Supplementary Information for

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

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.

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 mimick more natural progression of forest floor fires. Extra litters were present in each sample as found in a naural 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.

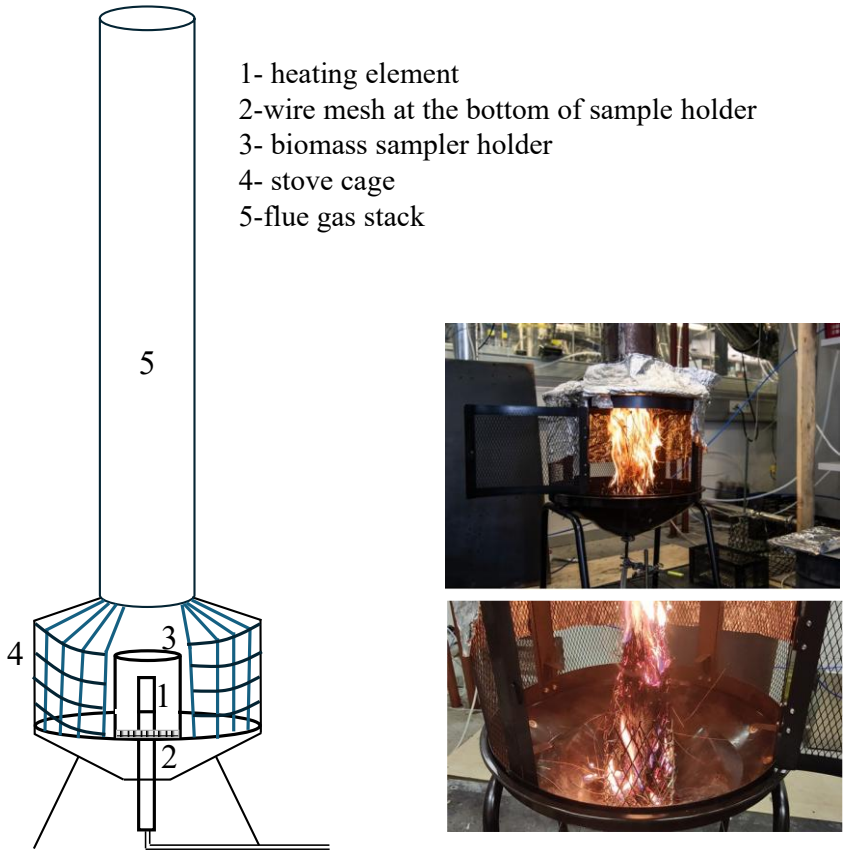

Figure S1: Graphical representation of the combustion set up with its 5 different components along with some pictures taken during the combustion experiments

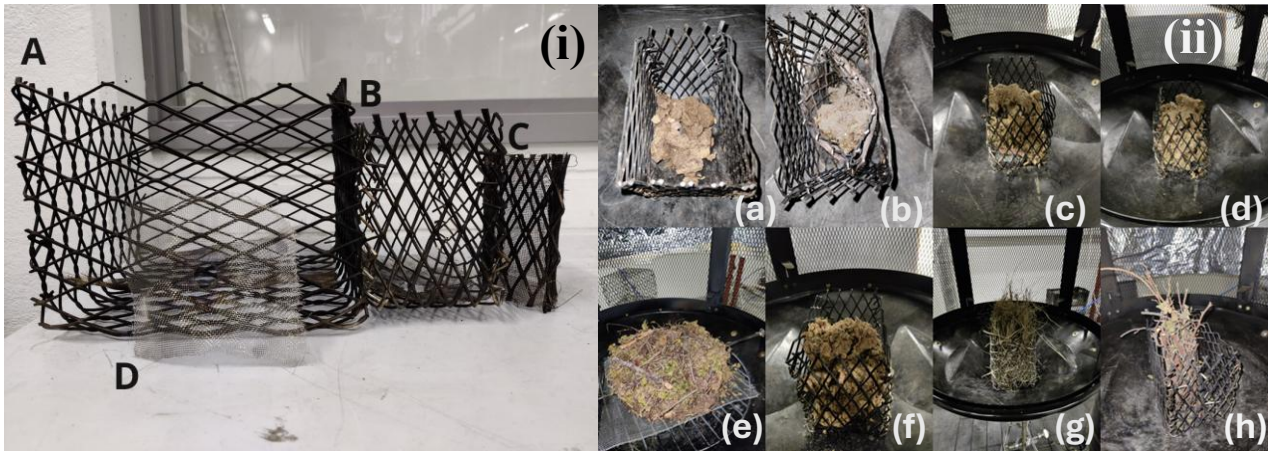

Figure S2: Pictures of different biomass holders used for the experiments. (i) *Left:* biomass holder for BFS samples (A), biomass holders (B and C) for savanna (SG) and peat samples (CP, FIA, FIB, RUS and NOR), and wired mesh used at the bottom of the holders (D) ; (ii) *Right:* Exemplary images of different biomasses in their respective holders before combustion; (a) Russian Peat, (b) Svalbard Peat (NOR), (c-d) Finnish peatlaland 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)

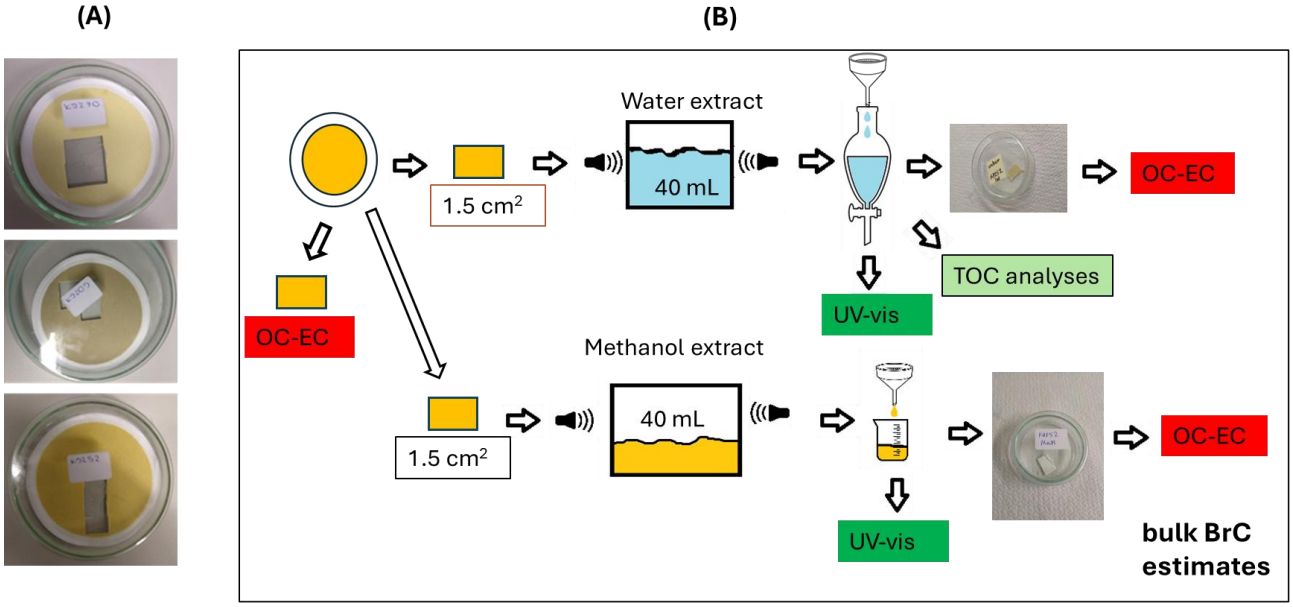

Figure S4: (A) representative images of 90 mm Quartz fiber filters collected for different fresh BB emissions and (B) graphical schematic of the extraction process for filters collecting fresh BB emissions

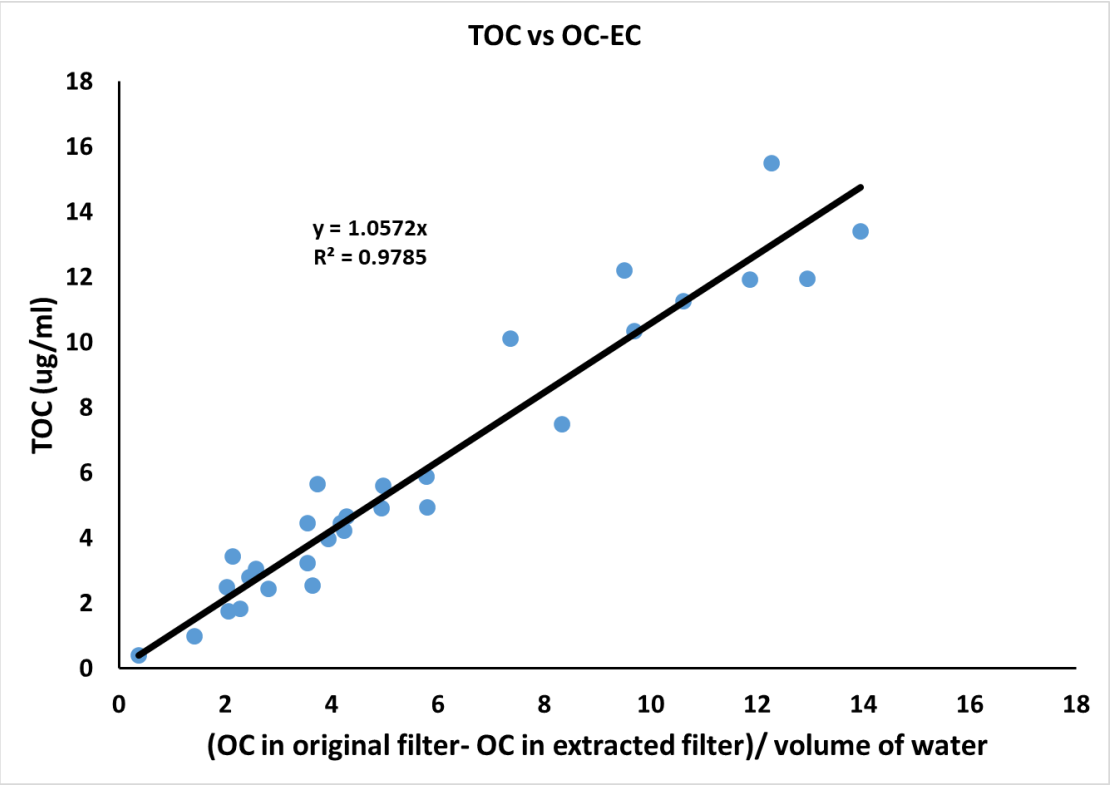

Fig. S5: Comparison between TOC and OC-EC analyzer based estimations of WSOC concentrations for fresh BB emissions

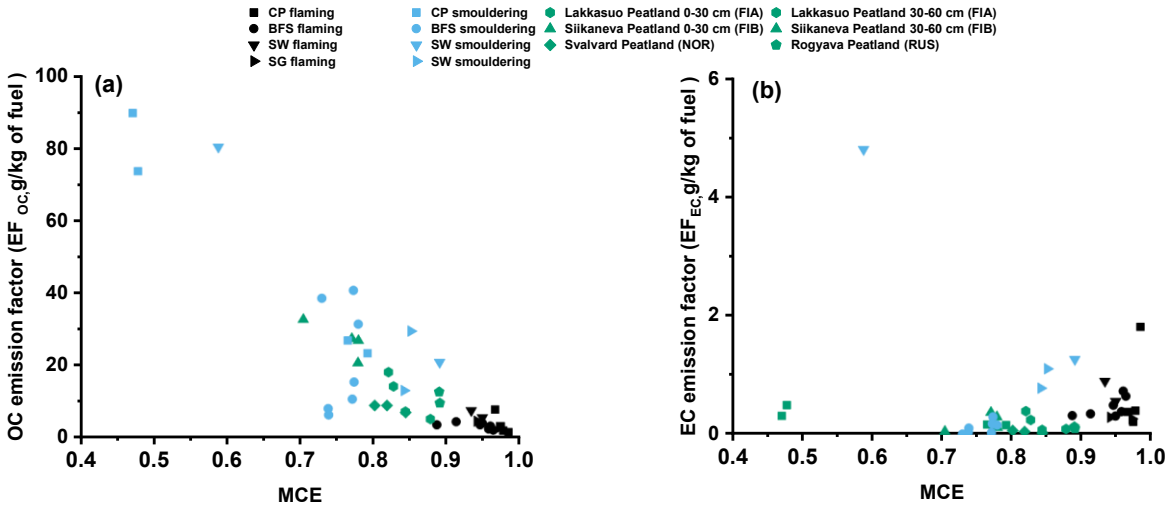

Figure S6: Dependence of EF_{EC} and EF_{OC} on MCE of the combustion

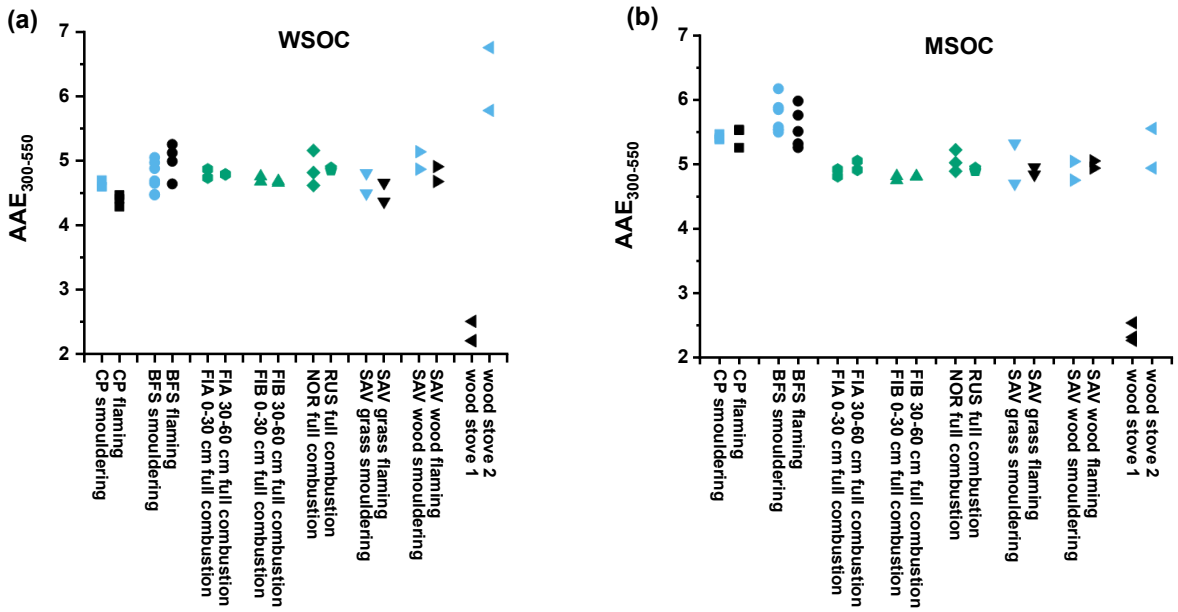

Fig. S7: $AAE_{300\text{-}550}$ for WSOC (a) and MSOC (b) of fresh BB emissions in this study

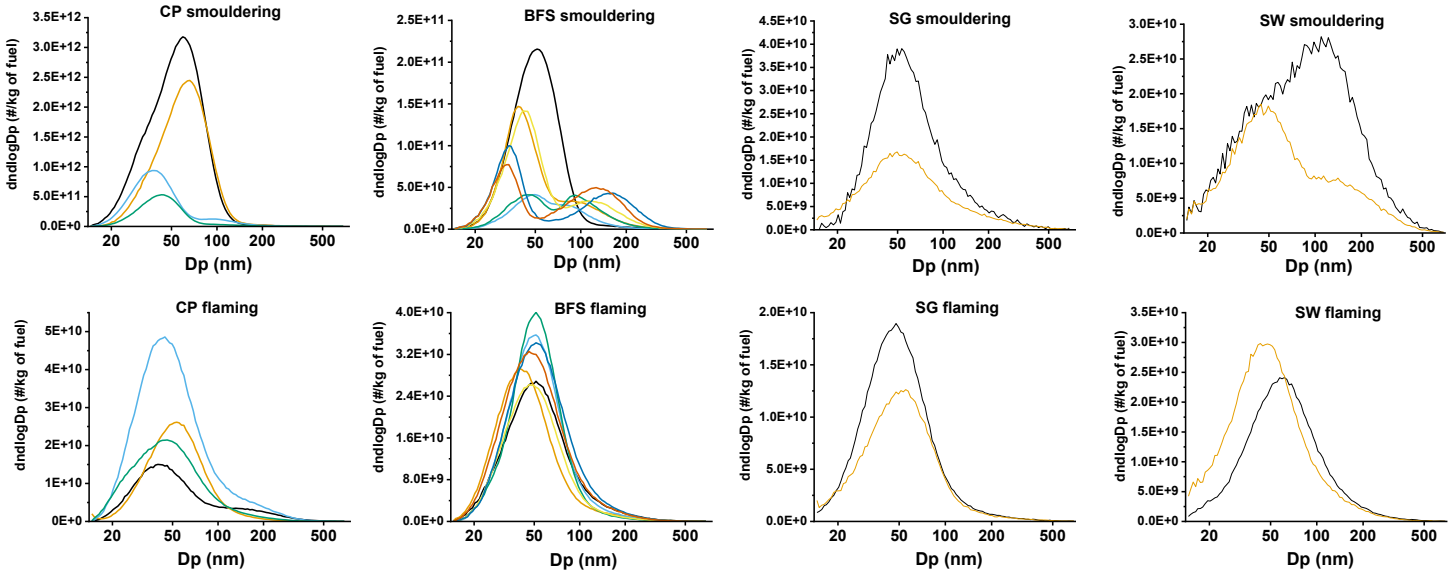

Fig. S8: particle number size distribution of different replicates of the environmental chamber experiments conducted in this study for smouldering and flaming burns of commercial peat (CP), Boreal Forest Surface (BFS), Savanna grass (SG) and savanna wood (SW)

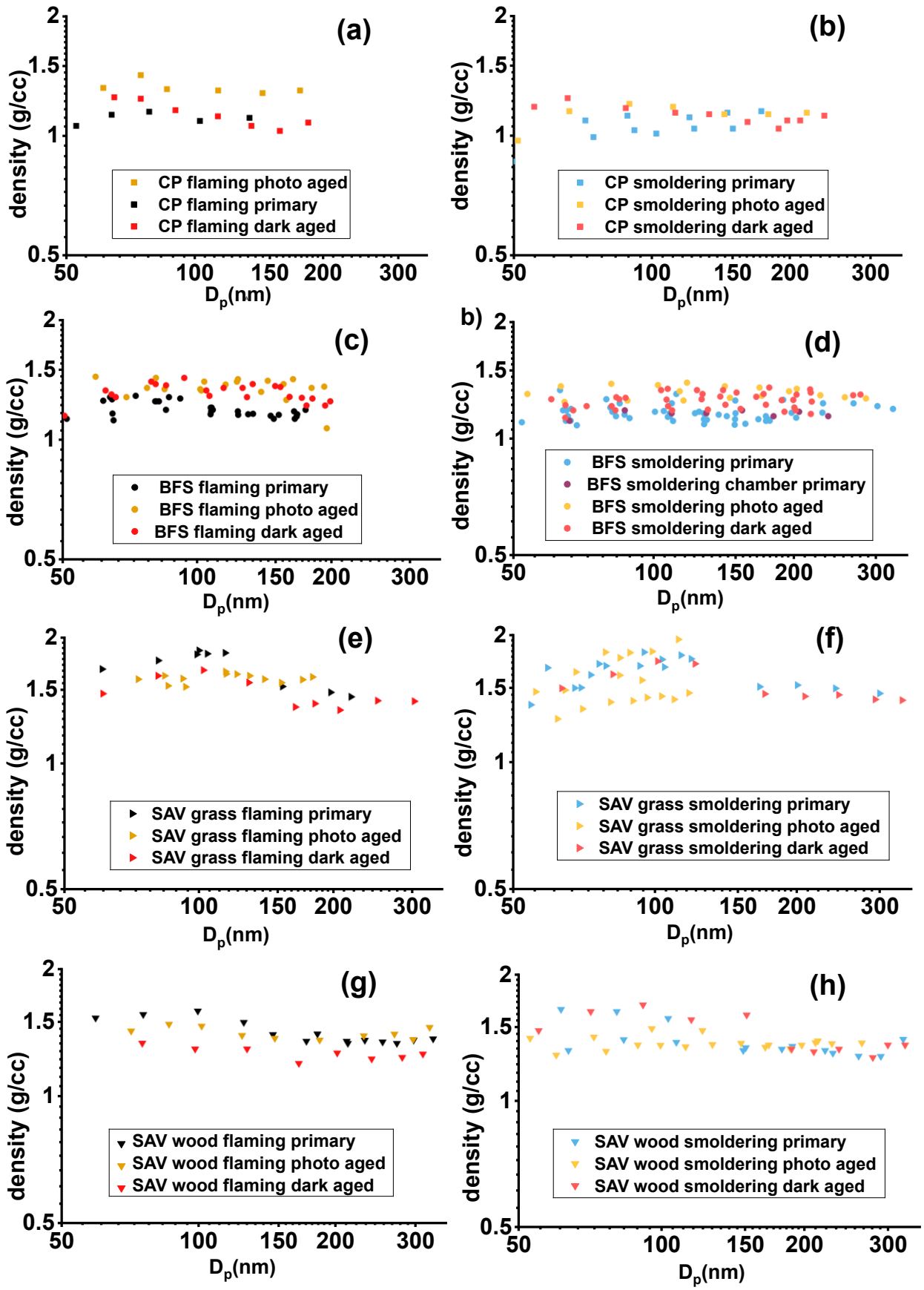

Fig. S9: particle effective densities measured by APM-SMPS

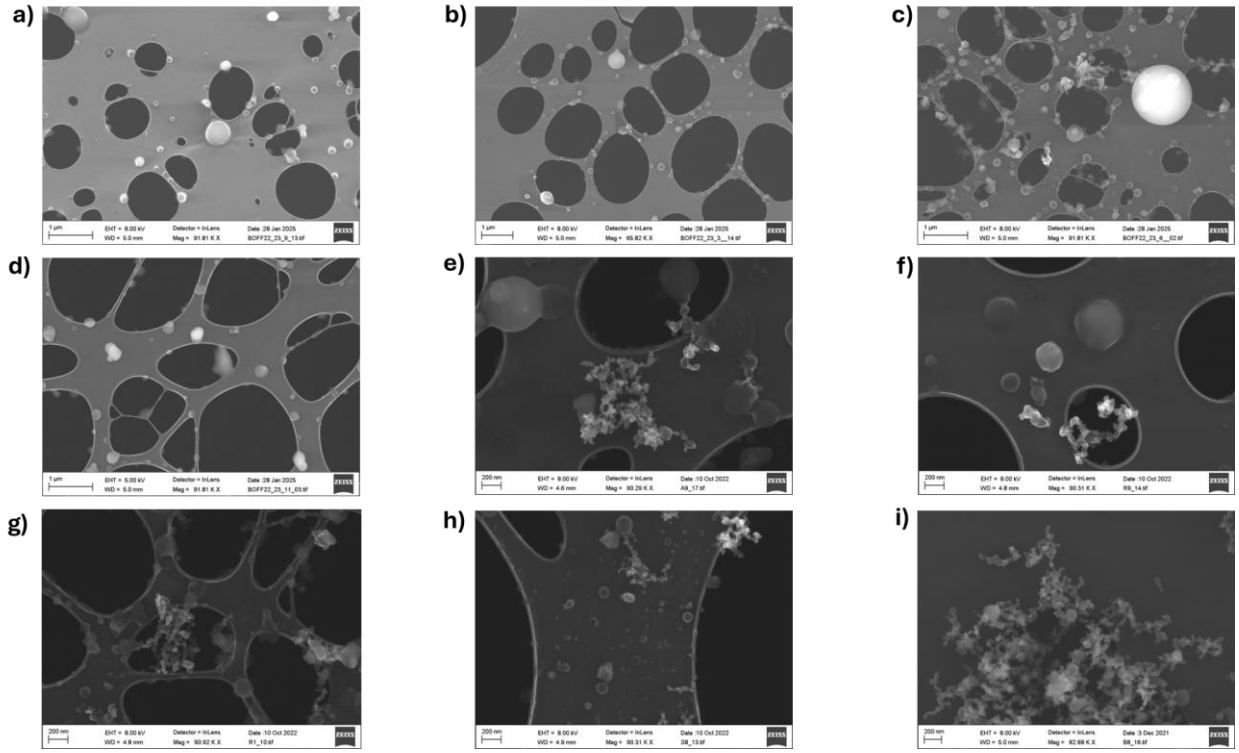

Fig. S10: Electron microscope images of primary particles from a) CP flaming, b) CP smouldering, c) BFS flaming, d) BFS smouldering, e) SG flaming, f) SG smouldering, g) SW flaming, h) SW smouldering and i) wood stove emissions

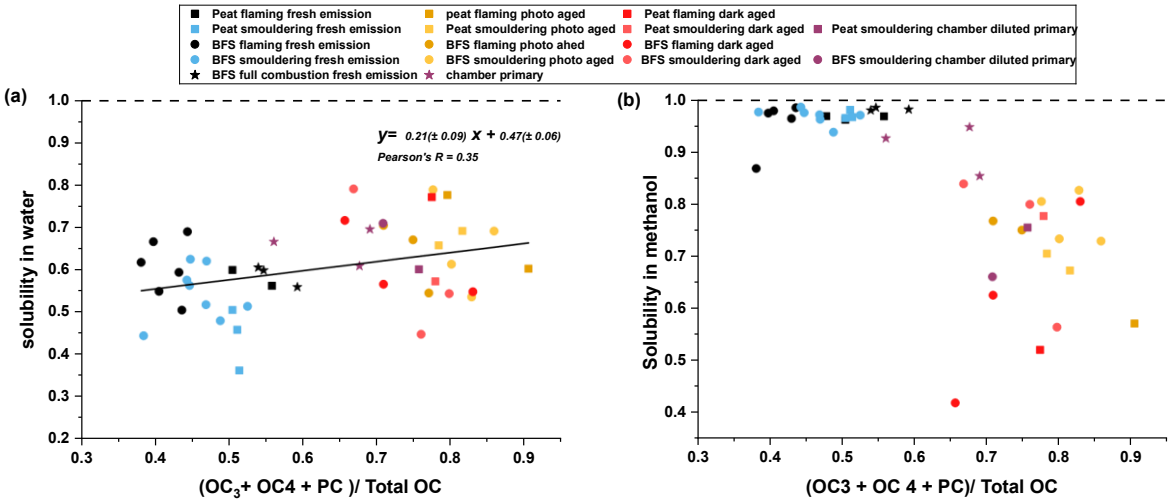

Fig. S11: Solubility of low volatile organics (OC3, OC4 and PC) in water (a) and methanol (b) for fresh emission, chamber diluted primary emissions and photochemically and dark aged emissions in chamber for smouldering and flaming burns of CP (square) and BFS (circle) biomasses.

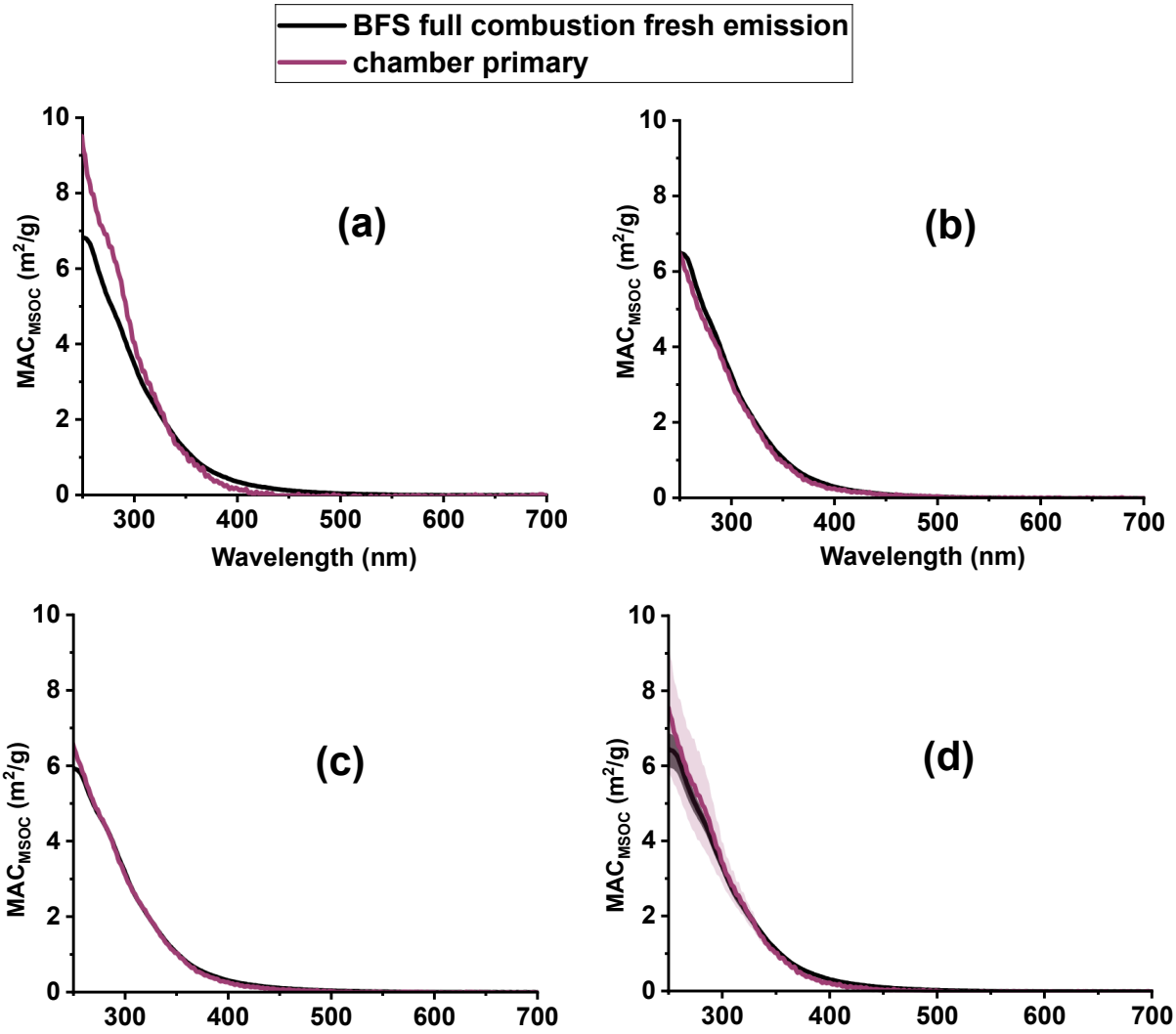

Fig. S12: Wavelength dependence of MAC_{MSOC} for fresh emission and chamber diluted primary samples from full combustion of BFS samples. (a-c) denote three separate replicates ,while (d) is the mean values (solid lines) of the three replicates and the standard deviation from mean (shaded area)

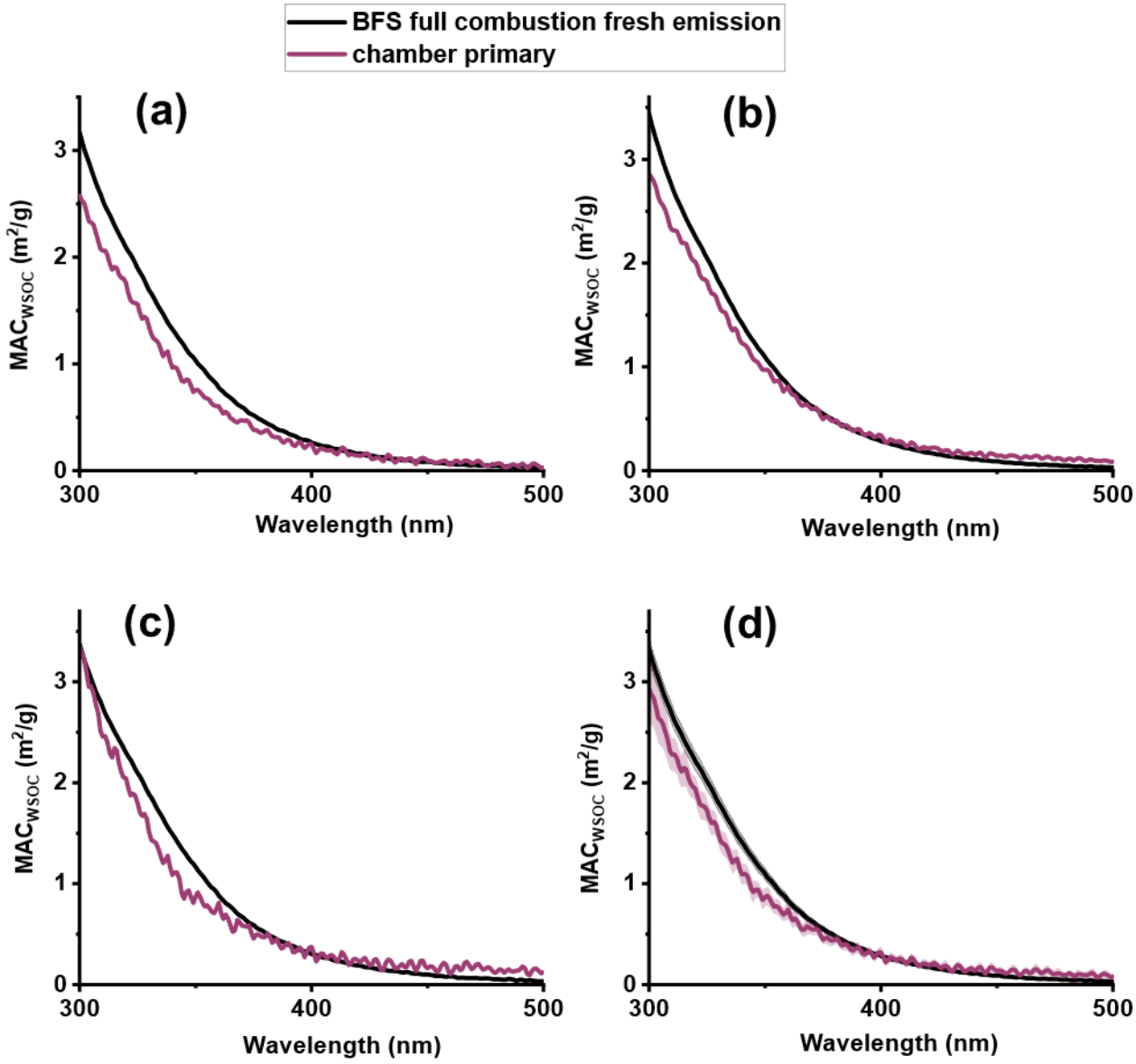

Fig. S13: Wavelength dependence of MAC_{WSOC} for fresh emission and chamber diluted primary samples from full combustion of BFS samples. (a-c) denote three separate replicates, while (d) is the mean values (solid lines) of the three replicates and the standard deviation from mean (shaded area)

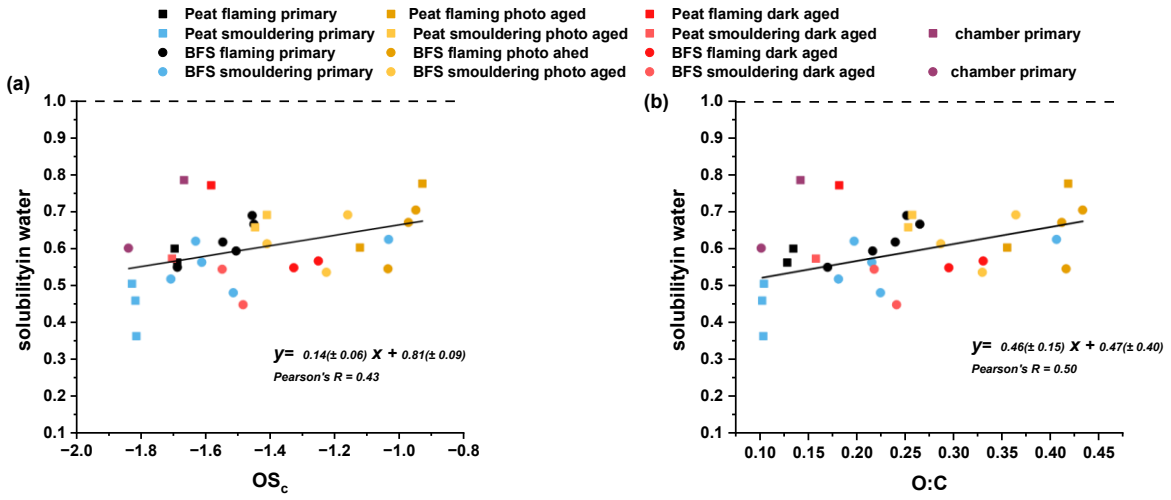

Fig. S14: solubility of OC in water (alternatively WSOC fraction of total OC) vs oxidation state of chamber diluted primary and aged particles (a) and O:C ratio of chamber diluted primary and aged particles (b)

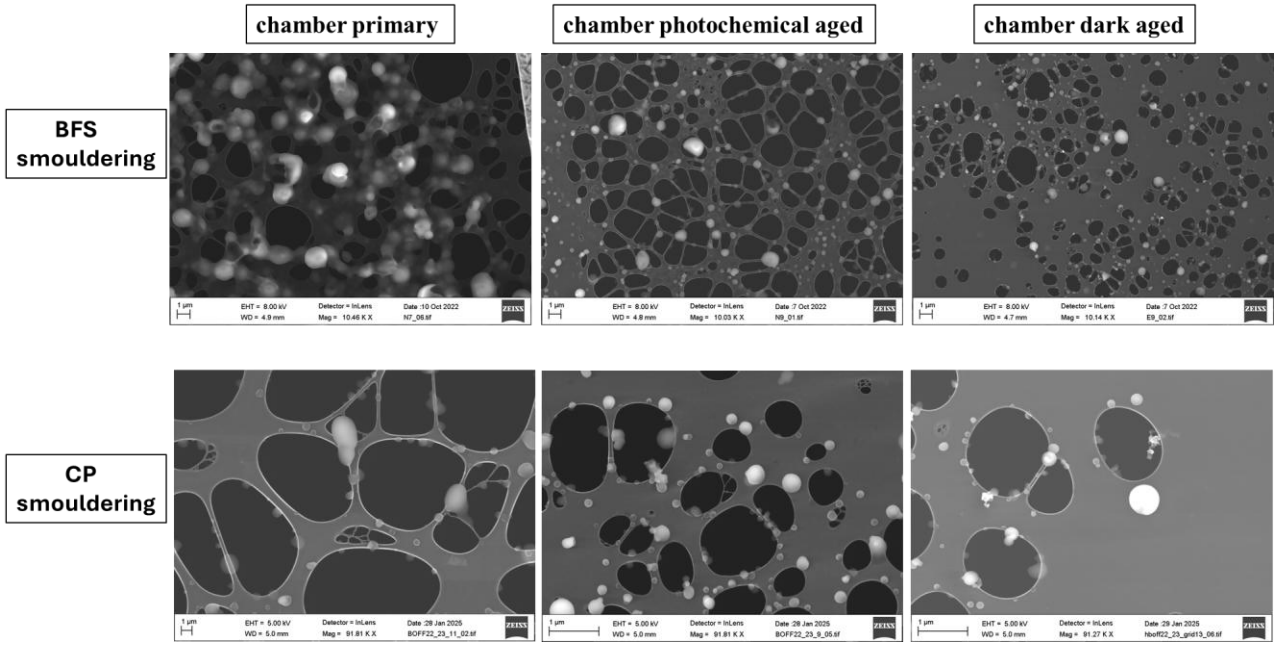

Fig. S15: Representative SEM images of chamber primary and oxidative aged emissions from smouldering combustion of CP and BFS. We observed higher abundance of spherical tarballs in aged samples compared to more amorphous morphology of primary emissions in the chamber.

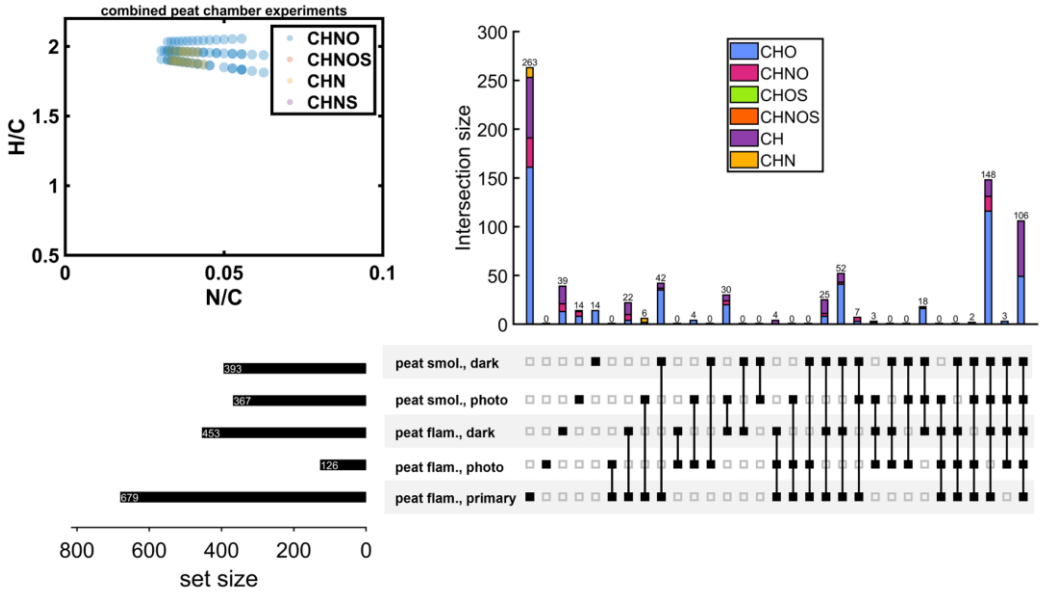

Fig. S16: Upset plot showing the number of unique sum formulae obtained from chamber diluted primary and aged samples from commercial peat (CP) combustions as well as the dominant chemical classes they belong to. Insufficient material on the filters collected from chamber resulted in identification of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

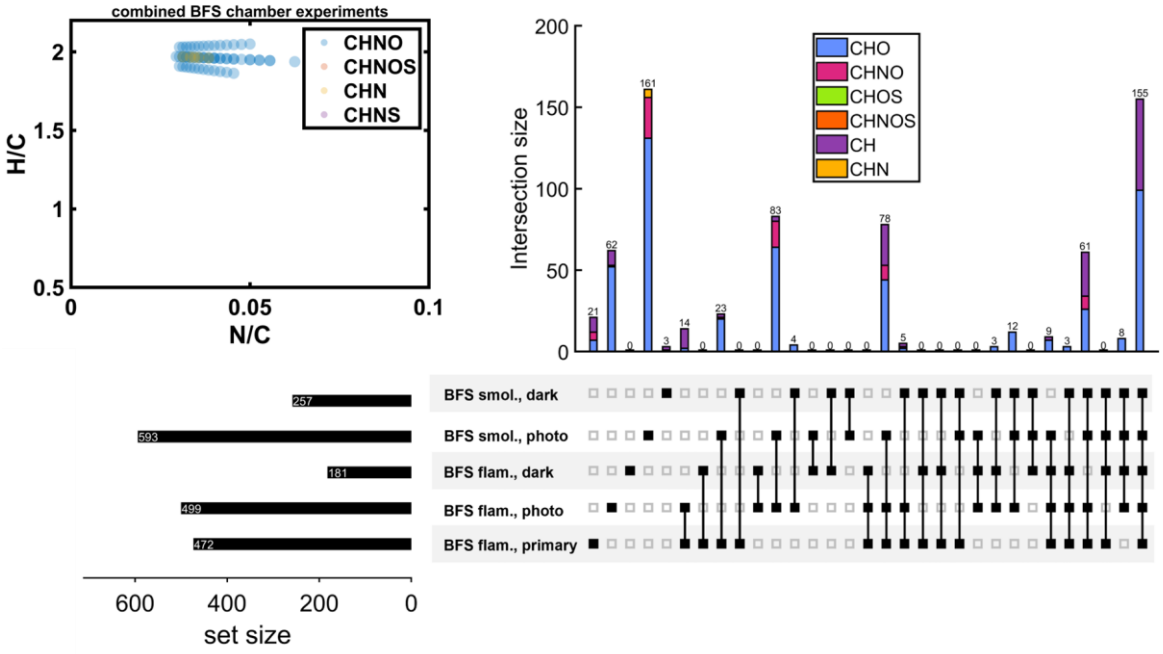

Fig. S17: Upset plot showing the number of unique sum formulae obtained from chamber diluted primary and aged samples from boreal forest surface (BFS) combustions as well as the dominant chemical groups they belong to. Insufficient material on the filters collected from chamber resulted in identification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

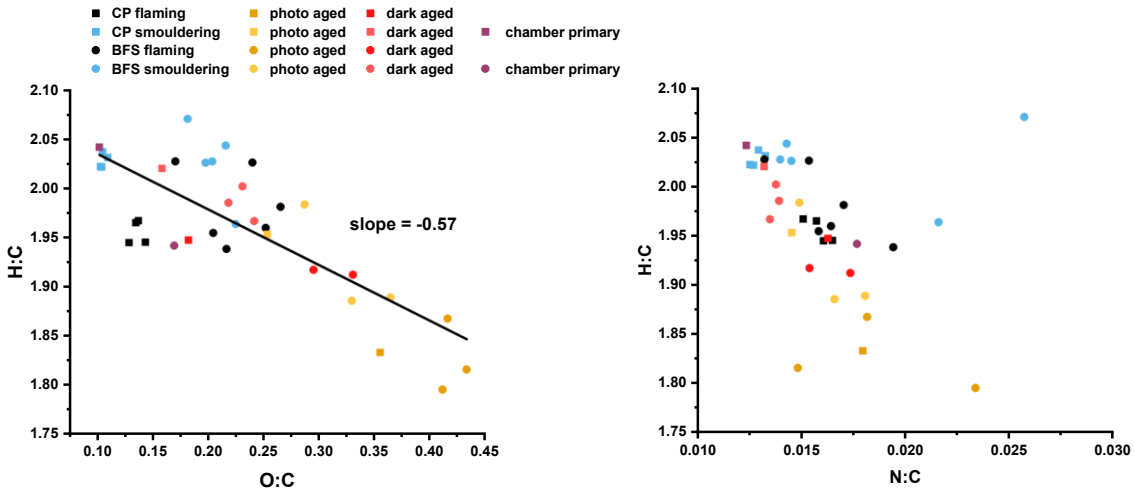

Fig. S18: Van-Krevelen diagrams for H:C vs O:C and H:C vs N:C ratios obtained from HR-AMS from the environmental chamber for CP and BFS combustion experiments. Data obtained for primary emission of flaming (black) and smouldering (grey) burns were compared to the elemental ratios at the end of photochemical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

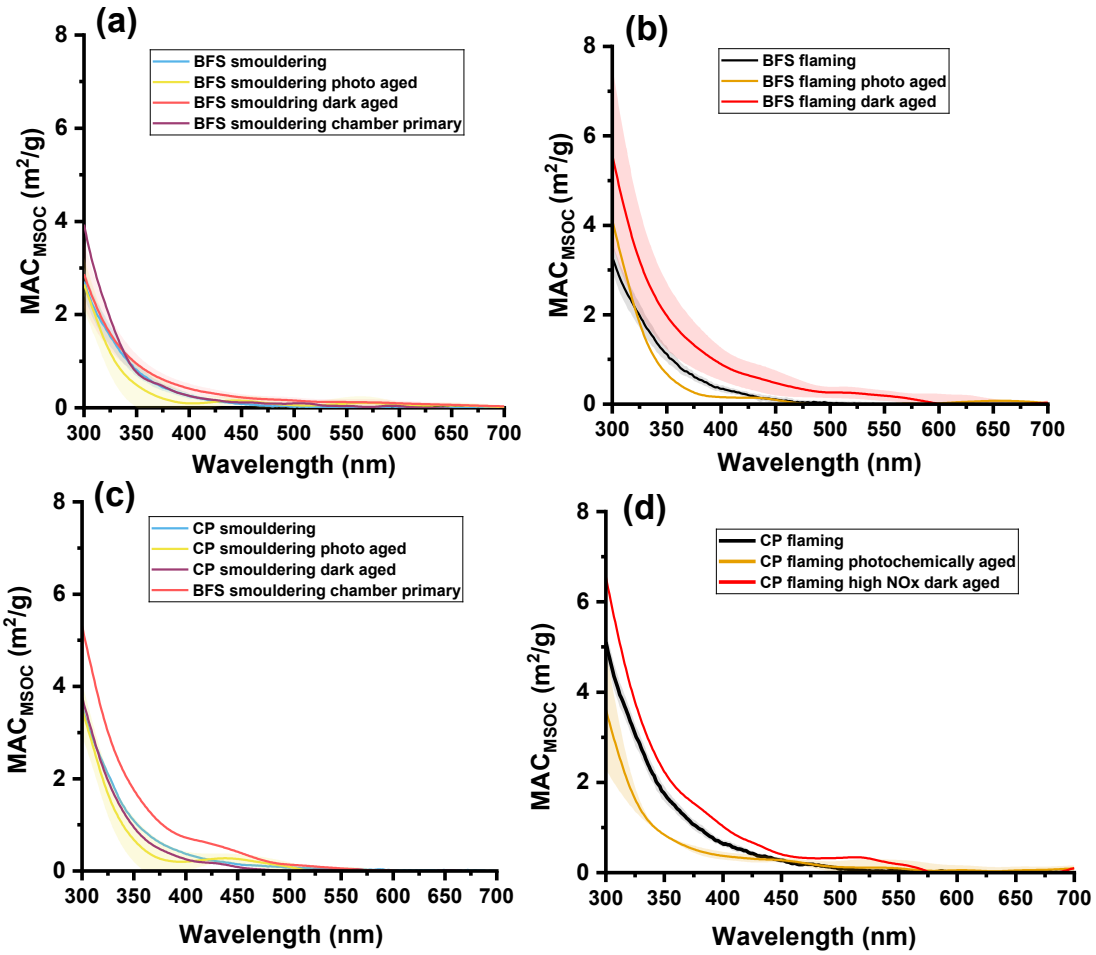

Fig. S19: wavelength dependence of MAC_{MSOC} for (a-b) BFS and (c-d) CP smouldering and flaming emissions. Here we have compared MAC_{MSOC} of fresh emission (black) with photochemically (yellow for smouldering, orange for flaming) and dark aged emission (light red for smouldering and dark red for flaming) 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)**	**moisture (%)**	**composition information (C/N/S/H) %**	**sample mass (g)**	
Boreal Forest Surface (BFS)	62.485098”N, 27.491264”E (Kiviniemi)	8.2-16.1	50.5/1.19/0.11/5.45	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

Component	*Formula*	*Calibration range*	*Unit*	*VOC group*
Water vapor	H2O	20	%	
Carbon dioxide	CO2	25	%	
Carbon monoxide	CO	5000	ppm	
	CO	10000	ppm	
Nitrous oxide	N2O	200	ppm	
Nitrogen monoxide	NO	1000	ppm	
Nitrogen dioxide	NO2	200	ppm	
Sulfur dioxide	SO2	1000	ppm	
Carbonyl sulfide	COS	100	ppm	
Ammonia	NH3	500	ppm	
Hydrogen chloride	HCl	200	ppm	
Hydrogen cyanide	HCN	100	ppm	
Hydrogen fluoride	HF	100	ppm	
Oxygen	O2	25	%	
Methane	CH4	1000	ppm	Methane
Ethane	C2H6	100	ppm	Aliphatic hydrocarbon
Propane	C3H8	100	ppm	Aliphatic hydrocarbon
Butane	C4H10	100	ppm	Aliphatic hydrocarbon
Pentane	C5H12	100	ppm	Aliphatic hydrocarbon
Hexane	C6H14	100	ppm	Aliphatic hydrocarbon
Heptane	C7H16	100	ppm	Aliphatic hydrocarbon
Octane	C8H18	100	ppm	Aliphatic hydrocarbon
Acetylene	C2H2	500	ppm	Aliphatic hydrocarbon
Ethylene	C2H4	500	ppm	Aliphatic hydrocarbon
Propene	C3H6	500	ppm	Aliphatic hydrocarbon
1,3-Butadiene	C4H6	500	ppm	Aliphatic hydrocarbon
Benzene	C6H6	500	ppm	Aromatic
Toluene	C7H8	100	ppm	Aromatic
m-Xylene	C8H10	100	ppm	Aromatic
o-Xylene	C8H10	200	ppm	Aromatic
p-Xylene	C8H10	100	ppm	Aromatic
1,2,3-Trimethylbenzene	C9H12	100	ppm	Aromatic
1,2,4-Trimethylbenzene	C9H12	100	ppm	Aromatic
1,35-Trimethylbenzene	C9H12	100	ppm	Aromatic
Phenol	C6H6O	200	ppm	Aromatic
Furan	C4H4O	200	ppm	Aromatic
Furfural	C5H4O2	200	ppm	Aromatic
Formic acid	CH2O	100	ppm	Non-aromatic oxygenated
Acetic acid	C2H4O2	200	ppm	Non-aromatic oxygenated
Formaldehyde	CHOH	500	ppm	Non-aromatic oxygenated
Acetaldehyde	C2H4O	100	ppm	Non-aromatic oxygenated
Methanol	CH4O	200	ppm	Non-aromatic oxygenated
Ethanol	C2H6O	200	ppm	Non-aromatic oxygenated
Propanol	C3H8O	100	ppm	Non-aromatic oxygenated
Methyl tert-butyl ether (MTBE)	C5H12O	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	**fresh emission (% of total)**
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	**chamber diluted primary (% of total)**
						14.3			OC2	
						37.0			OC3	
						10.8			OC4	
						20.7			PC	
						5.10			EC	
	6.90		5.20		13.0			4.73	OC1	**photo aged in chamber (% of total)**
	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	**dark aged in chamber (% of total)**
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	

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: MAC_{λ} and k_{λ} 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	**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	**MAC_{365_MSOC} (m^2/g)**
0.004 ± 0.000	0.004 ± 0.001	0.004	NaN	0.004 ± 0.00	NaN	0.007	0.007±0.001	**k_{550_MSOC} (fresh emission)**
0.88 ± 0.36	0.69 ± 0.13	1.43	NaN	1.45 ± 0.32	NaN	0.78	1.59 ± 0.14	**MAC_{365_WSOC} (m^2/g) (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_{550_WSOC} (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**
high NOx dark aged	photo aged	no aging	high NOx dark aged	photo aged	no aging	high NOx dark aged	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	**MAC_{365_MSOC} (m^2/g) (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_{550_MSOC} (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	**MAC_{365_WSOC} (m^2/g) (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_{550_WSOC} (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/cm^3) (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 dark aged	photo aged	low NOx dark aged	photo aged	low NOx dark aged	photo aged	low NOx dark aged	photo aged	no aging	high NOx dark aged	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

References:

1. Schneider, E., Rüger, C. P., Chacón-Patiño, M. L., Somero, M., Ruppel, M. M., Ihalainen, M., Köster, K., Sippula, O., Czech, H., & Zimmermann, R. (2024a). The complex composition of organic aerosols emitted during burning varies between Arctic and boreal peat. *Communications Earth and Environment*, *5*(1). https://doi.org/10.1038/s43247-024-01304-y