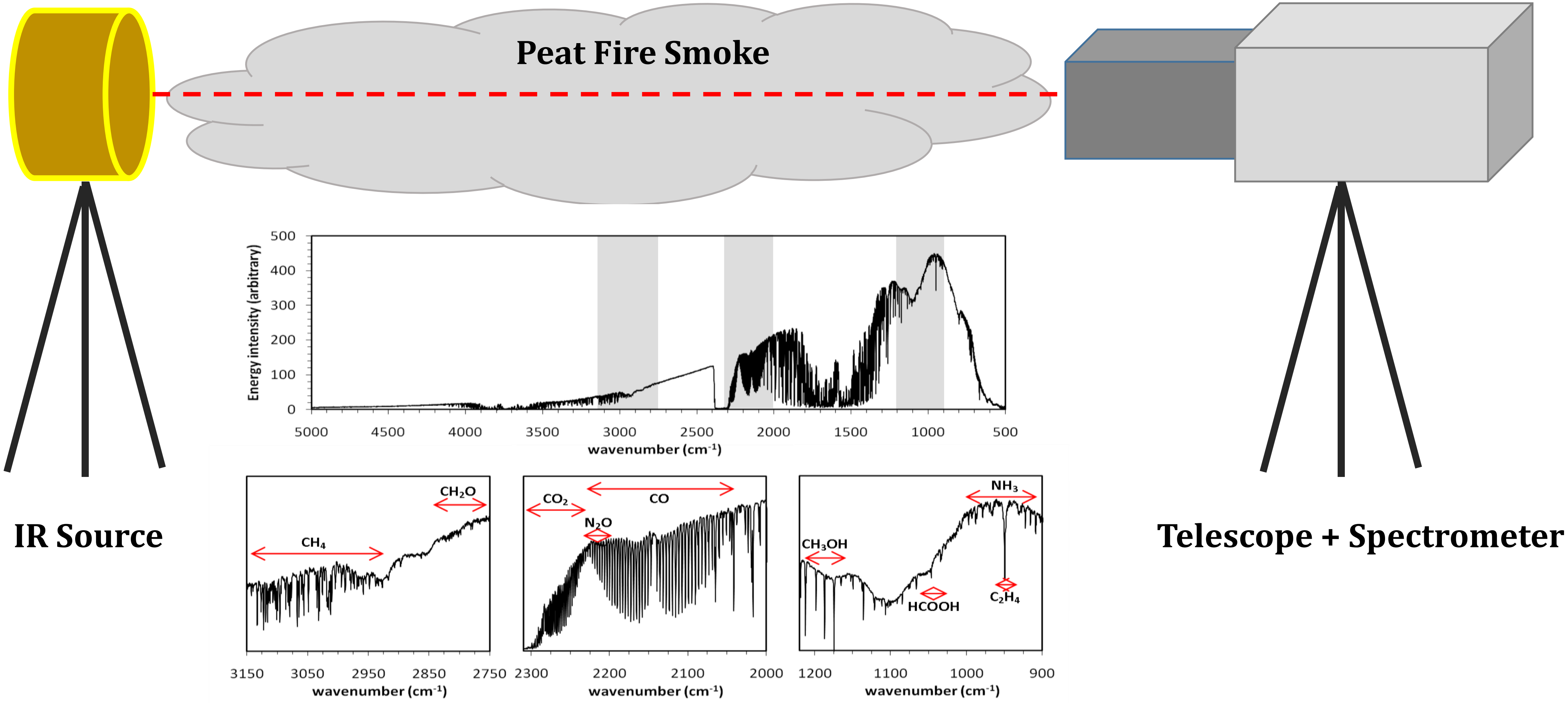




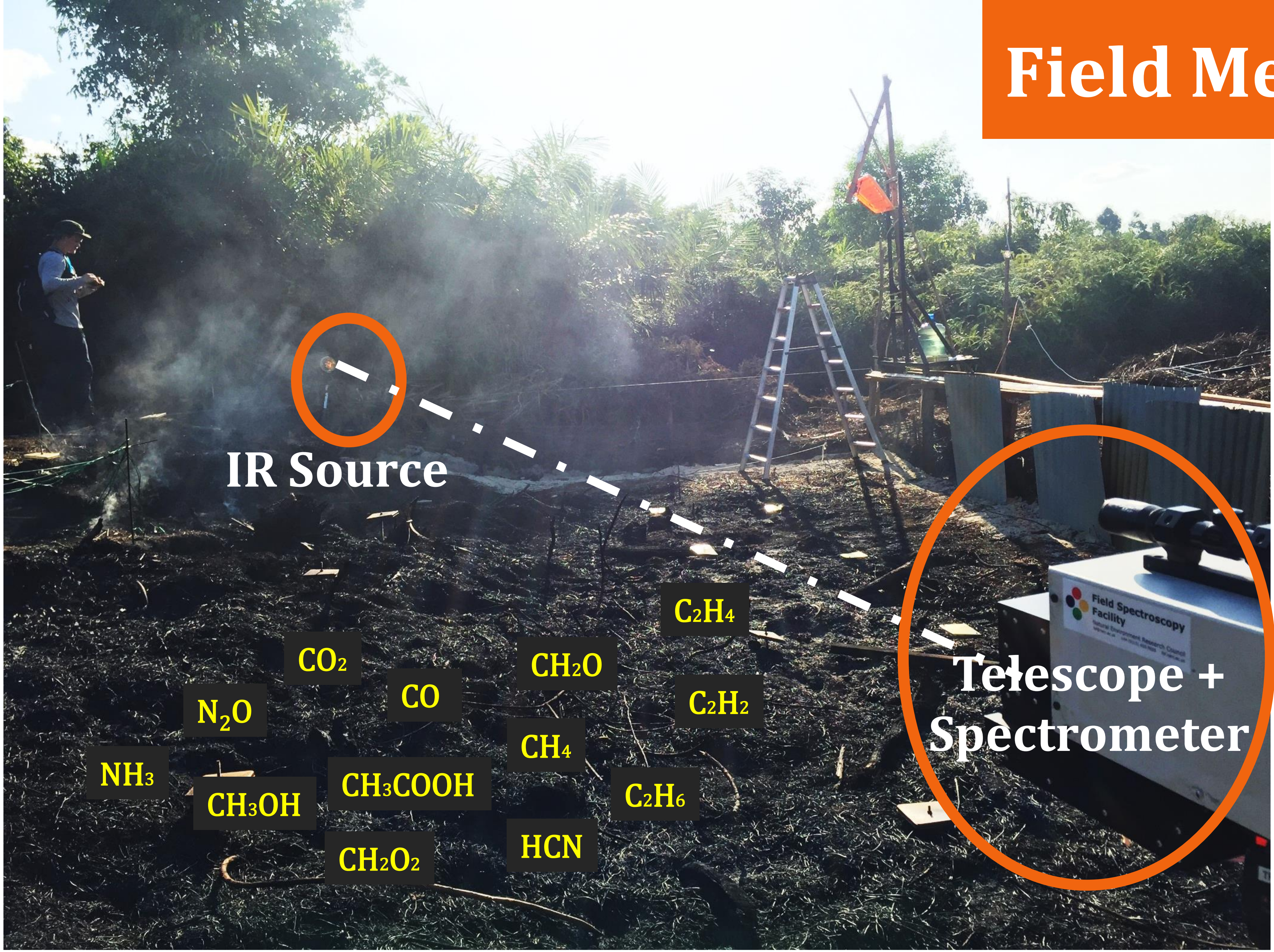
Life-cycle of emissions from tropical peatland fire

Open-path FTIR

Characterize biomass burning emissions → **Path-averaged trace gas mole fractions**



Field Measurement



- **12 gas species**
- **Mole fractions**
  μmol mol^{-1} (ppm)
- **Accuracy within 5%**

Emission Factor Quantification

Carbon balance approach *(Ward and Radke 1993)*

$$EF_i = F_c \cdot 1000\ (g\ kg^{-1}) \cdot \frac{MM_i}{12} \cdot \frac{C_i}{C_T}$$

$$\frac{C_i}{C_T} = \frac{\Delta[i]}{\sum_{j=1}^{n}(NC_j \times \Delta[j])}$$

→ CO_2 and CO

F_c: Carbon content of the peat
MM_i: Molar mass of species i
12 : The atomic mass of carbon (g mol^{-1})
C_i: Number of moles of species I
C_T: Total number of moles of carbon emitted

Δ[i] and Δ[j]: Excess mole fractions of species i and j
NC_j: Number of carbon atoms in species j;
The sum: All carbon-containing species emitted by the fire

$$ER_{i/CO} = \frac{[i] - [i]_{backgroud}}{[CO] - [CO]_{backgroud}}$$

$$EF_i = ER_{i/CO} \times \frac{MW_i}{MW_{CO}} \times EF_{CO}$$

→ CH_4, NH_3, C_2H_2, C_2H_4, C_2H_6, CH_3OH, HCN, CH_3COOH, CH_2O_2 and N_2O

$ER_{i/CO}$: Emission ratio (ER) of species i to the reference species (CO in this work)
MW_i : Molecular weight of species i
MW_{CO}: Molecular weights of CO (28.01 g mol^{-1})
EF_{CO}: EF of CO

Carbon balance ap

$EF_i = F_c \cdot 1000\ (g$

$\rightarrow$ CO_2 and CO

F_c: Carbon content of th
MM_i: Molar mass of specie
12 : The atomic mass of c
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species emitted by the fire

$ER_{i/CO} = \frac{[i] - [i]_{back}}{[CO] - [CO]_{b}}$

$ER_{i/CO}$: Emission ratio (
MW_i : Molecular weig
MW_{CO}: Molecular weig
EF_{CO}: EF of CO

$_4$, NH_3, C_2H_2,
$_4$, C_2H_6, CH_3OH,
N, CH_3COOH,
$_2O_2$ and N_2O

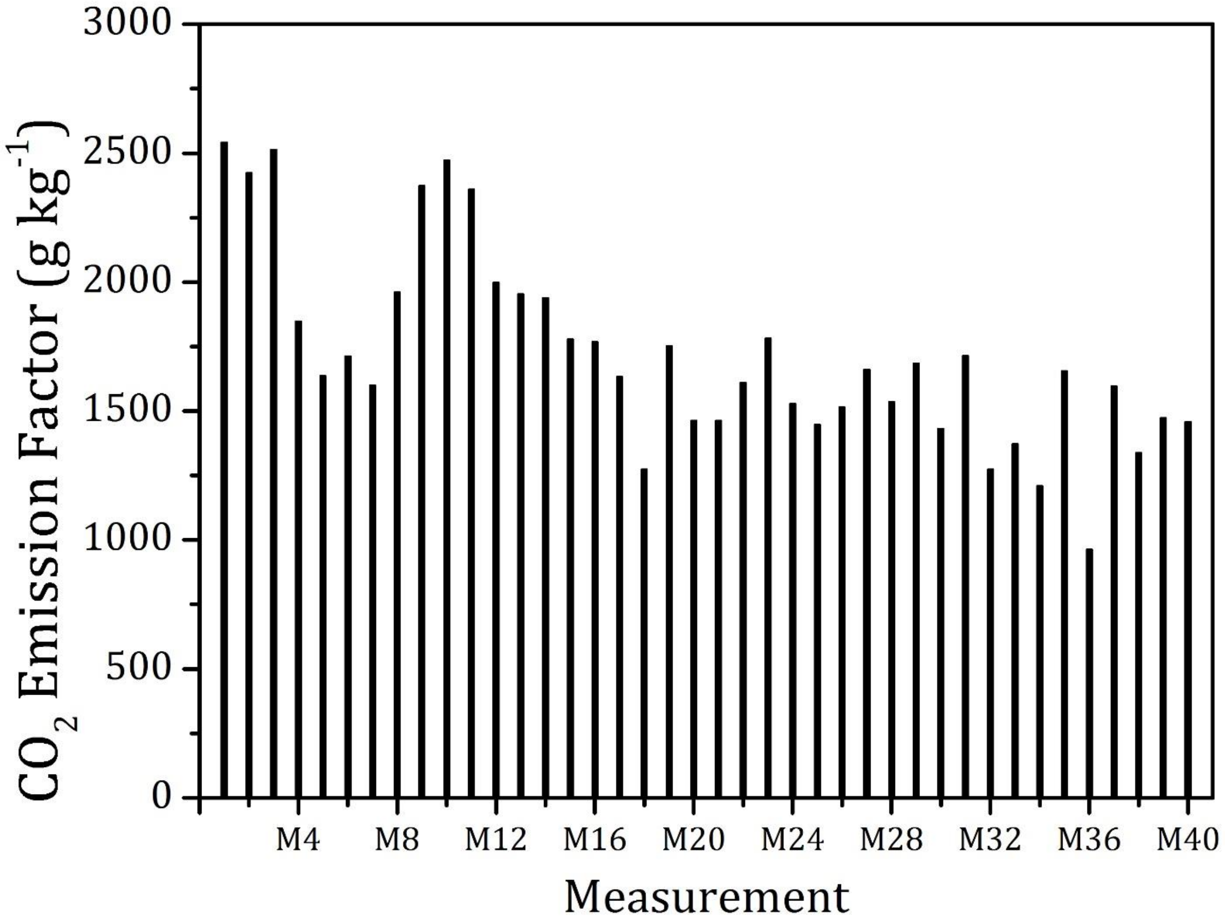
Emission Factor (EF, $g \cdot kg^{-1}$)

$$\frac{\text{mass of species emitted}}{\text{mass of dry fuel consumed}}$$

Atmospheric chemistry modelling

Carbon budget calculations

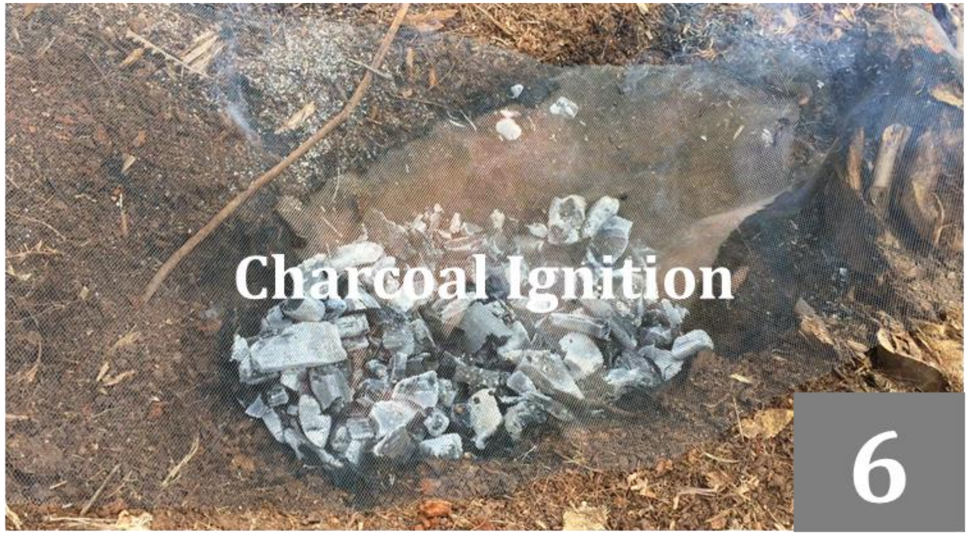
40 fire plumes measured, 9000+ gas spectrums recorded



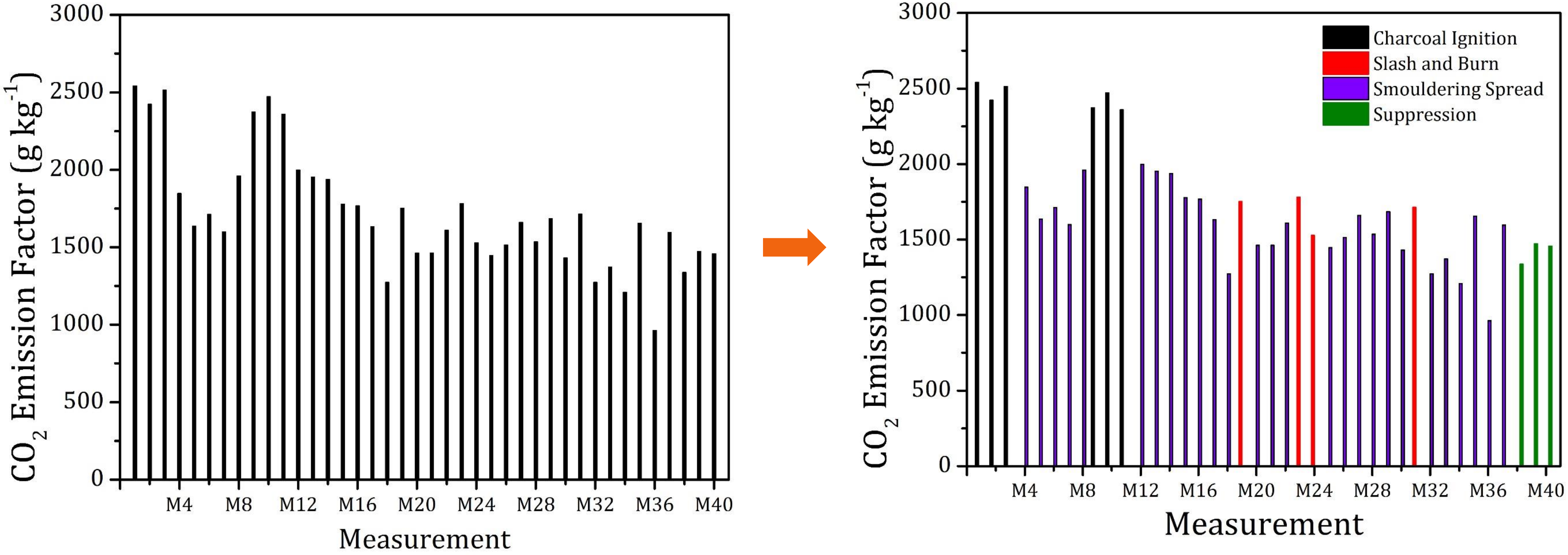
- **Fire-plume averaged emission factor**
- **Substantial inter-plume variability**
- **Classification needed**

Measurement Number	Date	Field Day	Ambient Pressure (mb)	Temperature (°C)	Humidity (%)	Wind Speed (m/s)	Rain Rate (mm/h)	General Description [a]	Location [j]	Path Length
M1	19/08	6	1008.8	33.1-34.5	51-60	1.5-2.3	0	Charcoal Ignition	P1S	10.5
M2	19/08	6	1006.8	33.7-33.9	54-56	1.28	0	Charcoal Ignition	P1S	10.5
M3	19/08	6	1006.5	32.4-33.5	54-60	1.08-1.59	0	Charcoal Ignition	P1S	10.5
M4	20/08	7	1008.2	30.1-31.2	68-72	1.59-1.8	0	Smouldering [b]	P1S	10.5
M5	20/08	7	1007.5	32.2-32.4	62-65	2.3-2.4	0	Smouldering	P1S	10.5
M6	20/08	7	1007.1	32.9-34.0	52-60	1.38-2.1	0	Smouldering	P1S	10.5
M7	20/08	7	1005.6	31.2-31.8	64-76	0.8-1.4	0	Smouldering	P1S	10.5
M8	21/08	8	1009.0	28.7-30.8	69-78	0.8-1.8	0	Smouldering	P1S	10
M9	21/08	8	1006.5	32.9-33.2	59-61	2.1-2.7	0	Charcoal Ignition	P1S	10
M10	21/08	8	1005.8	33.1-34.8	52-60	1.3-2.1	0	Charcoal Ignition	P1S	10
M11	21/08	8	1004.3	30.4-31.8	68-80	0-0.6	0	Charcoal Ignition	P1S	10
M12	22/08	9	1009.4	28.7-29.5	69-72	1.8	0	Smouldering	P1S	10.5
⋮										
M38	29/08	16	1008.6	32.8-33.3	54-60	1.1-1.3	0	Suppression (Water Spray)	P2C	13
M39	29/08	16	1006.3	31.7-33.6	54-61	1.3-1.8	0	Suppression (Injection)	P1S	11.5
M40	29/08	16	1005.8	30.7-31.2	66-69	1.3-2.1	0	Suppression (Water Spray)	P1N	13.5

Life-cycle of emissions from tropical peatland fire

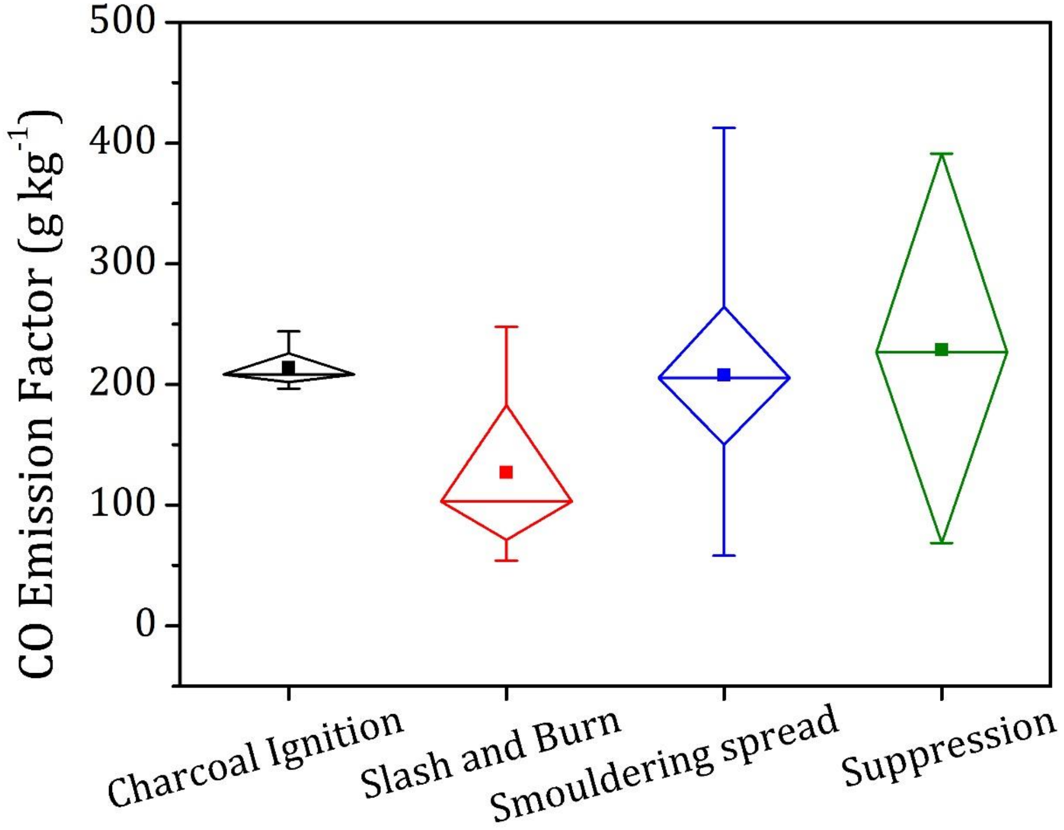


Life-cycle Emission Factor of Peatland Fire

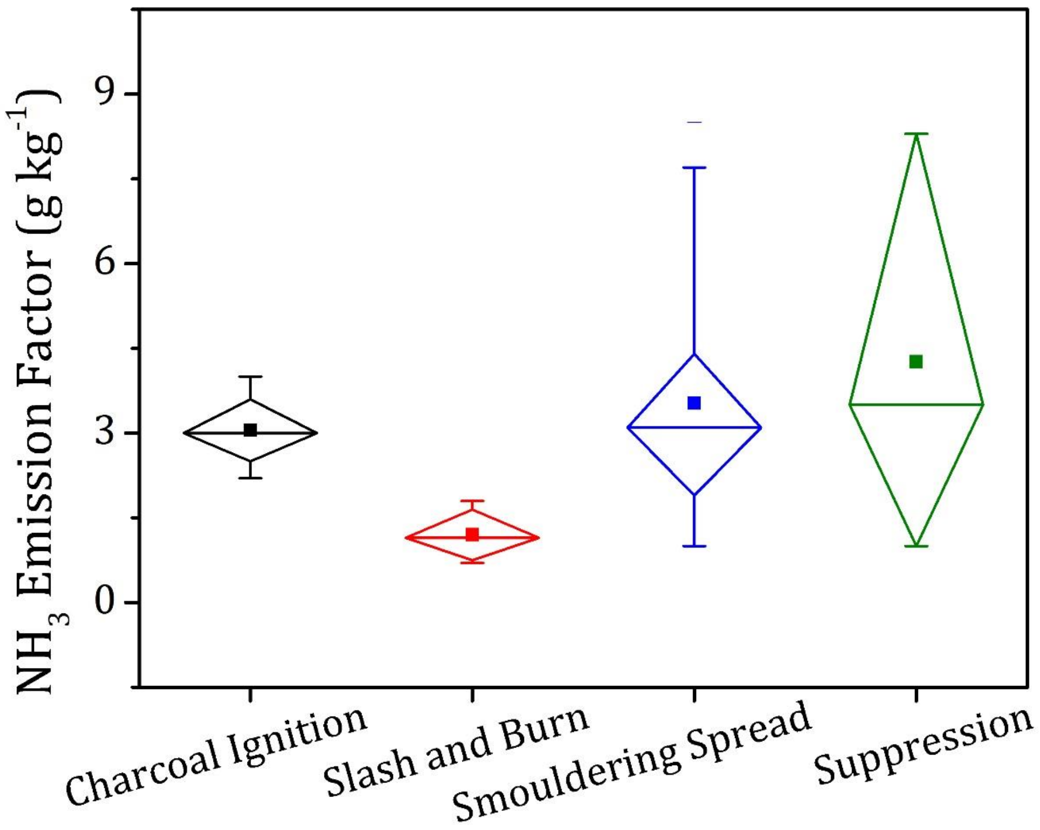


Emission Factor from Different Fire Stages

CO



NH_3



Charcoal Ignition: n=6; Slash and Burn: n=4; Smouldering Spread: n=27; Suppression: n=3

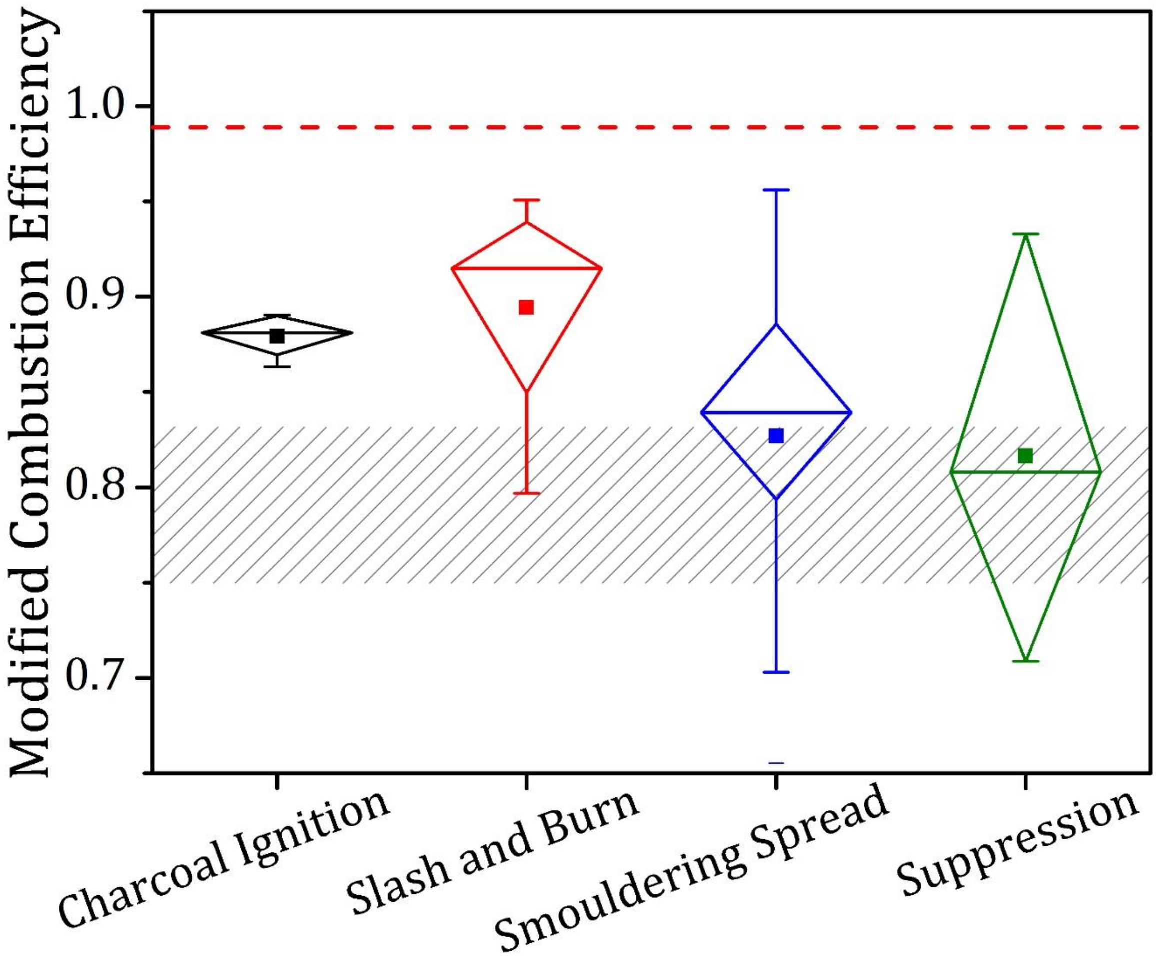
Influence of Rain on Fire Emission Factor

Compared to when it is not rainy:

CO_2	+ 6.7%	CO	- 17.2%
CH_4	- 10.8%	C_2H_6	- 25.3%
NH_3	- 40.3%	CH_3OH	- 23.8%
N_2O	- 62.5%	HCN	- 53.7%

Measurement conducted during a heavy rain (32.3 mm/h)

Modified Combustion Efficiency (MCE)



- Combustion regime indicator
- Remote Sensing & Atmospheric Science

Species' mole fraction

$$MCE = \frac{\Delta CO_2}{\Delta CO_2 + \Delta CO}$$

"MCE-indicated fire regimes" vs. real fire regimes

LARGE CONTRADICTIONS

MCE is highly sensitive to unknown field variables

Stockwell et al. Atmospheric Chemistry & Physics 16.18 (2016)

Conclusion

- **Field-scale controlled** tropical peatland fire experiment in Sumatra, Indonesia
- **Life-cycle** fire emissions **from ignition to spread and suppression** from 40 fire smoke plume measurements were quantified using an open-path FTIR spectroscopy
- Gas emission factor vary among **fire types** and **fire stages**
- First investigation of the influence of local **weather** (e.g., rain) on emissions and the universality of **MCE** in the field
- Advanced understanding of peat fire emissions, **haze mitigation strategy**

Human Dimension

Imperial College

Universitas Indonesia

London School of Economics

Universitas Riau

Imperial College London

LSE Geography & Environment

BPSDM Rokan Hilir
Kementrian Dalam Negeri
Universitas Riau
Badan Restorasi Gambut

IMPERIAL HAZELAB

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Field Spectroscopy Facility
Natural Environment Research Council

EPSRC
Engineering and Physical Sciences Research Council

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Thank you!

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