



Supplement of

Brown carbon emissions from laboratory combustion of Eurasian arctic-boreal and South African savanna biomass

Arya Mukherjee et al.

Correspondence to: Arya Mukherjee (arya.mukherjee@uef.fi) and Olli Sippula (olli.sippula@uef.fi)

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S1 : Description of Fuels and combustion set up:

Samples of Finnish boreal forest surface (BFS), South African savanna grass and wood (SG and SW), and four different types of peat, including commercially available peat fuel (CP), natural peatlands from Finland (FIA and FIB), subarctic permafrost area of Russia (RUS) and arctic Svalbard peat from Norway (NOR) were used in the experiments (Table S1). Details of the savanna biomasses used in this study can be found in Vakkari et al. (2025), while details regarding the NOR, RUS, FIA and FIB biomasses have been described by Schneider et al., 2024.

Finnish boreal forest biomass and Arctic-boreal peats were selected for this study, specifically due to the lack of knowledge regarding aerosol emission from these biomasses. Furthermore, with ongoing climate warming, unprecedented wildfires have been recorded both in the boreal forest and Arctic and are projected to increase in the future (Jain et al., 2024; Descals et al., 2022). Boreal and particularly Arctic wildfires largely consume soil organic matter, in many cases consisting of peat (Huang and Rein, 2017; Walker et al., 2020). South African savanna biomasses, on the other hand, constitutes a major fraction of wildfire emissions from continental Africa and contributes significantly to global carbon emissions (Vakkari et al., 2018,2025; van Wees et al., 2022). Even though savanna wildfires are open surface fires, yet the emissions contain much more EC (or BC) compared to Eurasian biomasses, therefore allowing us a wider range to study the effects of BB emitted EC/OC on the optical properties of the emission. We also included a few data points in this study from modern European chimney stove emissions, which are classified as residential wood combustion (RWC) emissions. We have previously shown that modern RWC emissions are EC-rich (Mukherjee et al., 2024) due to their high combustion temperatures. Therefore, including these data points in the current study helped us explore the temperature and EC/OC continuum of biomass burning in three regimes such as:

1) the low temperature combustion of Arctic-boreal surface and corresponding OC-rich emissions, 2) the high temperature wood combustion and resulting EC-rich emissions and 3) the woody and grassy savanna fire emissions, which fall in between 1) and 2).

With that background, we then explored how these temperature continuum influence the BC-BrC continuum in the BB emissions along with their corresponding light absorption properties.

Savanna biomass was cultivated in the North-West University's garden in South Africa and delivered to Finland. The savanna biomass used in the study consisted of ten different species representing indigenous savanna biomass from South Africa, including: *Celtis africana*, *Searsia pyroides*, *Vachellia karroo*, *Ziziphus mucronata*, *Asparagus laricinus*, *Gymnosporia buxifolia*, *Euclea undulata*, *Senegalia caffra*, *Pavetta zeyheri*, *Vangueria infausta*, and *Zanthoxylum capense*. The savanna biomass was divided into grass and woody samples. The savanna grasses were burned in an upright position in 50 g batches without shortening or other modification of the samples. The burning samples of savanna trees were prepared as composite batches, including material from all savanna tree species for a total of 60 g. The savanna tree batches included thorns, leaves, and branches from the species. The savanna tree material was cut into smaller pieces to fit into the B and C sample holders marked in Figure S2(i).

Different sample holders were used for different biomasses in our experiments which are illustrated in Supplementary Fig. S2. Boreal forest surface (BFS) samples needed large piece of wire mesh below it on the open biomass burning setup to keep the sample intact so that it doesn't fall between the spaces on grate during long smoldering phase. BFS samples were burnt from top to bottom by placing a heating rod horizontally on top of the sample surface in order to mimic more natural progression of forest floor fires. Extra litters were present in each sample as found in a natural Finnish BFS.

Savanna and peat samples had the heating rod in the middle of the burned sample to provide more surface-area for the sample to heat up for the combustion experiment. Keeping the mass of combusted biomass same between different sample types of peat needed two different sample holder setups. CP, RUS and NOR samples were more dense and solid compared to FIA and FIB, which were more porous and fluffy in texture (Figure S2). Clam shaped (CP, Svalbard, savanna material) sample holder was used to keep the burning material close to the electrical resistor (heating rod), because during the combustion there was a possibility that burned material lost its shape and wasn't close enough to resistor to continue burning. This wasn't necessary for FIA, FIB and Russian sample types because they settled better on the heating rod. Minimal modifications were made to the samples before combustion to keep them as they were provided to us.

S2: Description of OC-EC analyses:

Thermal-optical carbon analysis with the IMPROVE-A protocol was carried out by placing a filter punch in the sample oven of a carbon analyzer. The filter punches were first heated in completely inert (100 % He) condition where various OC subfractions gradually volatilized at temperature ramps of 140 °C (OC1), 280 °C (OC2), 480 °C (OC3), and 580 °C (OC4). The system then switched to an oxidizing atmosphere (He with a fixed amount of O₂) where EC subfractions combusted at 580 °C (EC1), 740 °C (EC2), and 840 °C (EC3). The released carbon compounds were converted to either carbon dioxide (CO₂) or methane (CH₄), followed by infrared absorption (CO₂) or flame ionization (CH₄) detection. During the thermal analysis, a fraction of OC pyrolyzed or charred (Pyrolyzed Carbon, PC) under the inert He atmosphere into EC-like substances and were accounted for using optical correction by reflectance. Specifically, the instrument monitored the sample filter reflectance throughout the analysis using a laser source. The filter reflectance decreased in response to the formation of PC and then increased as the PC was combusted off the filter. The split between OC and EC is defined as the point at which reflectance returns to its initial reading before the heating started. OC and EC data discussed in this work refer to those after the correction as per the following equations:

$$\text{Corrected OC} = \text{OC1} + \text{OC2} + \text{OC3} + \text{OC4} + \text{PC}$$

$$\text{Corrected EC} = \text{EC1} + \text{EC2} + \text{EC3} - \text{PC}$$

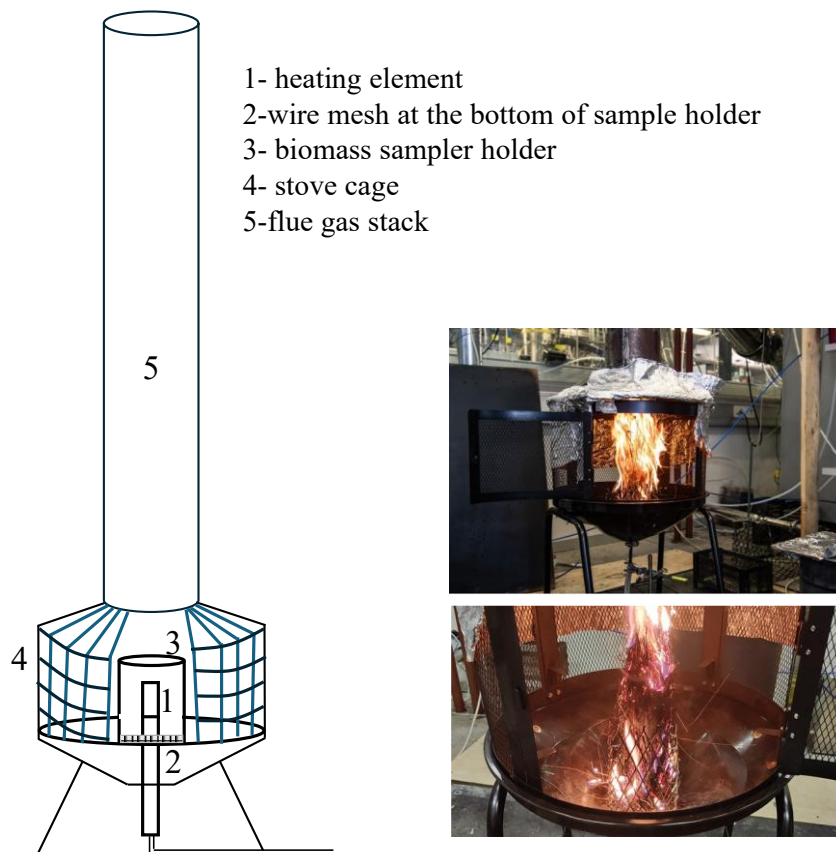


Figure S1: Graphical representation of the combustion set up with its 5 different components along with some pictures taken during the combustion experiments

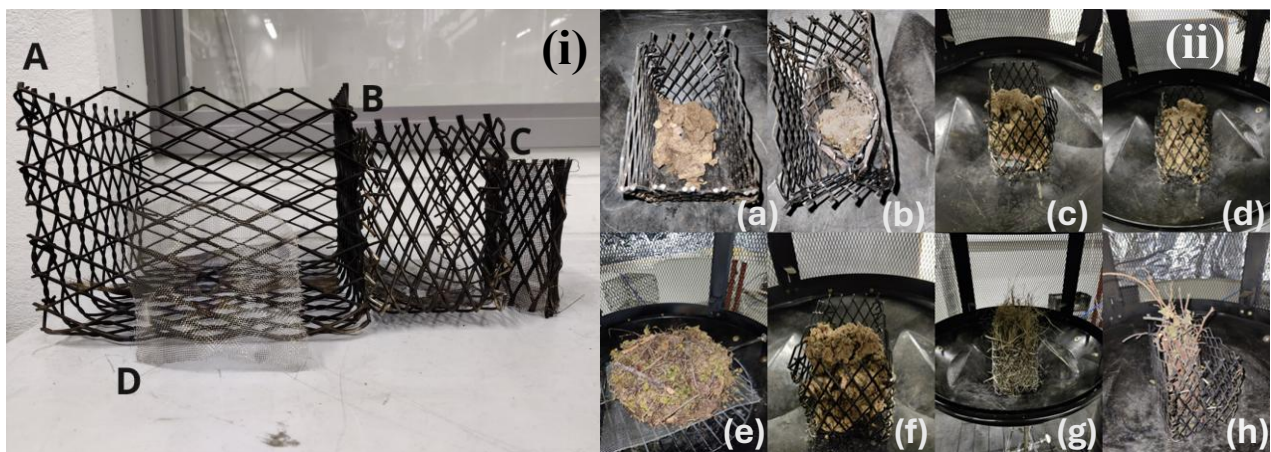


Figure S2: Pictures of different biomass holders used for the experiments. (i) *Left*: biomass holder for BFS samples (A), biomass holders (B and C) for savanna (SG) and peat samples (CP, FIA, FIB, RUS and NOR), and wired mesh used at the bottom of the holders (D) ; (ii) *Right*: Exemplary images of different biomasses in their respective holders before combustion; (a) Russian Peat, (b) Svalbard Peat (NOR), (c-d) Finnish peatland from Lakkasuo (FIA) (e) Boreal forest surface (BFS), (f) Finnish peatland from Siikaneva (FIB), (g) savanna grass (SG) and (h) savanna wood (SW)



Figure S3: Geographic locations of the (a) Northern European Biomass and (b) South African savanna biomass used for this study (© Google maps 2025)

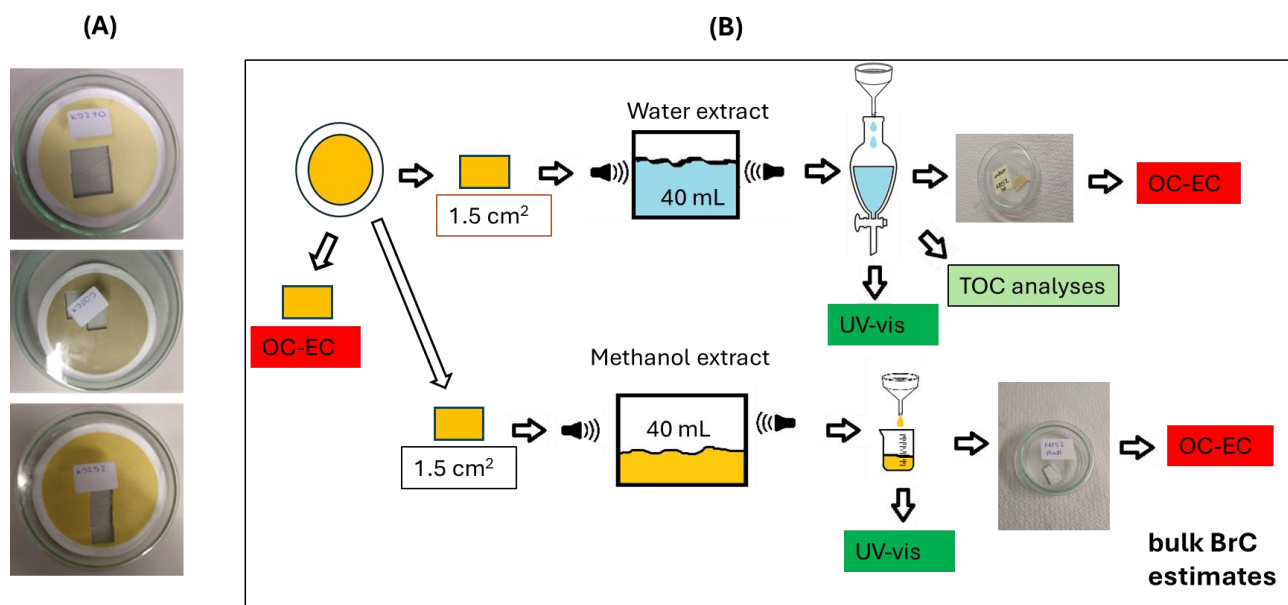


Figure S4: (A) representative images of 90 mm Quartz fiber filters collected for different fresh BB emissions and (B) graphical schematic of the extraction process for filters collecting fresh BB emissions

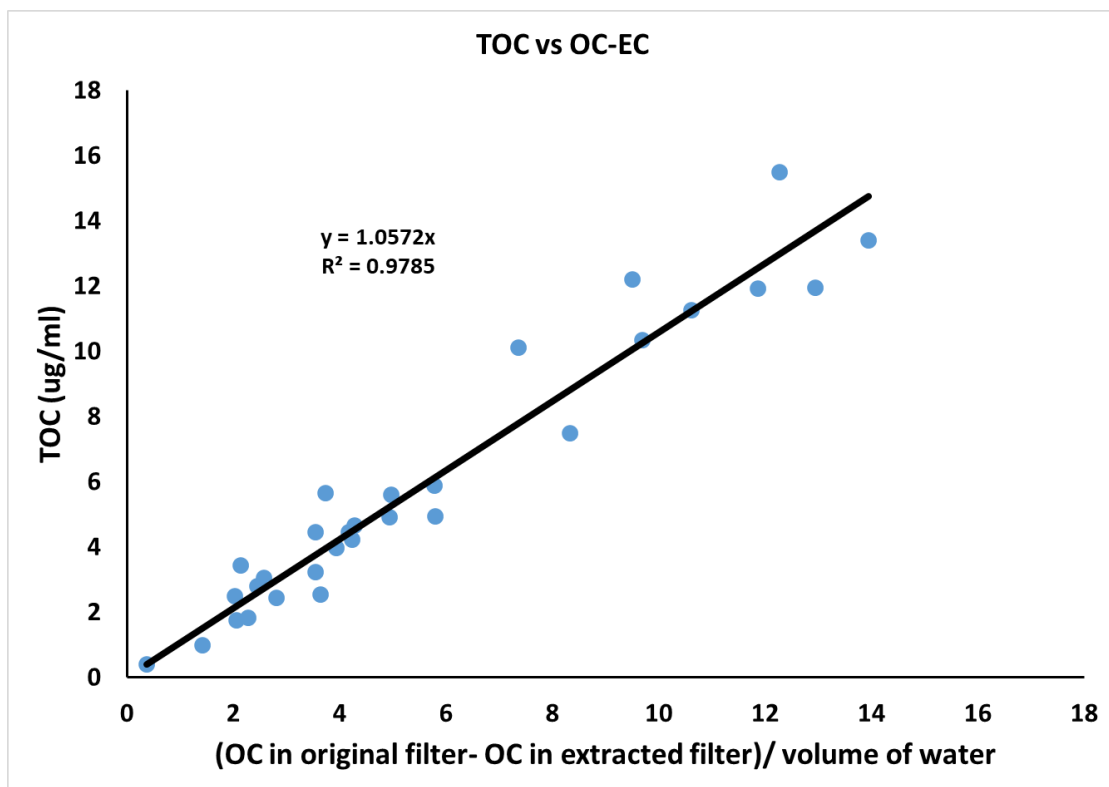


Fig. S5: Comparison between TOC and OC-EC analyzer based estimations of WSOC concentrations for fresh BB emissions

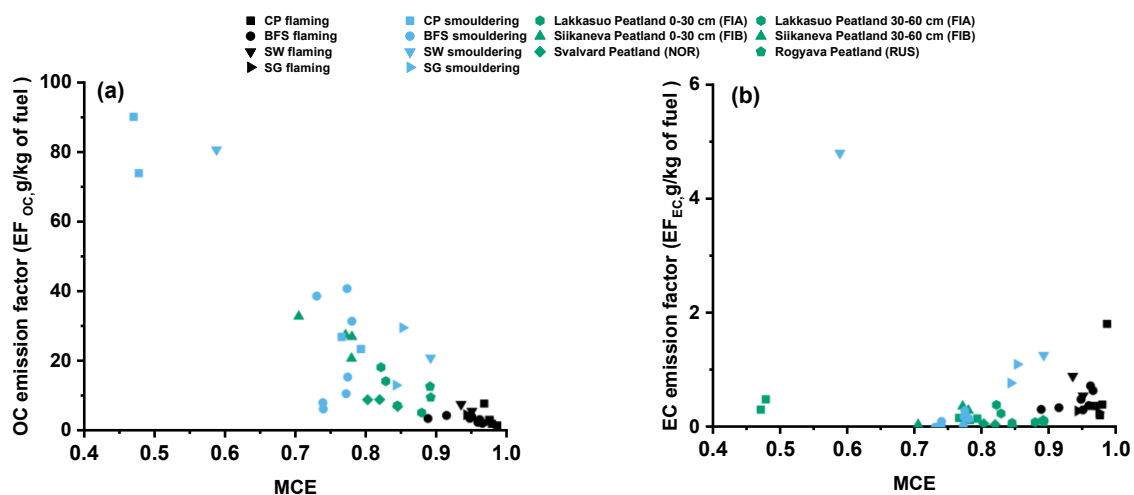


Figure S6: Dependence of EF_{EC} and EF_{OC} on MCE of the combustion

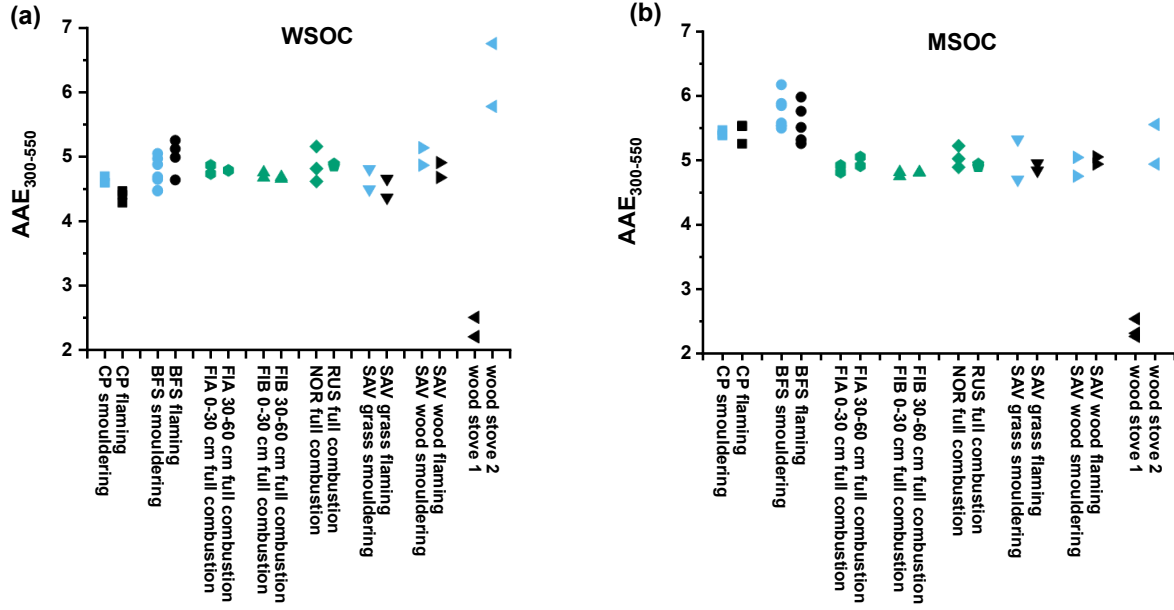


Fig. S7: $AAE_{300-550}$ for WSOC (a) and MSOC (b) of fresh BB emissions in this study

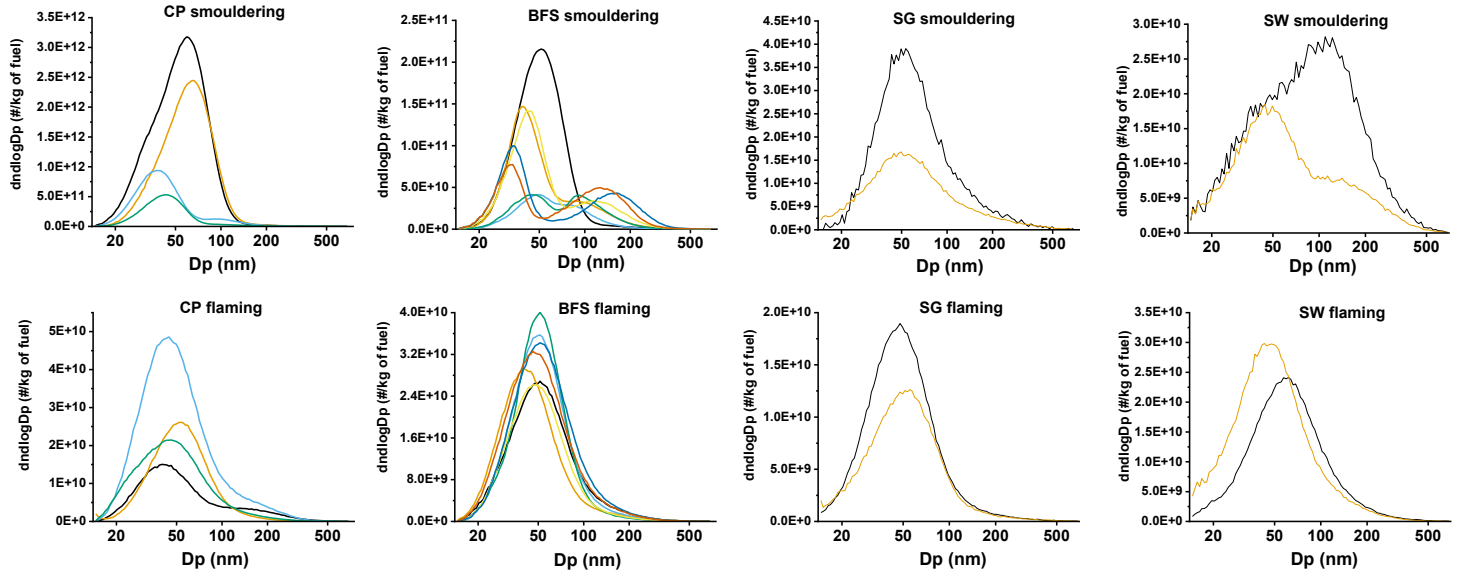


Fig. S8: particle number size distribution of different replicates of the environmental chamber experiments conducted in this study for smouldering and flaming burns of commercial peat (CP), Boreal Forest Surface (BFS), Savanna grass (SG) and savanna wood (SW)

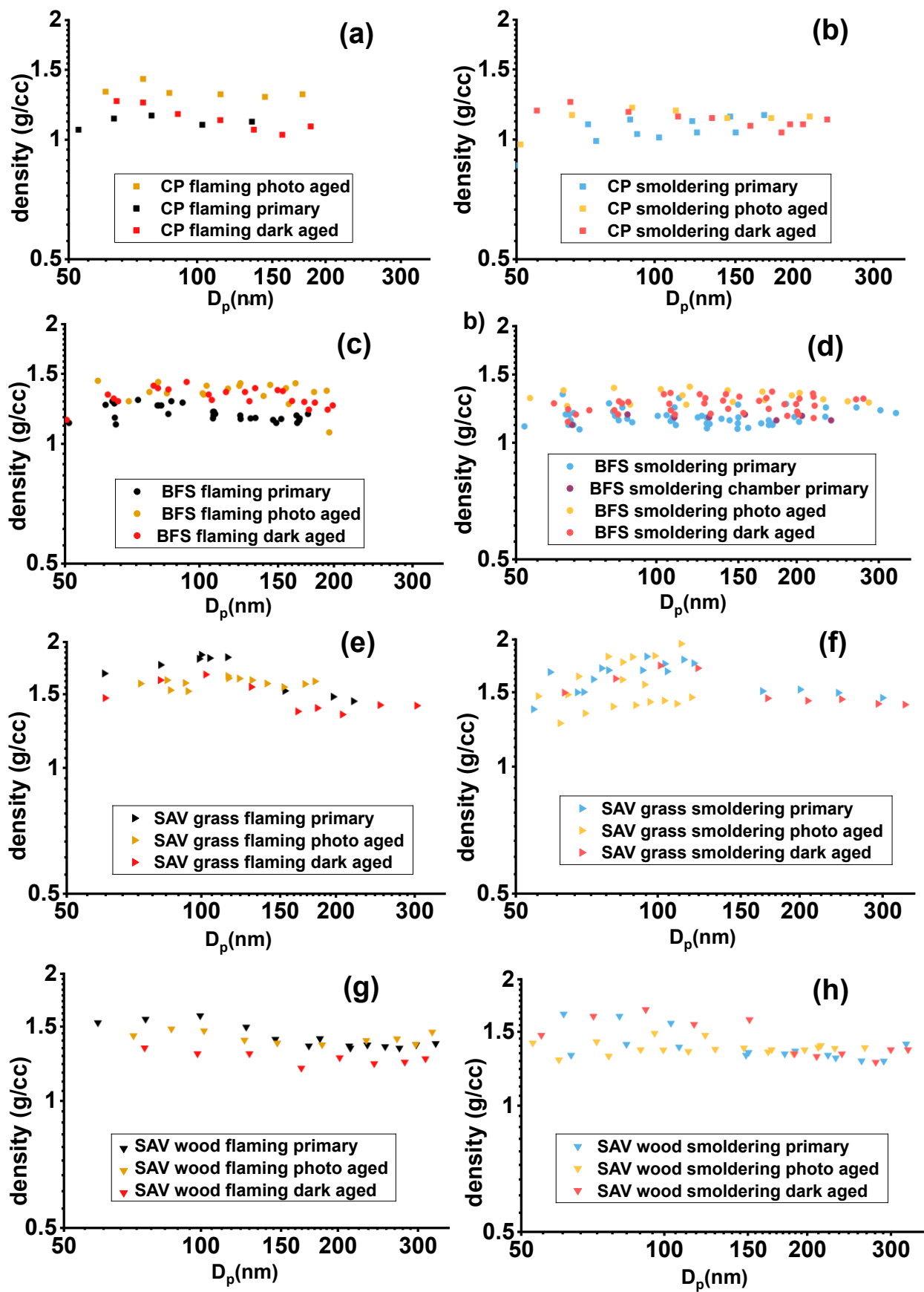


Fig. S9: particle effective densities measured by APM-SMPS

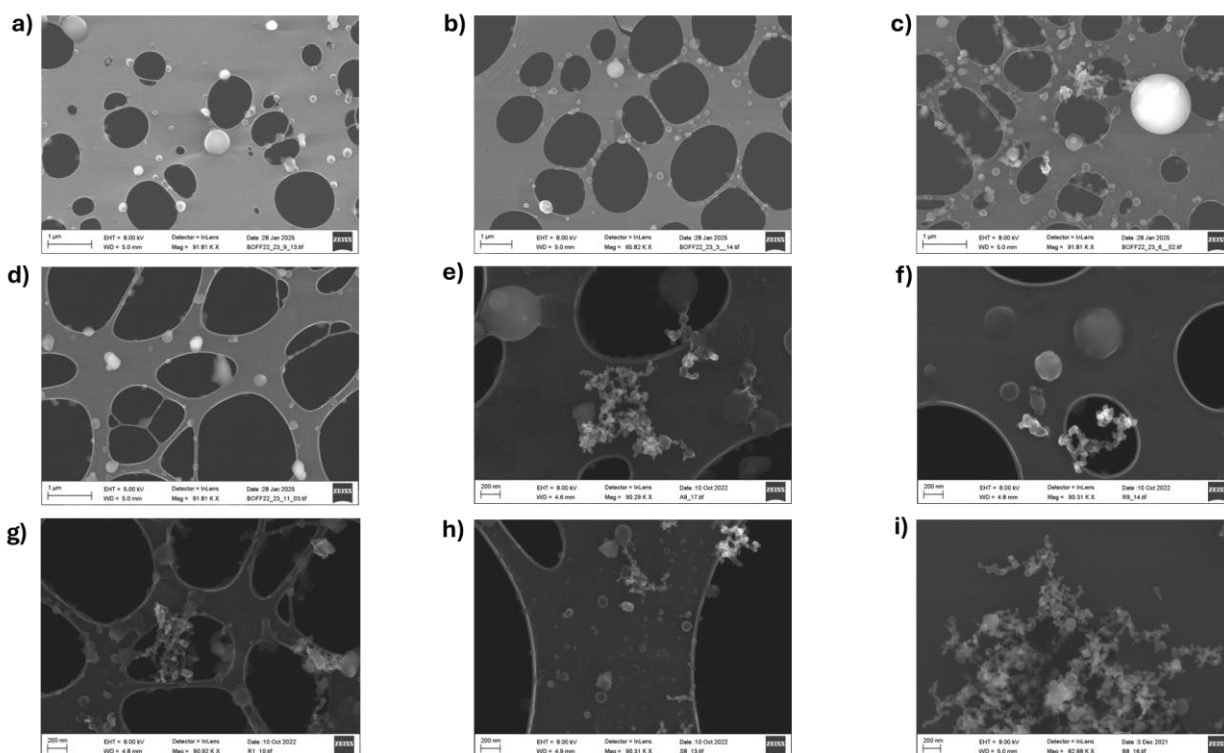


Fig. S10: Electron microscope images of primary particles from a) CP flaming, b) CP smouldering, c) BFS flaming, d) BFS smouldering, e) SG flaming, f) SG smouldering, g) SW flaming, h) SW smouldering and i) wood stove emissions

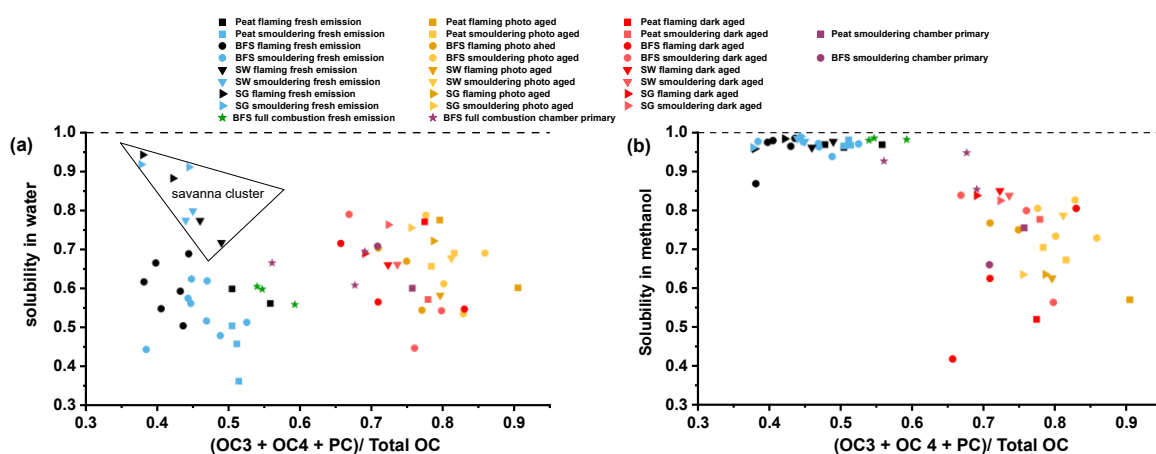


Fig. S11: Solubility of low volatile organics (OC3, OC4 and PC) in water (a) and MeOH (b) for fresh emission, chamber diluted primary emissions and photochemically and dark aged emissions in chamber for smouldering and flaming burns of CP (square) and BFS (circle) biomasses.

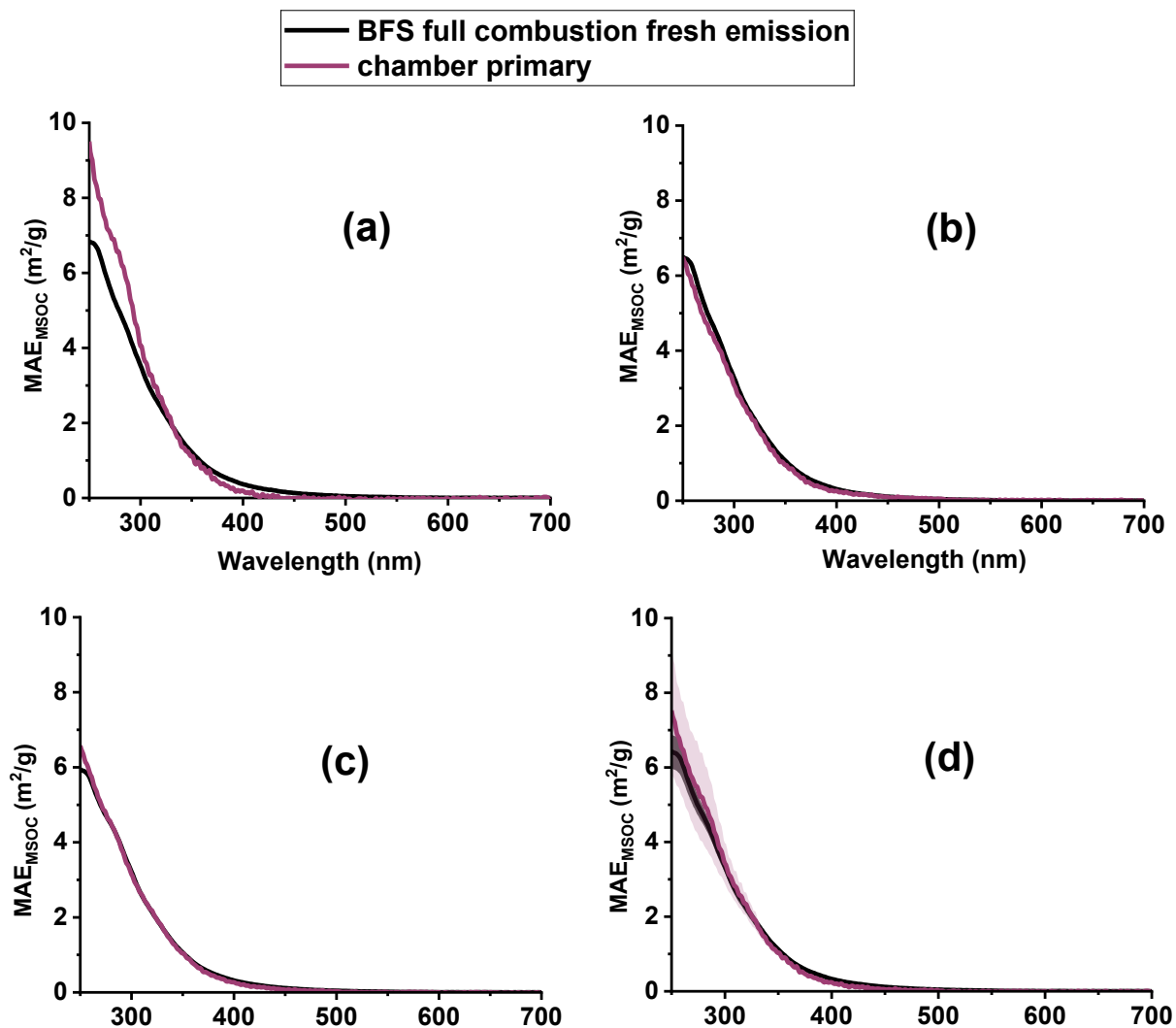


Fig. S12: Wavelength dependence of MAE_{MSOC} for fresh emission and chamber diluted primary samples from full combustion of BFS samples. (a-c) denote three separate replicates, while (d) is the mean values (solid lines) of the three replicates and the standard deviation from mean (shaded area)

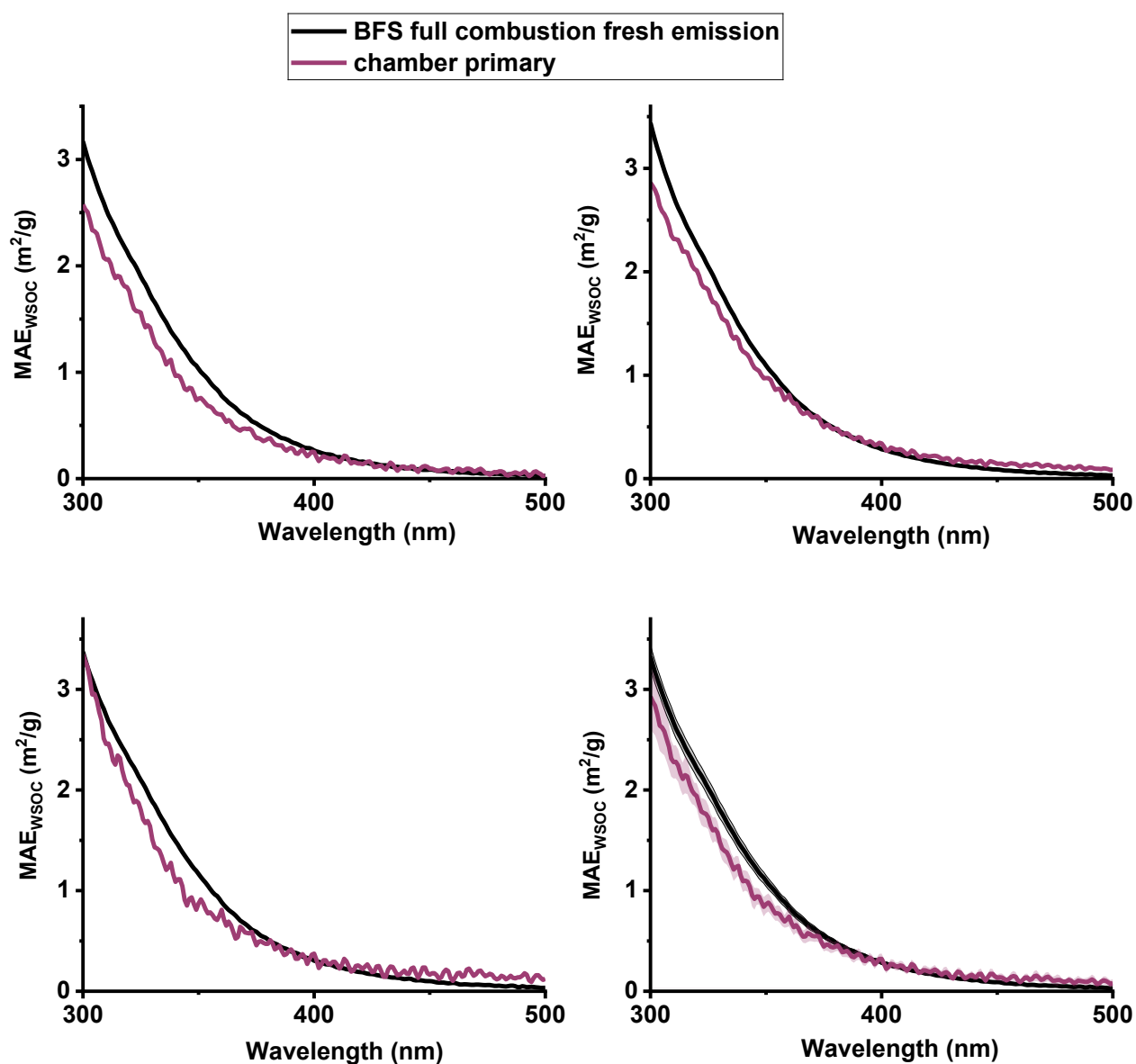


Fig. S13: Wavelength dependence of MAE_{wsoc} for fresh emission and chamber diluted primary samples from full combustion of BFS samples. (a-c) denote three separate replicates, while (d) is the mean values (solid lines) of the three replicates and the standard deviation from mean (shaded area)

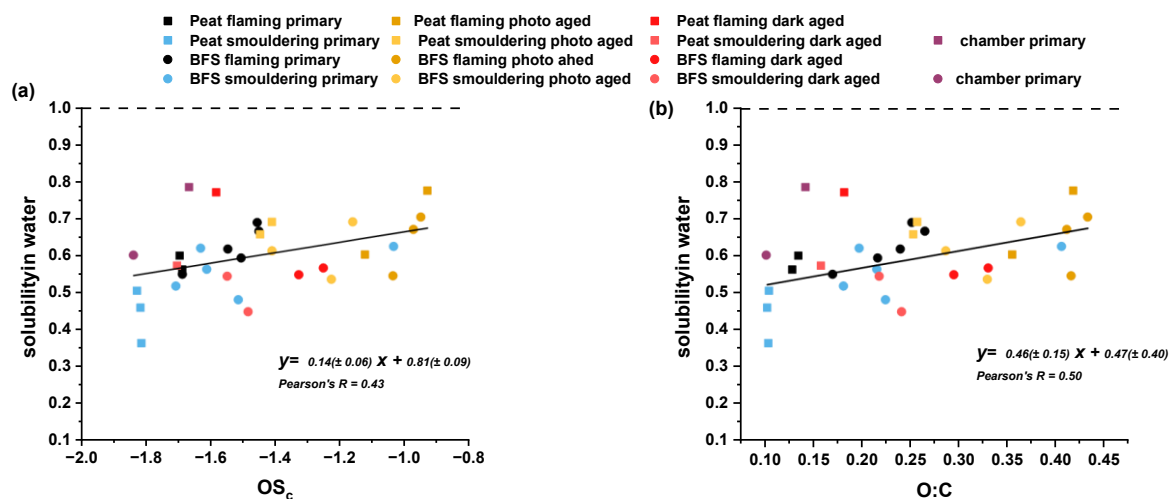


Fig. S14: solubility of OC in water (alternatively WSOC fraction of total OC) vs oxidation state of chamber diluted primary and aged particles (a) and O:C ratio of chamber diluted primary and aged particles (b)

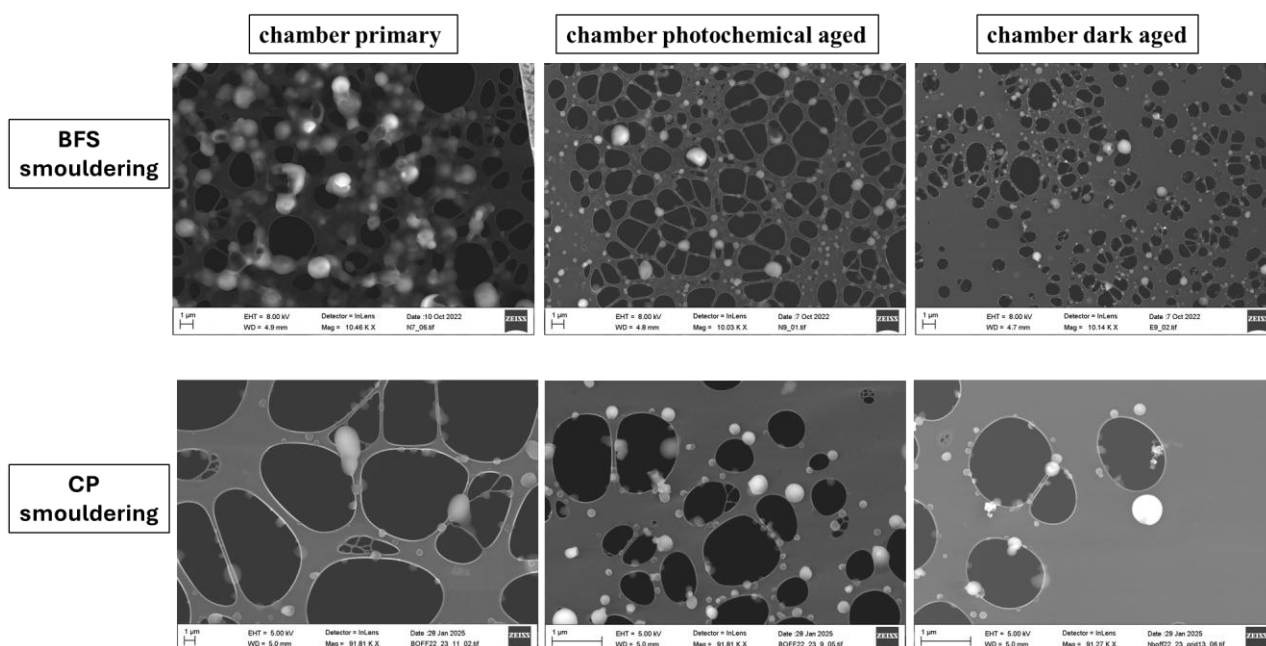


Fig. S15: Representative SEM images of chamber primary and oxidative aged emissions from smouldering combustion of CP and BFS. We observed higher abundance of spherical tarballs in aged samples compared to more amorphous morphology of primary emissions in the chamber.

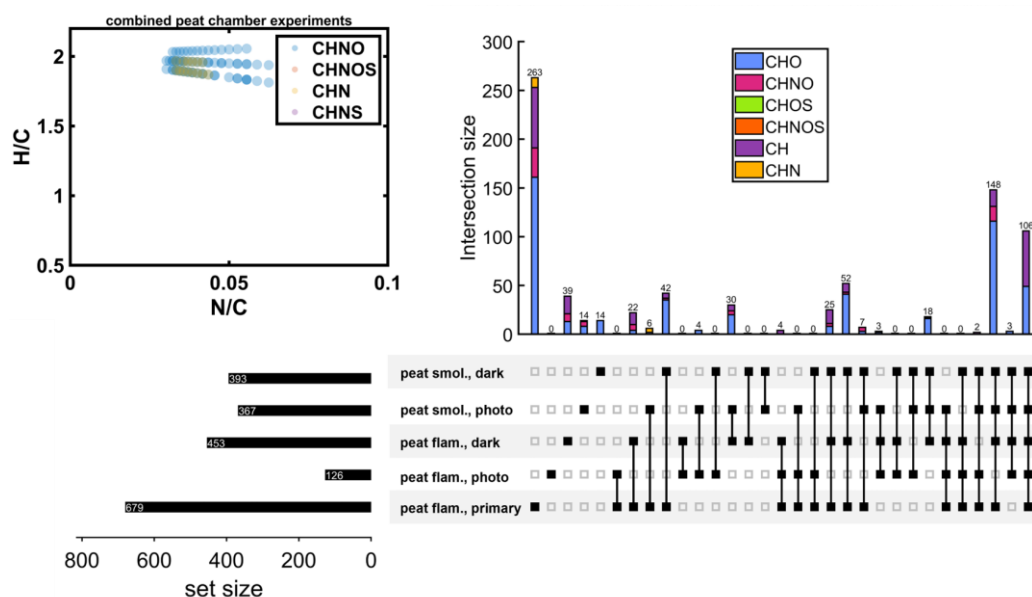


Fig. S16: Upset plot showing the number of unique sum formulae obtained from chamber diluted primary and aged samples from commercial peat (CP) combustions as well as the dominant chemical classes they belong to. Insufficient material on the filters collected from chamber resulted in identification of fewer chemical formulae of only highly abundant chemical groups

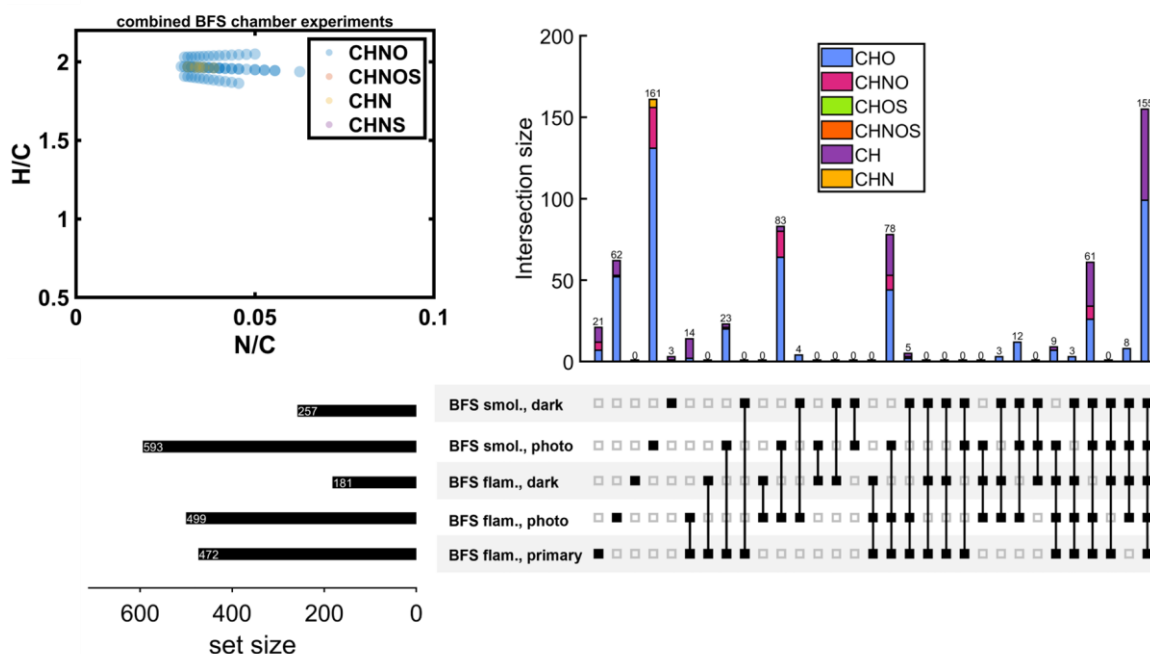


Fig. S17: Upset plot showing the number of unique sum formulae obtained from chamber diluted primary and aged samples from boreal forest surface (BFS) combustions as well as the dominant chemical groups they belong to. Insufficient material on the filters collected from chamber resulted in identification of fewer chemical formulae of only highly abundant chemical groups

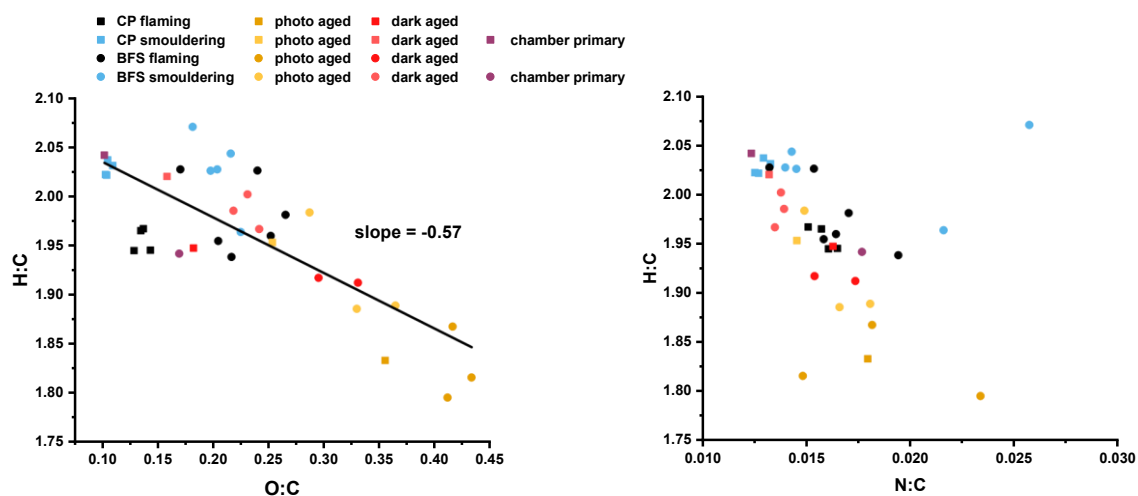


Fig. S18: Van-Krevelen diagrams for H:C vs O:C and H:C vs N:C ratios obtained from HR-AMS from the environmental chamber for CP and BFS combustion experiments. Data obtained for primary emission of flaming (black) and smouldering (grey) burns were compared to the elemental ratios at the end of photochemical (orange for flaming emission, yellow for smouldering emissions) and dark (dark blue for flaming emissions and light blue for smouldering emissions) aging in the chamber.

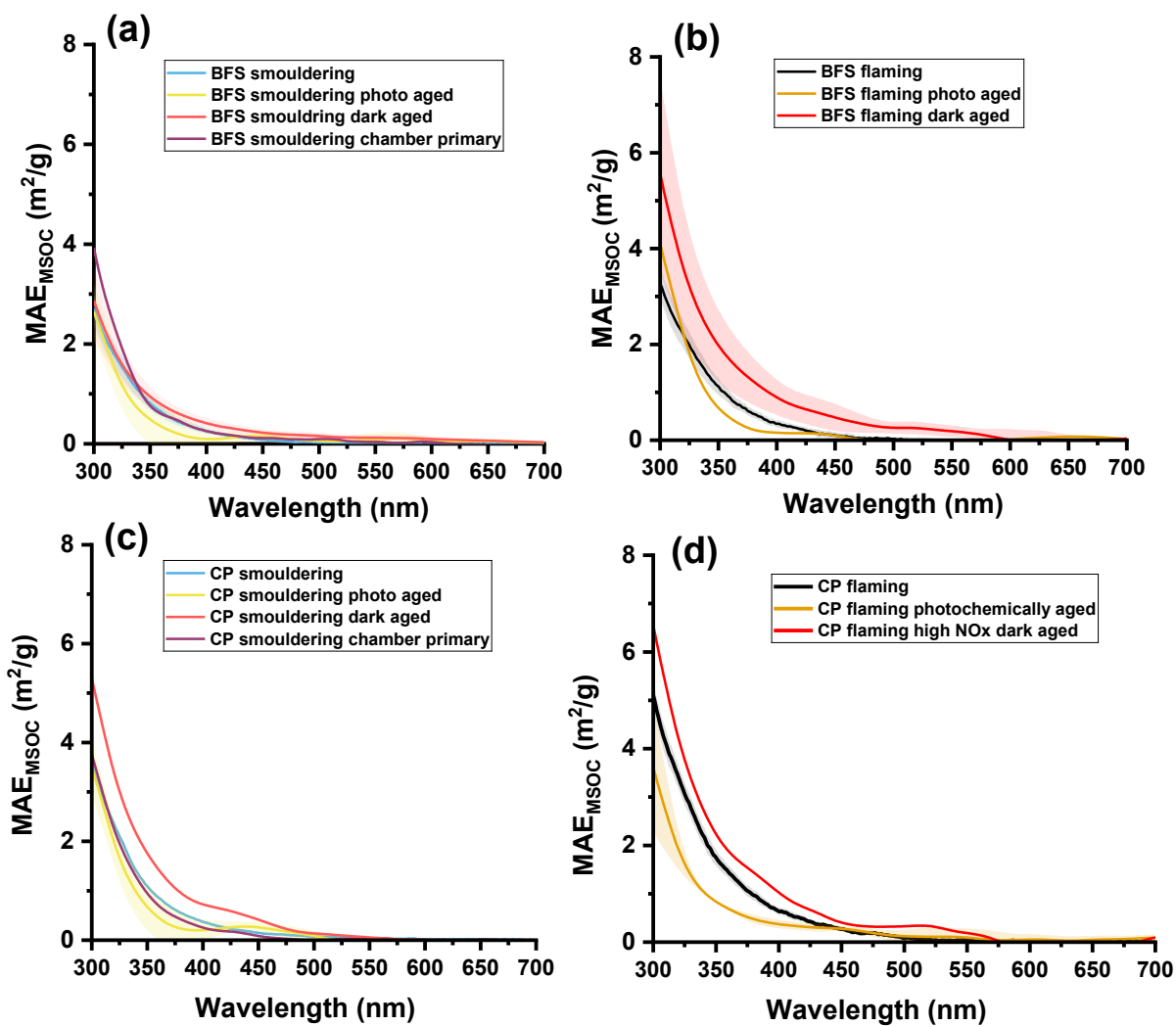


Fig. S19: wavelength dependence of MAE_{MSOC} for (a-b) BFS and (c-d) CP smouldering and flaming emissions. Here we have compared MAE_{MSOC} of fresh emission (black) with photochemically (yellow for smouldering, orange for flaming) and dark aged emission (light red for smouldering and dark red for flaming) in the chamber. Straight line denotes the mean of replicates, while the shaded areas highlight the standard deviation of mean.

Table S1: Origins and compositions of the biomasses used in the experiments

Fuel	Origin (longitude/latitude)	moistur e (%)	composition information (C/N/S/H) %	sampl e mass (g)	
Boreal Forest Surface (BFS)	62.485098"N, 27.491264"E (Kiviniemi)	8.2-16.1	50.5/1.19/0.11/5.4 5	155- 550	Extra litter 10- 24 g
Commercial Peat (CP)	??	9.7	57/1.92/0.2/5.8	50	
Finnish Peatland (FIA)	61°47'21.6"N, 24°18'35.9"E (Lakkasuo)	-	46.5/-/-/-	50	
Finnish Peatland (FIB)	61°49'28.0"N, 24°08'25.8"E (Siikaneva)	-	47.6/-/-/-	50	
Norwegian Peatland (NOR)	78°13'00.0"N, 13°45'00.0"E (Svalbard)	-	27.9/1.85/-/-	50	
Russian Peatland (RUS)	66°33'10.2"N, 60°37'57"E (Rogovaya)	-	51.7/2.9/-/-	50	
Savanna Wood (SW)	26°34'12"S, 26°56'24"E (South Africa)	9.4	48.8/0.88/0.05/5.6	60	
Savanna Grass (SG)	26°34'12"S, 26°56'24"E	8.6	43/0.94/0.10/5.1	50	

Table S2. Components measured by the FTIR and the grouping for the gaseous organic compounds

<i>Component</i>	<i>Formula</i>	<i>Calibration range</i>	<i>Unit</i>	<i>VOC group</i>
Water vapor	H ₂ O	20	%	
Carbon dioxide	CO ₂	25	%	
Carbon monoxide	CO	5000	ppm	
	CO	10000	ppm	
Nitrous oxide	N ₂ O	200	ppm	
Nitrogen monoxide	NO	1000	ppm	
Nitrogen dioxide	NO ₂	200	ppm	
Sulfur dioxide	SO ₂	1000	ppm	
Carbonyl sulfide	COS	100	ppm	
Ammonia	NH ₃	500	ppm	
Hydrogen chloride	HCl	200	ppm	
Hydrogen cyanide	HCN	100	ppm	
Hydrogen fluoride	HF	100	ppm	
Oxygen	O ₂	25	%	
Methane	CH ₄	1000	ppm	Methane
Ethane	C ₂ H ₆	100	ppm	Aliphatic hydrocarbon
Propane	C ₃ H ₈	100	ppm	Aliphatic hydrocarbon
Butane	C ₄ H ₁₀	100	ppm	Aliphatic hydrocarbon
Pentane	C ₅ H ₁₂	100	ppm	Aliphatic hydrocarbon
Hexane	C ₆ H ₁₄	100	ppm	Aliphatic hydrocarbon
Heptane	C ₇ H ₁₆	100	ppm	Aliphatic hydrocarbon
Octane	C ₈ H ₁₈	100	ppm	Aliphatic hydrocarbon
Acetylene	C ₂ H ₂	500	ppm	Aliphatic hydrocarbon
Ethylene	C ₂ H ₄	500	ppm	Aliphatic hydrocarbon
Propene	C ₃ H ₆	500	ppm	Aliphatic hydrocarbon
1,3-Butadiene	C ₄ H ₆	500	ppm	Aliphatic hydrocarbon
Benzene	C ₆ H ₆	500	ppm	Aromatic
Toluene	C ₇ H ₈	100	ppm	Aromatic
m-Xylene	C ₈ H ₁₀	100	ppm	Aromatic
o-Xylene	C ₈ H ₁₀	200	ppm	Aromatic
p-Xylene	C ₈ H ₁₀	100	ppm	Aromatic
1,2,3-Trimethylbenzene	C ₉ H ₁₂	100	ppm	Aromatic
1,2,4-Trimethylbenzene	C ₉ H ₁₂	100	ppm	Aromatic
1,3,5-Trimethylbenzene	C ₉ H ₁₂	100	ppm	Aromatic
Phenol	C ₆ H ₆ O	200	ppm	Aromatic
Furan	C ₄ H ₄ O	200	ppm	Aromatic
Furfural	C ₅ H ₄ O ₂	200	ppm	Aromatic
Formic acid	CH ₂ O	100	ppm	Non-aromatic oxygenated
Acetic acid	C ₂ H ₄ O ₂	200	ppm	Non-aromatic oxygenated
Formaldehyde	CHOH	500	ppm	Non-aromatic oxygenated
Acetaldehyde	C ₂ H ₄ O	100	ppm	Non-aromatic oxygenated
Methanol	CH ₄ O	200	ppm	Non-aromatic oxygenated
Ethanol	C ₂ H ₆ O	200	ppm	Non-aromatic oxygenated
Propanol	C ₃ H ₈ O	100	ppm	Non-aromatic oxygenated
Methyl tert-butyl ether (MTBE)	C ₅ H ₁₂ O	100	ppm	Non-aromatic oxygenated

Table S3: Relative abundance of different OC fractions and EC in fresh emission and diluted primary and aged emissions in teflon chamber

BFS			CP						Fuel	
2c	2b	2a	1f	1e	1d	1c	1b	1a	Experiment	
20.3	24.6	23.8	21.6	21.8	22.3	8.73	20.8	19.7	OC1	fresh emission (% of total)
25.7	26.2	27.7	26.9	27.0	26.5	11.0	22.2	24.5	OC2	
26.7	27.7	26.3	29.9	31.6	29.8	14.1	25.7	30.4	OC3	
4.62	5.39	4.32	6.21	6.39	6.54	4.38	5.0	5.95	OC4	
3.55	4.75	4.39	14.7	12.6	14.3	5.27	8.67	13.9	PC	
19.1	11.4	13.5	0.66	0.65	0.47	56.5	17.7	5.54	EC	
8.03			9.8			5.70			OC1	chamber diluted primary (% of total)
13.4			14.5			10.6			OC2	
33.4			36.3			28.1			OC3	
12.3			12.1			11.6			OC4	
0.42			27.3			4.70			PC	
32.4			0.01			39.3			EC	
		6.85			6.07			5.15	OC1	photo aged in chamber (% of total)
		14.0			13.9			9.40	OC2	
		34.2			40.1			35.5	OC3	
		12.8			12.1			13.0	OC4	
		13.0			27.8			34.8	PC	
		19.1			0.03			2.15	EC	
	7.92			7.46			7.50		OC1	dark aged in chamber (% of total)
	13.4			14.6			12.5		OC2	
	33.5			35.8			29.9		OC3	
	12.6			12.1			12.6		OC4	
	13.7			30.0			26.2		PC	
	18.8			0.01			11.3		EC	

SG		SW				BFS			Fuel
4b	4a	3d	3c	3b	3a	2f	2e	2d	Experiment
27.7	35.0	29.2	27.0	26.8	24.7	19.1	23.1	27.5	OC1
26.1	24.7	24.6	26.1	23.0	21.6	27.5	30.6	28.1	OC2
24.1	20.6	22.9	26.3	27.3	24.4	29.5	31.5	28.2	OC3
5.00	5.30	6.20	6.70	6.80	7.1	6.34	5.40	5.10	OC4
8.20	8.40	11.4	8.40	7.00	11.5	15.7	9.00	10.4	PC
8.90	6.0	5.65	5.60	9.10	10.7	1.86	0.40	0.70	EC
						12.1			OC1
						14.3			OC2
						37.0			OC3
						10.8			OC4
						20.7			PC
						5.10			EC
	6.90		5.20		13.0			4.73	OC1
	14.4		13.6		20.8			12.1	OC2
	34.0		37.0		28.2			41.4	OC3
	13.1		14.0		9.30			14.6	OC4
	31.6		30.2		16.0			27.2	PC
	0.01		0.01		12.7			0.01	EC
9.21		9.2		8.90			8.80		OC1
16.7		16.1		16.5			13.2		OC2
29.8		34.5		36.4			38.0		OC3
10.7		9.1		9.50			14.2		OC4
12.6		14.0		25.1			22.2		PC
20.9		17.1		3.60			3.50		EC

fresh emission (% of total)

chamber diluted primary (% of total)

photo aged in chamber (% of total)

dark aged in chamber (% of total)

SG		Fuel	
4d	4c	Experiment	
27.3	31.6	OC1	fresh emission (% of total)
26.2	27.1	OC2	
26.5	25.0	OC3	
4.80	4.20	OC4	
9.60	8.50	PC	
5.60	3.60	EC	
		OC1	chamber diluted primary (% of total)
		OC2	
		OC3	
		OC4	
		PC	
		EC	
	5.42	OC1	photo aged in chamber (% of total)
	8.97	OC2	
	18.7	OC3	
	8.22	OC4	
	17.5	PC	
	41.2	EC	
10.9		OC1	dark aged in chamber (% of total)
15.8		OC2	
30.4		OC3	
10.3		OC4	
27.2		PC	
5.40		EC	

Table S4: MAE,k in fresh and chamber aged BB emissions along with effective density of bulk BB aerosol (mean ± standard deviation)

2b	2a	1f	1e	1d	1c	1b	1a	Experiment No.
Boreal forest surface (BFS)		Commercial Peat (CP)						Fuel
flaming (n = 3)	flaming (n = 3)	smouldering (n = 1)	smouldering (n = 1)	smouldering (n = 2)	flaming (n = 1)	Flaming (n = 1)	flaming (n = 2)	Combustion Condition (no. of replicates)
0.75 ± 0.04	0.71 ± 0.15	0.78	NaN	0.76 ± 0.02	NaN	1.31	1.32 ± 0.16	MAE_{MSOC_365} (m² g⁻¹) (fresh emission)
0.004 ± 0.000	0.004 ± 0.001	0.004	NaN	0.004 ± 0.00	NaN	0.007	0.007 ± 0.001	k_{MSOC_550} (fresh emission)
0.88 ± 0.36	0.69 ± 0.13	1.43	NaN	1.45 ± 0.32	NaN	0.78	1.59 ± 0.14	MAE_{WSOC_365} (m² g⁻¹) (fresh emission)
0.006 ± 0.003	0.004 ± 0.001	0.011	NaN	0.010 ± 0.002	NaN	0.007	0.012 ± 0.001	k_{WSOC_550} (fresh emission)
1.20 ± 0.05	1.20 ± 0.05	NaN	1.10	1.00 ± 0.02	NA	1.10	NA	density (g cm⁻³) (chamber primary)
high NOx dark	photo aged	no aging	high NOx	photo aged	no aging	high NOx	photo aged	Aging condition (in chamber)
2.21 ± 1.23	0.71 ± 0.22	0.61	1.29	1.56 ± 0.69	NaN	1.75	0.65 ± 0.07	MAE_{MSOC_365} (m² g⁻¹) (chamber aged)
0.014 ± 0.009	0.003 ± 0.001	0.003	0.007	0.009 ± 0.005	sNaN	0.01	0.003 ± 0.002	k_{MSOC_550} (chamber aged)
0.82 ± 0.08	0.75 ± 0.12	0.34	0.77	0.48 ± 0.011	NaN	0.62	1.49 ± 0.27	MAE_{WSOC_365} (m² g⁻¹) (chamber aged)
0.004 ± 0.003	0.002 ± 0.001	0.002	0.005	0.002 ± 0.000	NaN	0.003	0.0078 ± 0.001	k_{WSOC_550} (chamber aged)
1.30 ± 0.07	1.30 ± 0.09	NA	1.10	1.20 ± 0.03	NaN	1.10	1.30 ± 0.05	density (g/cm³) (chamber aged)

4d	4c	4b	4a	3d	3c	3b	3a	2f	2e	2d	2c
Savanna grass (SG)				Savanna wood (SW)				Boreal forest surface (BFS)			
smouldering (n = 1)	smouldering (n = 1)	flaming (n = 1)	flaming (n = 1)	smouldering (n = 1)	smouldering (n = 1)	flaming (n = 1)	flaming (n = 1)	smouldering (n = 1)	smouldering (n = 3)	smouldering (n = 3)	flaming (n = 1)
0.68	0.94	0.93	0.89	1.05	1.11	1.06	1.38	0.58	0.48 ± 0.05	0.62 ± 0.11	0.95
0.005	0.012	0.009	0.009	0.008	0.009	0.009	0.011	0.003	0.002 ± 0.005	0.003 ± 0.001	0.005
1.18	0.84	0.94	1.22	0.85	1.03	1.08	1.28	0.92	0.78 ± 0.11	1.17 ± 0.26	0.65
0.011	0.006	0.008	0.01	0.007	0.007	0.008	0.009	0.006	0.005 ± 0.001	0.006 ± 0.002	0.004
1.60	1.70	1.70	1.80	1.40	NA	1.50	1.40	1.20	1.10 ± 0.03	1.20 ± 0.1	NaN
low NOx	photo aged	low NOx	photo aged	low NOx	photo aged	low NOx	photo aged	no aging	high NOx	photo aged	no aging
1.32	NaN	1.21	1.35	0.73	0.68	NaN	1.06	0.64	0.65 ± 0.11	0.50 ± 0.06	NaN
0.01	NaN	0.01	0.005	0.006	0.004	NaN	0.007	0.022	0.003 ± 0.001	0.002 ± 0.000	NaN
0.83	2.10	1.56	3.43	0.86	0.40	1.22	1.03	0.31	0.60 ± 0.04	0.26 ± 0.04	NaN
0.005	0.010	0.008	0.012	0.005	0.001	0.007	0.003	0.002	0.002 ± 0.001	0.001 ± 0.000	NaN
1.50	1.40	1.50	1.60	1.40	1.40	1.30	1.40	1.20	1.10 ± 0.03	1.30 ± 0.05	NaN

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