

Supplementary materials:

The effect of the wood species on fine particle and gaseous emissions from modern wood stove

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1. Measurement of fuel density

There is no standard method for the measurement of density of firewood logs. In this work, we used a new method to measure the density of wood logs by measuring the mass and volume of the pieces of firewood logs by dipping them into the fully filled beaker. We measured both the dry and wet mass of the wood log and subtracted from wet to dry mass to calculate the water mass sucked into the log. We also measured the mass of overflow water and residual water in the beaker after the wood log is soaked and taken out of the beaker. Then, we calculated actual mass of wood log by subtracting residual water mass and water mass sucked into the log from the full volume of the water mass in the beaker, which is the volume of wood log. Finally, the density of the wood log is calculated by dividing the wood volume by the dry mass of wood.

2. Supplementary tables

A schematic of the test procedure and wood species used in tests are presented in Table S1. Ash content, volatile substances and the chemical characteristics of wood species are presented in Table S2, Limit values in Table S3 and PAH concentrations in Table S4.

Table S1. A schematic of the test procedure and wood species used in the tests.

Experiment	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6
1	BirchA1	Pine	Pine	Pine	Pine	Pine
2	BirchA1	Spruce	Spruce	Spruce	Spruce	Spruce
3	BirchA1	Alder	Alder	Alder	Alder	Alder
4	BirchA1	BirchA	BirchA	BirchA	BirchA	BirchA
5	BirchA1	Pine	Pine	Pine	Pine	Pine
6	BirchA1	BirchB	BirchB	BirchB	BirchB	BirchB
7	BirchA1	SpruceDry	SpruceDry	SpruceDry	SpruceDry	SpruceDry
8	BirchA1	Spruce	Spruce	Spruce	Spruce	Spruce
9	BirchA1	Alder	Alder	Alder	Alder	Alder
10	BirchA1	BirchA	BirchA	BirchA	BirchA	BirchA
11	BirchA1	BirchB	BirchB	BirchB	BirchB	BirchB

The combustion started always with BirchA ignition batch (named BirchA1). The ignition batch consisted of 3 logs of 500 ± 20 g, 3 logs of 333 ± 20 g, and 5 logs of 100 g and two fire starter bites of approximately 10 g per bite. The subsequent batches consisted of three wood logs. Log sizes were 500 g for BirchA, 485 g for BirchB, 500 g for Alder, 515 g for Pine, 515 g for Spruce and 450 g for SpruceDry.

Table S2. Characteristics of fuel properties.

Analysis	Unit	BirchA	BirchB	Alder	Pine	Spruce
Ash content (550 °C) ¹	%,dry	0,4	0,4	0,7	0,3	0,6
Volatile substances ²	%,dry	87,6	86,4	84,3	84,1	83,2
Carbon ³	%,dry	50,4	50,3	50,5	51,5	51,5
Hydrogen ³	%,dry	6,1	6,0	6,0	6,0	5,9
Nitrogen ³	%,dry	0,24	0,27	0,49	0,25	0,31
Chloride ⁴	%,dry	0,003	0,004	0,002	0,002	0,005
Fluride ⁵	%,dry	<0,001	<0,001	<0,001	<0,001	<0,001
Bromine ⁶	%,dry	<0,001	<0,001	<0,001	<0,001	<0,001
Calcium	mg/kg	910	660	1400	760	1300
Magnecium	mg/kg	180	310	220	190	130
Sodium	mg/kg	<50	<50	<50	<50	<50
Potassium	mg/kg	520	720	1300	450	740
Phosphorus	mg/kg	98	130	350	75	120
Sulphur	mg/kg	78	88	230	69	110
Iron	mg/kg	<30	<30	<30	<30	33
Aluminum	mg/kg	< 100	< 100	< 100	< 100	< 100
Silicon	mg/kg	<400	<400	<400	<400	<400
Titanium	mg/kg	<50	<50	<50	<50	<50
Manganese	mg/kg	110	29	9,8	68	63
Barium	mg/kg	21	5	19	2,4	52
Zinc	mg/kg	46	33	16	6,6	17
Coppur	mg/kg	<2	<2	<2	<2	<2
Vanadium	mg/kg	<2	<2	<2	<2	<2
Lead	mg/kg	<2	<2	<2	<2	<2
Chromium	mg/kg	<2	<2	<2	<2	<2
Nickel	mg/kg	<1	<1	<1	<1	<1

Analyses are defined by the standards: ¹SFS-EN ISO 18122; ²SFS-EN ISO 18123; ³SFS-EN ISO 16948; ⁴SFS-EN ISO 16994 mod.; ⁵SFS-EN ISO 16995 mod.; ⁶SFS-EN ISO 16996 mod.; Other components are defined by the three standards: SFS-EN ISO 11885:2009, SFS-EN ISO 16967:2015 mod. and SFS-EN ISO 16968:2015 mod.

Table S3. The limit values of PM, CO, NOx and OGC compared to EU Ecodesign, German Blue Angel and Italian star limits (IEA, 2022). Values are normalized to 1 atm, 20 °C, 13% O₂ (originally are at 0 °C).

	CO	OGC	NO _x	PM
Ecodesign	1398	112	186	37
Blue Angel	466	65	168	14
Italian 4-star	1165	65	149	28
Italian 5-star	606	33	93	23

Reference:.

IEA 2022: https://task32.ieabioenergy.com/wp-content/uploads/sites/24/2022/10/NationalStrategies_Report-final.pdf.

Italian regional restrictions: Starting from 2018, four Regions (Lombardia, Piemonte, Veneto, Emilia-Romagna) introduced the “Po basin agreement” with restrictions for domestic heating appliances and boilers up to 35 kW. In this agreement the rules are given for assignation of the number of classes (“Stars”) that each appliance will be allocated depending on results reported in the certificate of type testing, measured at nominal power output. From January 2020 only appliances with more than “4-Stars” can be installed.

The Blue Angel (German Ecolabel) for stoves (DE-UZ 212) aims to encourage innovation in the sector and promote new developments in the design of stoves for the improvement of air quality. This will be achieved using equipment to lower emissions for an efficient and controlled combustion process with a significant reduction in the emission of particulate matter and other flue gases in comparison to conventional stoves.

Table S4. Average PAH concentrations (normalized to 1 atm, 20 °C, 13% O₂ ±sd) measured from the combustion of different wood species.

Compound	BirchA1	BirchA	BirchB	Alder	Pine	Spruce	SpruceDry
Acenaphthylene	1.7±1.0	1.3±0.9	1.1±0.8	4.6±4.1	0.4±0.3	1.6±1.0	3.3±1.6
Acenaphthene	bdl	bdl	bdl	0.9	bdl	bdl	bdl
Fluorene	2.3±0.8	2.4±2.1	2.0±0.9	8.0±10.4	0.5±0.5	1.7±1.0	4.8±2.9
Phenanthrene	16.5±25.2	2.9±0.9	3.9±1.5	12.5±8.9	3.3±1.4	1.8±0.9	15.2±12.1
Anthracene	63.7±116.2	11.9±2.8	9.2±7.0	16.9±19.0	2.2±1.1	10.6±6.8	14.0±9.4
1-Methylphenanthrene	0.3	bdl	1.0±0.7	3.9±1.7	1.1±0.5	bdl	3.1±0.5
Fluoranthene	20.7±16.7	10.5±4.0	24.1±11.2	55.2±41.5	29.4±26.7	5.1±1.9	95.8±102.9
Pyrene	36.9±46.9	13.6±4.9	25.2±10.1	60.5±46.1	34.5±25.2	6.6±2.4	101.1±115.4
Benzo[c]phenanthrene	7.9±9.5	3.5±0.0	4.9±1.6	16.9±13.5	6.4±4.5	5.6±2.7	28.5±23.4
Benzo[a]anthracene	21.7±28.9	9.9±2.6	26.2±23.3	67.7±50.1	24.3±16.4	21.5±16.0	86.6±87.8
Cyclopenta[c,d]pyrene	33.9±62.2	3.0±1.1	22.4±40.9	80.1±77.3	13.0±11.9	14.5±19.0	87.6±115.7
Triphenylene	3.0±2.9	1.8±0.5	4.1±3.5	12.7±8.5	3.9±6.0	5.4±3.0	12.0±9.9
Chrysene	20.5±25.4	10.3±2.6	27.6±20.8	72.5±51.8	24.1±15.5	25.8±17.5	74.1±70.2
5-Methylchrysene	0.7	bdl	0.7±0.2	1.7±0.5	0.4±0.5	1.7±	3.6±2.7
Benzo[b]fluoranthene	27.7±38.9	7.8±2.0	26.2±21.5	84.1±54.1	16.6±12.4	33.8±27.7	73.7±58.7
Benzo[k]fluoranthene	15.4±19.2	4.4±1.1	18.3±15.5	42.9±23.2	16.8±15.4	20.2±20.3	52.3±46.4
Benzo[j]fluoranthene	19.0±30.9	3.8±1.1	17.2±10.9	66.1±43.7	12.6±9.9	24.1±24.4	58.4±50.8
Benzo[e]pyrene	20.6±28.6	6.0±1.7	19.7±17.3	66.8±43.6	12.3±8.8	25.2±22.1	52.7±41.8
Benzo[a]pyrene	24.3±34.9	5.7±1.8	25.2±33.8	81.3±58.8	18.6±15.8	20.0±25.1	88.1±87.9
Perylene	6.2±8.6	bdl	4.8±5.2	13.5±9.3	2.8±2.5	5.6±6.0	15.1±11.2
Indeno[1,2,3-cd]pyrene	27.9±37.0	5.2±2.4	23.5±27.9	76.7±48.0	13.4±11.3	29.4±30.6	67.5±52.9
Dibenzo[a,h]anthracene	4.2±5.5	0.7±0.1	3.1±3.6	9.2±6.4	3.6±2.1	3.4±4.0	12.7±9.3
Benzo[g,h,i]perylene	29.3±37.9	6.6±2.9	27.3±30.0	85.3±54.2	13.0±11.6	30.6±30.8	66.0±48.7
Anthanthrene	4.2±4.2	bdl	5.2±5.4	5.8±3.6	8.8±6.4	bdl	10.0±12.3
Dibenzo[a,l]pyrene	14.3±7.3	bdl	13.6±18.1	31.3±20.0	2.3±2.2	20.9±24.5	31.3±14.9
Dibenzo[a,e]pyrene	10.5	bdl	3.6±4.9	12.6±6.2	4.3±2.5	11.5±	11.7±8.5
Coronene	12.9±14.2	2.5±1.0	11.9±14.3	29.5±18.2	10.2±12.1	12.2±11.6	22.2±14.1
Dibenzo[a,i]pyrene	3.4	bdl	bdl	bdl	bdl	bdl	bdl
Dibenzo[a,h]pyrene	bdl	bdl	bdl	bdl	1.9±1.2	bdl	bdl
Sum of PAHs	416±376	107±31	285±168	1005±674	250±199	309±280	1065±1004
Genotoxic PAHs	296±395	76±24	247±171	907±621	215±173	287±282	927±870

bdl = below detection limit.

Sum of genotoxic PAH compounds is calculated based on WHO's classification (WHO 1998) were calculated.

Reference:.

World Health Organization (WHO). Selected Non-heterocyclic Polycyclic Hydrocarbons. In WHO International Programme on Chemical Safety (IPCS); Environmental Health Criteria 202; WHO: Geneva, Switzerland, 1998.

3. Supplementary figures

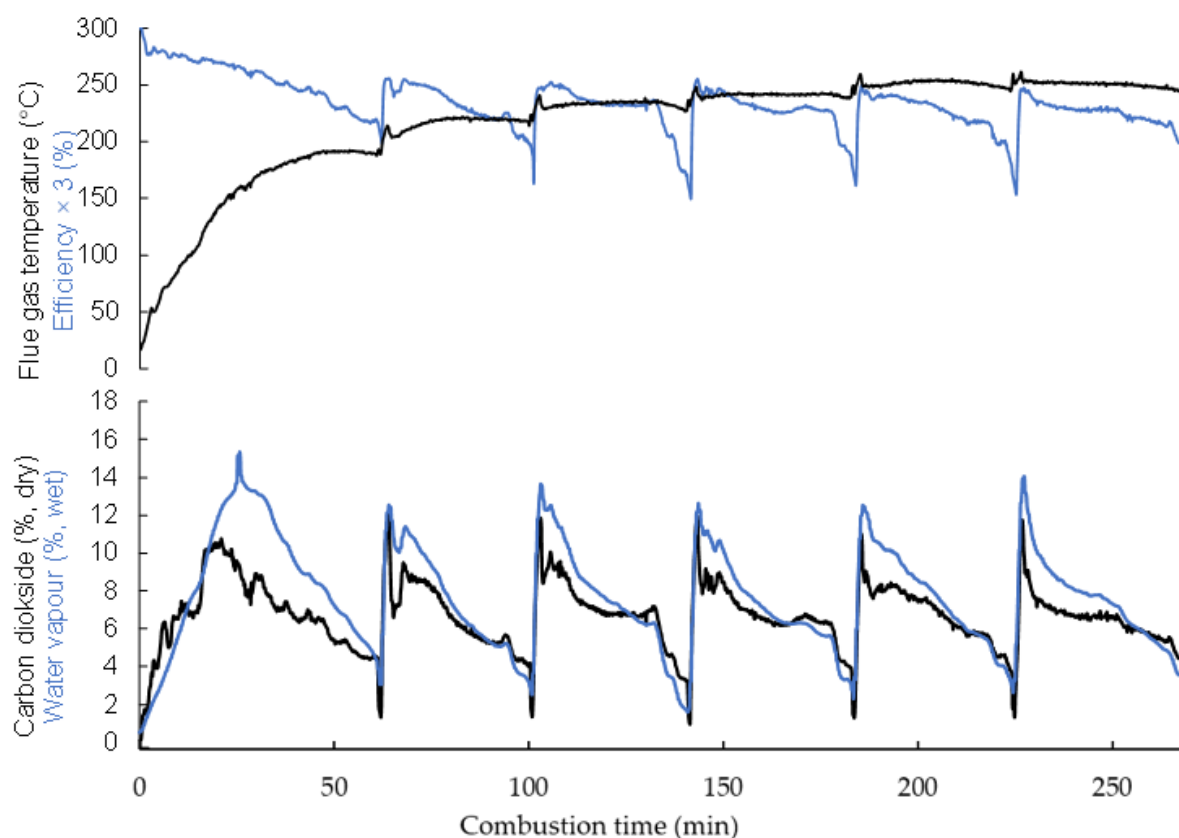


Figure S1. Description of combustion process. Flue gas temperature, efficiency, and CO₂ and H₂O concentrations from BirchA experiment.

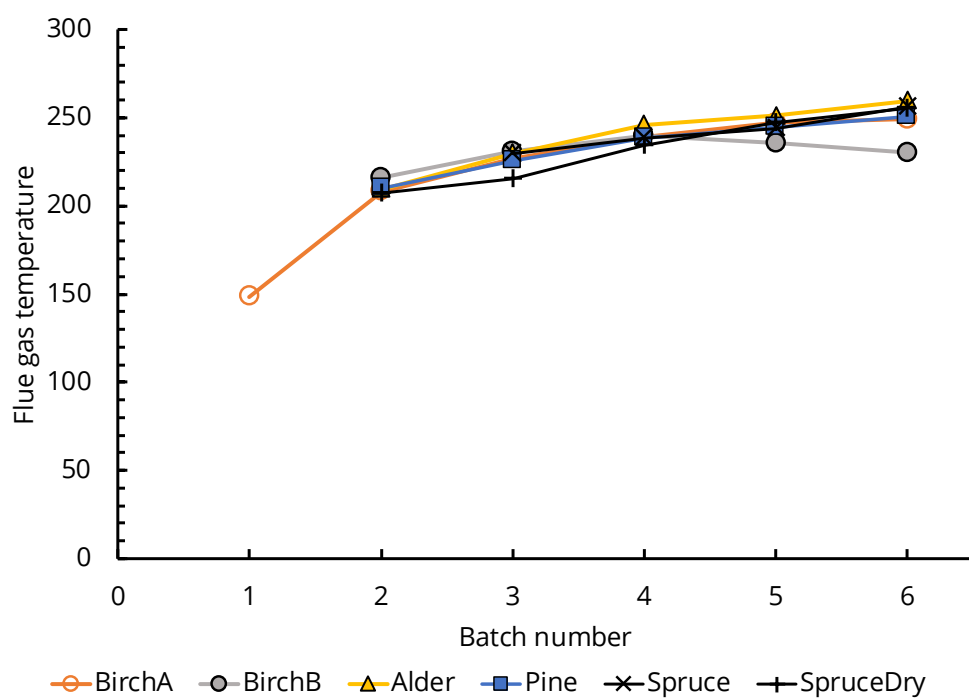


Figure S2. Evolution of flue gas temperature (°C) from batch to batch from combustion of different wood species (average values in each batch).

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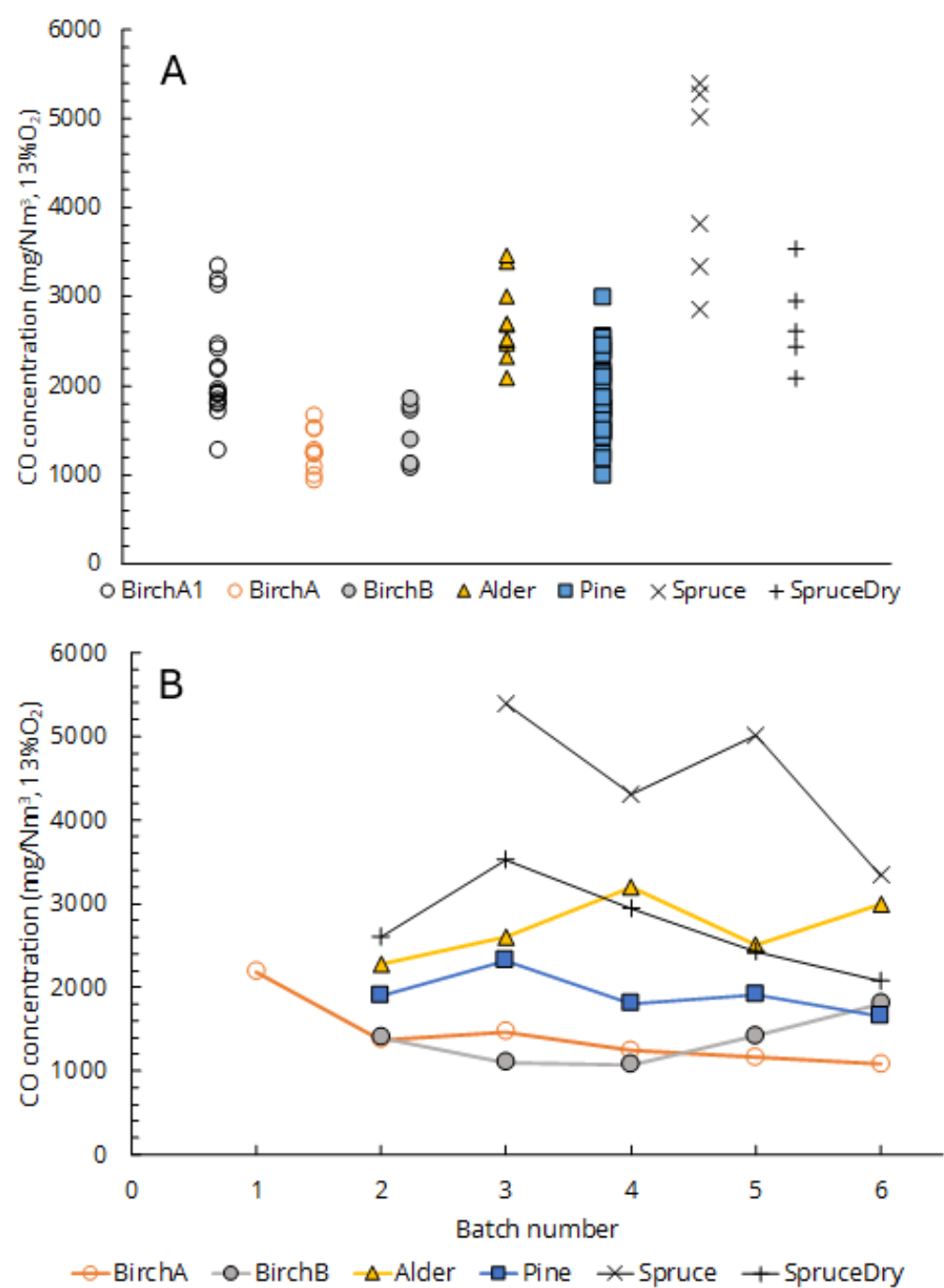


Figure S3. Average CO concentrations (are normalized to 1 atm, 20 °C, 13% O₂) from each investigated batch (A) and evolution of CO concentrations (average values in each batch) from batch to batch (B).

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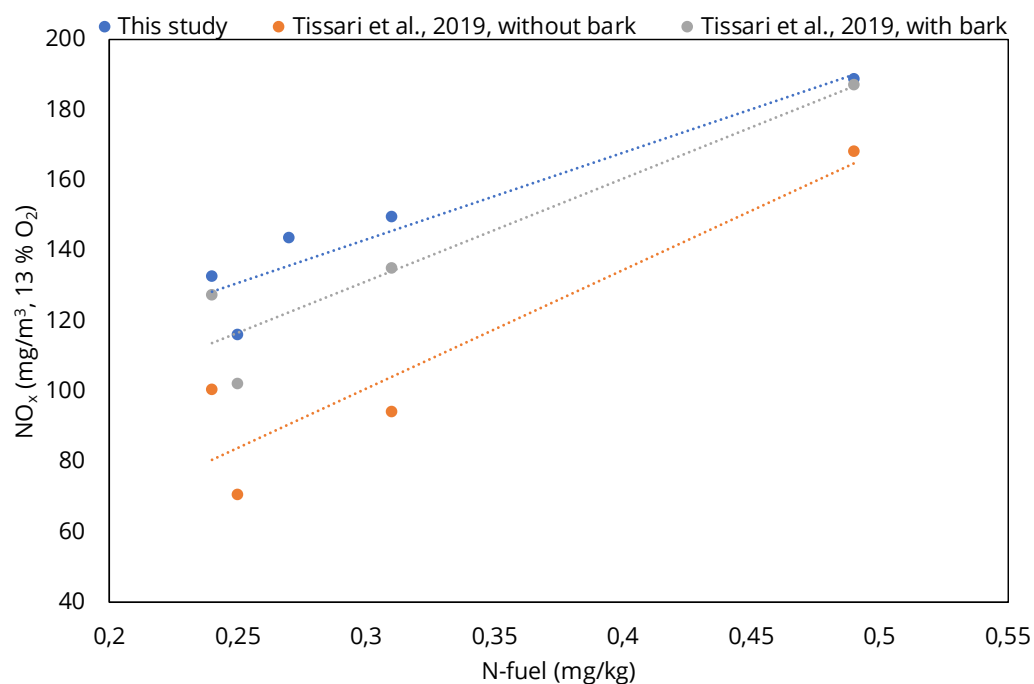


Figure S4. Correlation between fuel-N content and NO_x concentration in this study and in Tissari et al. (2019).

Reference:

Tissari, J.; Väättäinen, S.; Leskinen, J.; Savolahti, M.; Lamberg, H.; Kortelainen, M. et al. Fine particle emissions from sauna stoves: Effects of combustion appliance and fuel, and implications for the finnish emission inventory. *Atmosphere* 2019, 10.

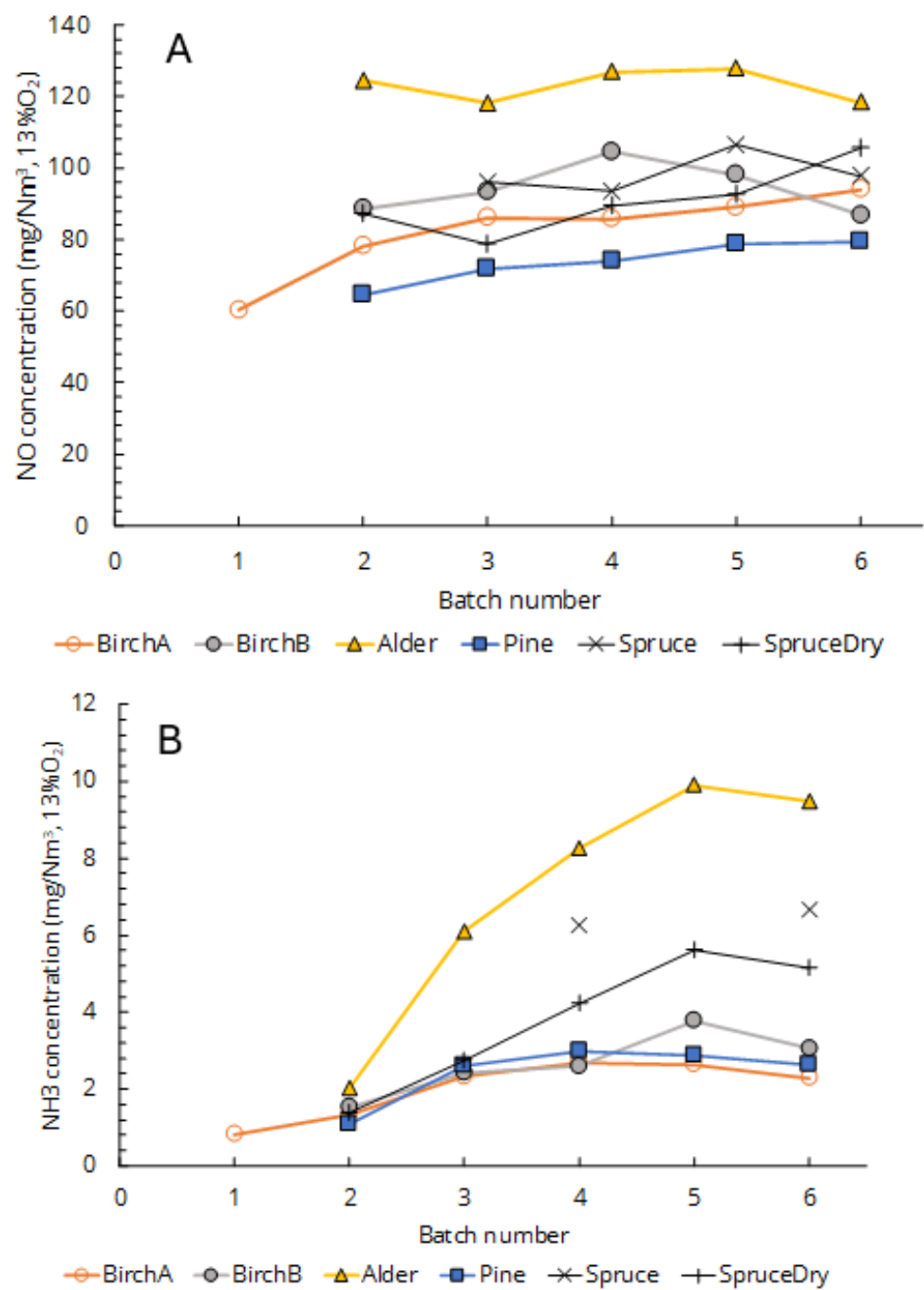


Figure S5. Evolution of NO_x (A) and NH₃ (B) concentrations (normalized to 1 atm, 20 °C, 13% O₂, average values in each batch) from batch to batch.

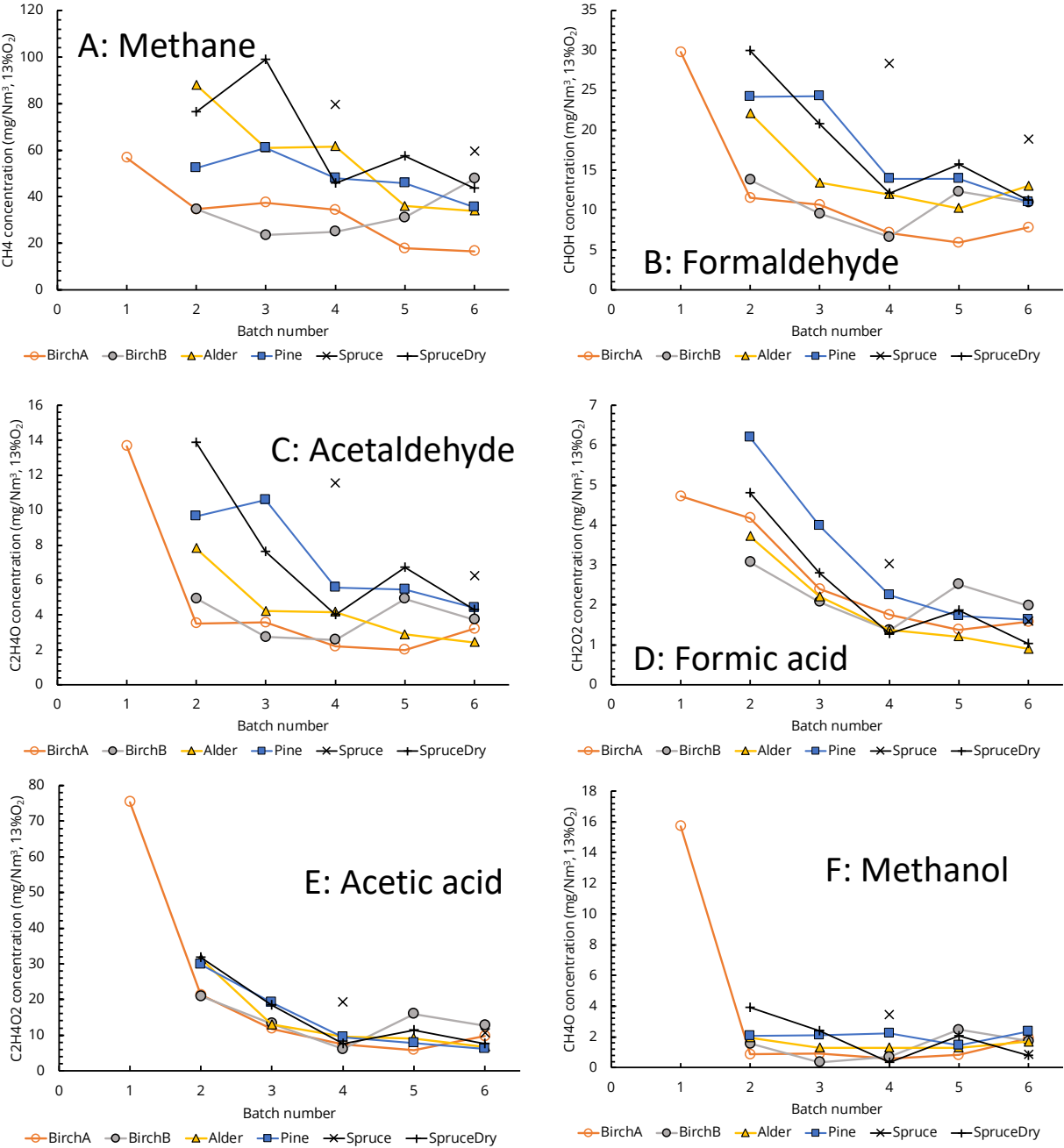


Figure S6. Evolution of VOC concentrations (mg/m³, normalized to 1 atm, 20 °C, 13% O₂) from batch to batch.

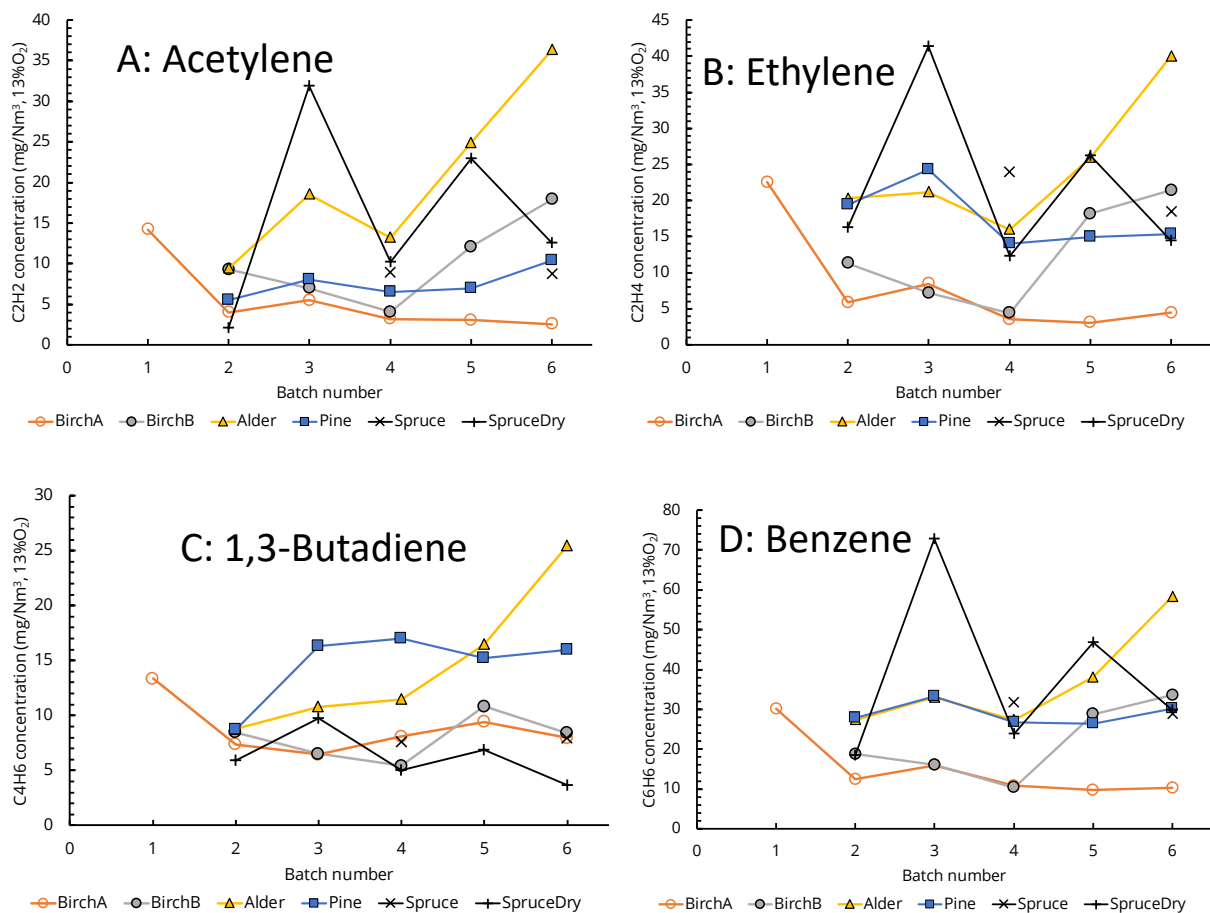


Figure S7. Evolution of VOC concentrations (mg/m³, normalized to 1 atm, 20 °C, 13% O₂) from batch to batch.

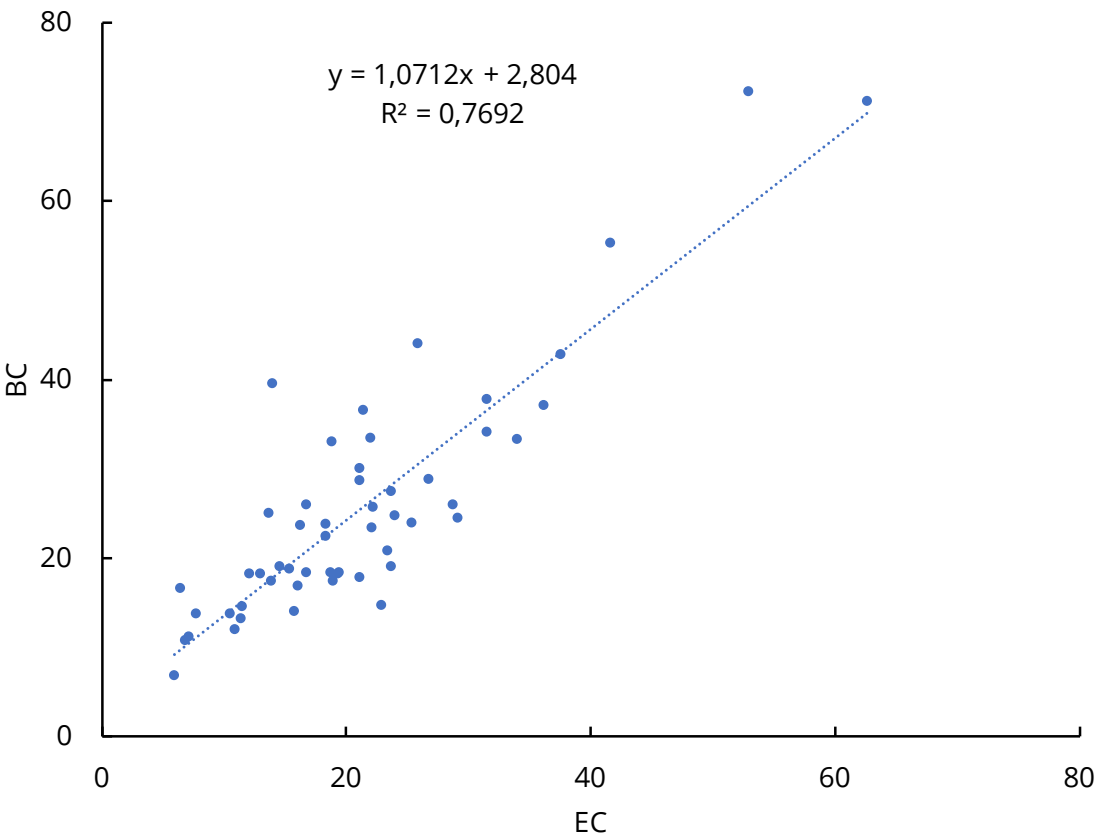


Figure S8. Correlation between eBC and EC with samples from all wood species.

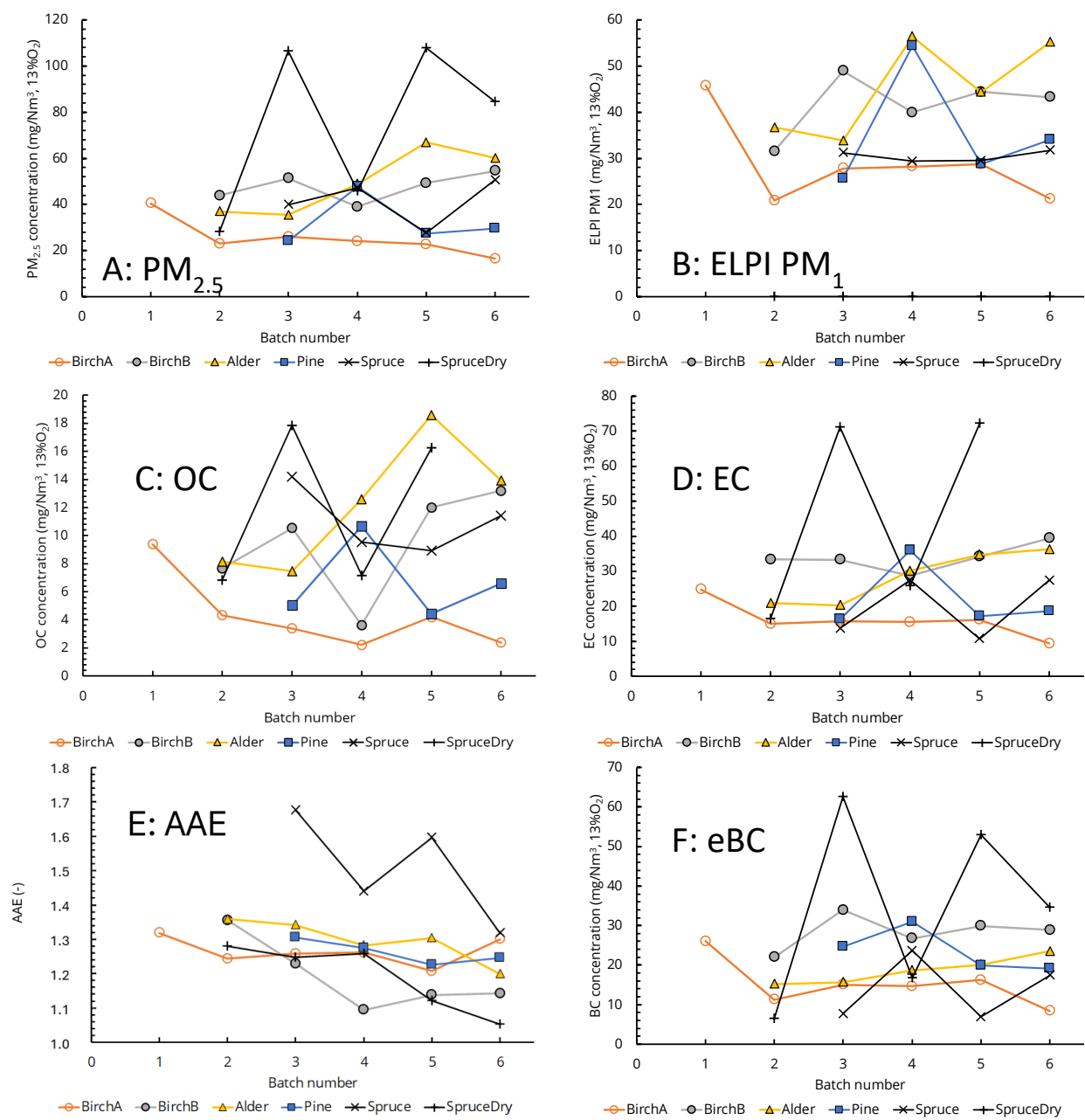


Figure S9. Trends of particulate parameters from batch to batch.

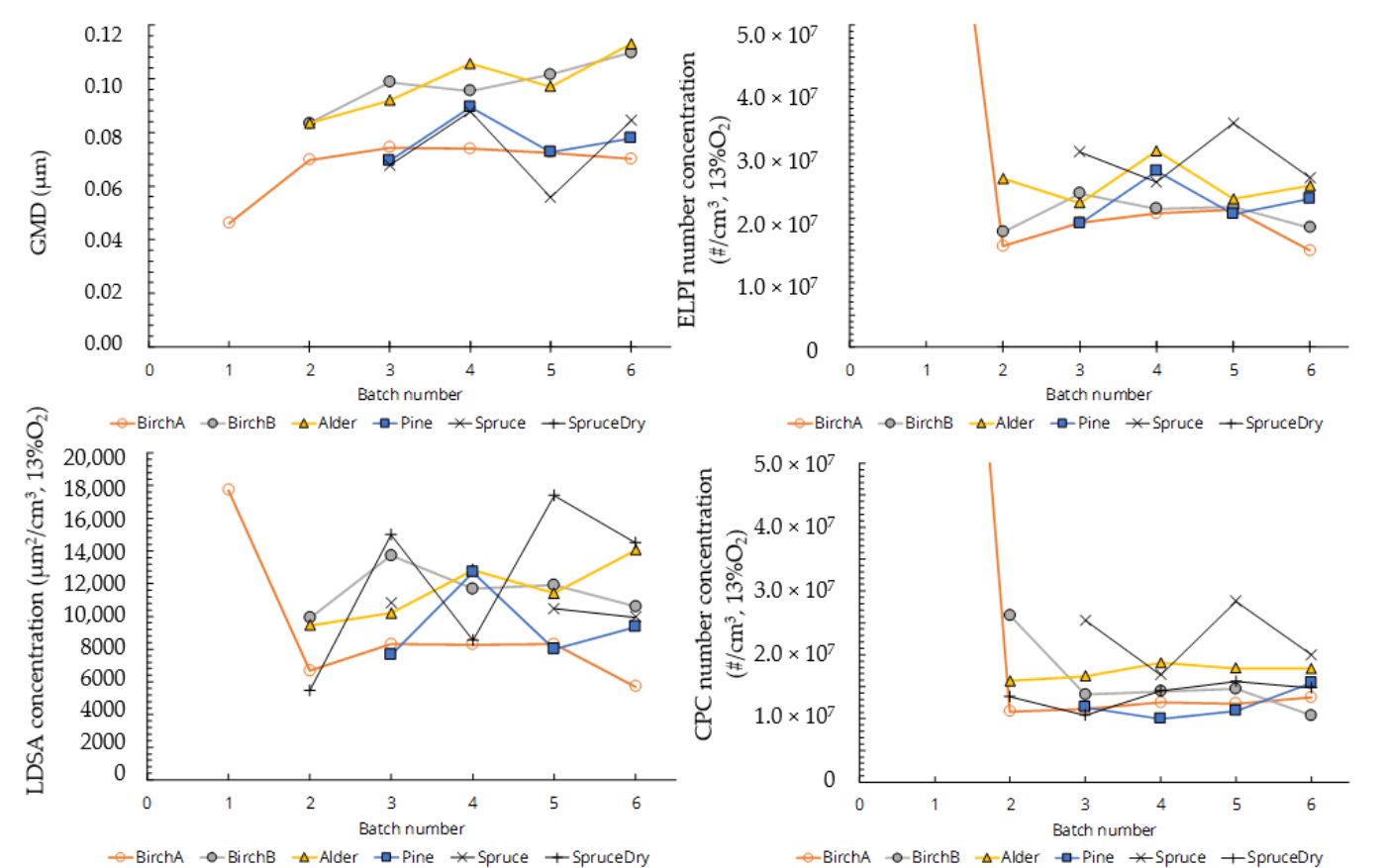


Figure S10. Trends of particulate parameters (GMD (ELPI), number (ELPI and CPC) and LDSA from batch to batch.

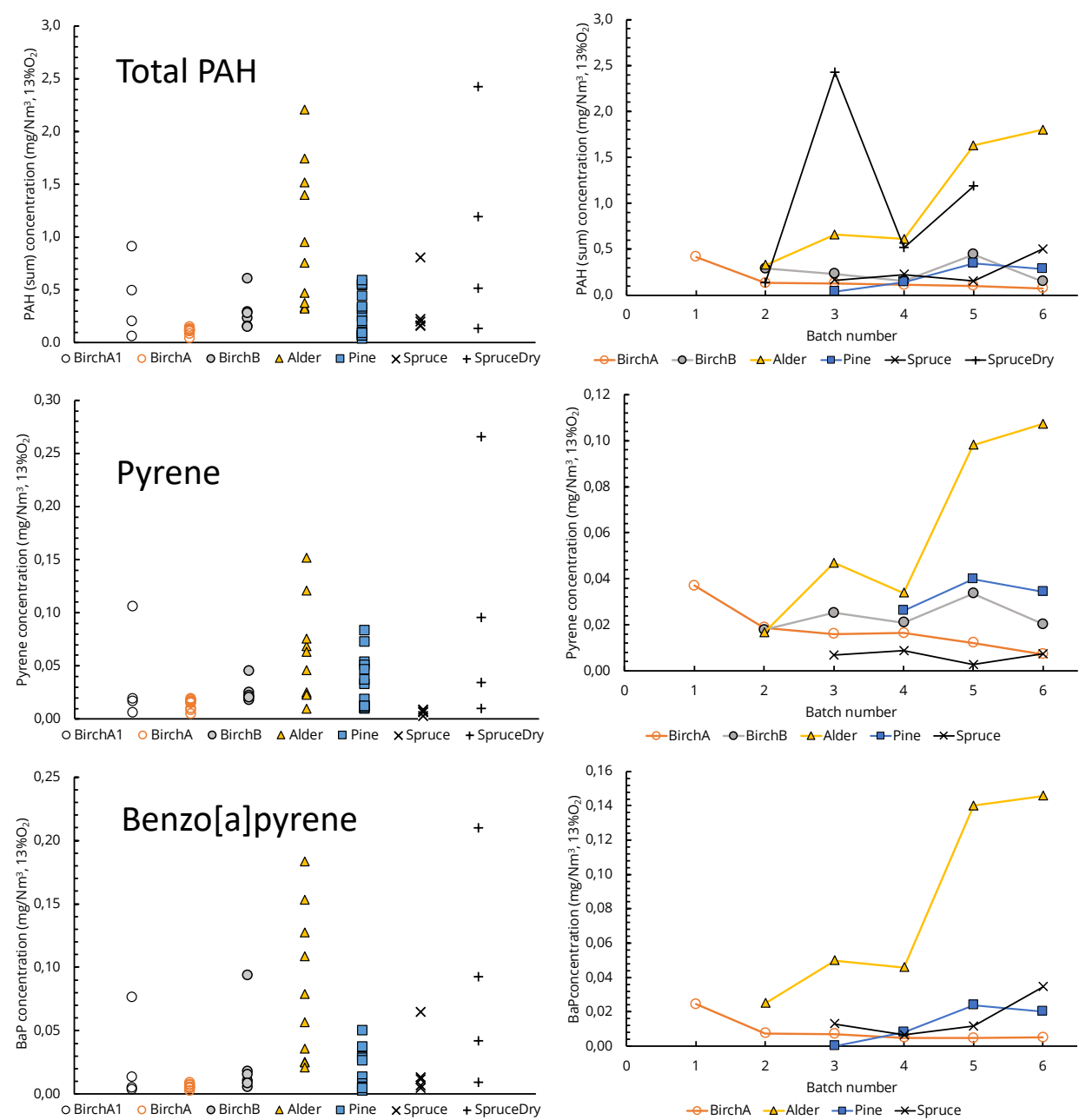


Figure S11A. Average PAH concentrations from each investigated batches (left) and evolution of PAH concentrations from batch to batch (right) of total PAH, pyrene and benzo[a]pyrene.

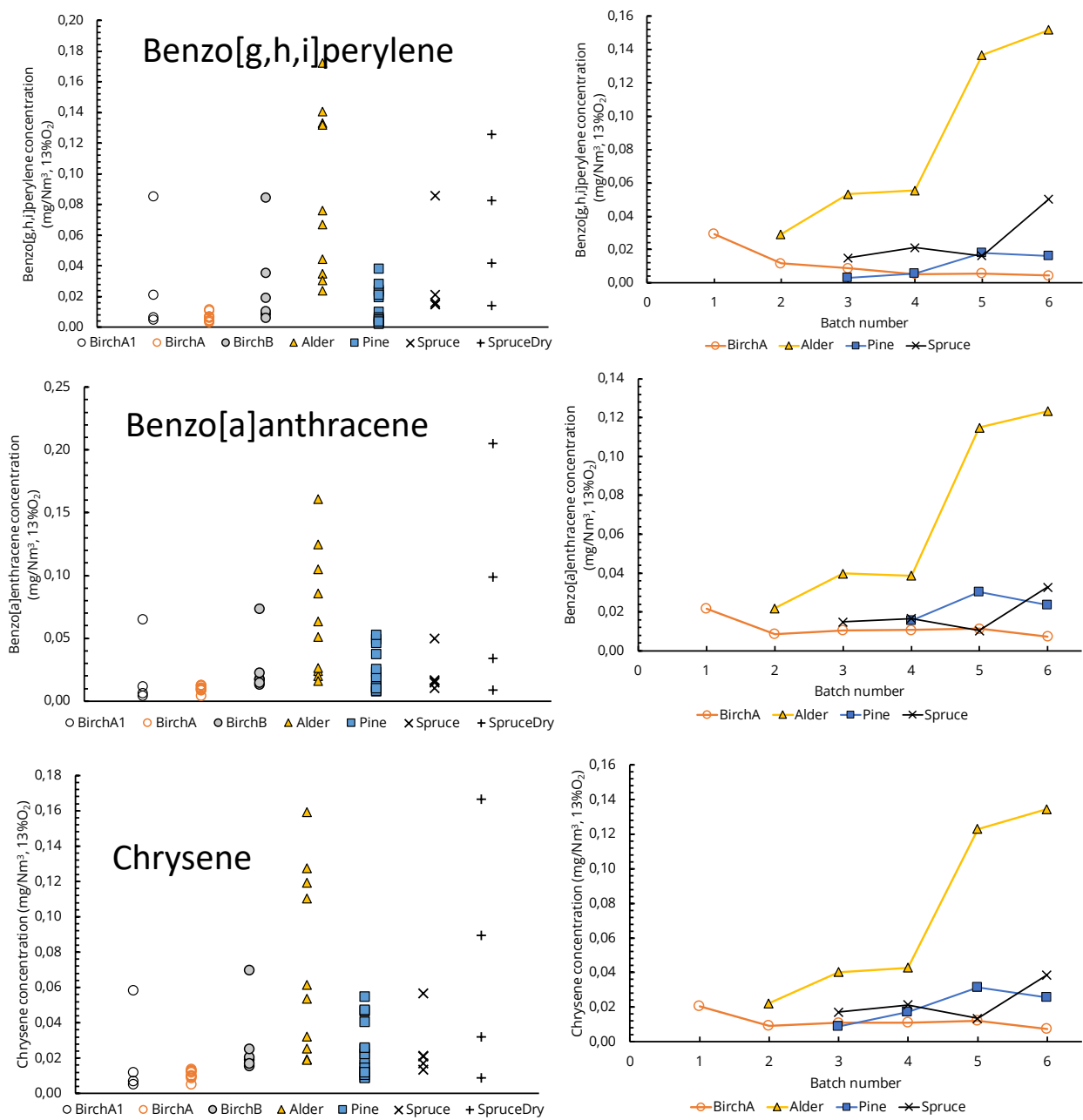


Figure S11B. Average PAH concentrations from each investigated batches (left) and evolution of PAH concentrations from batch to batch (right) of benzo[g,h,i]perylene, benzo[a]anthracene and chrysene.

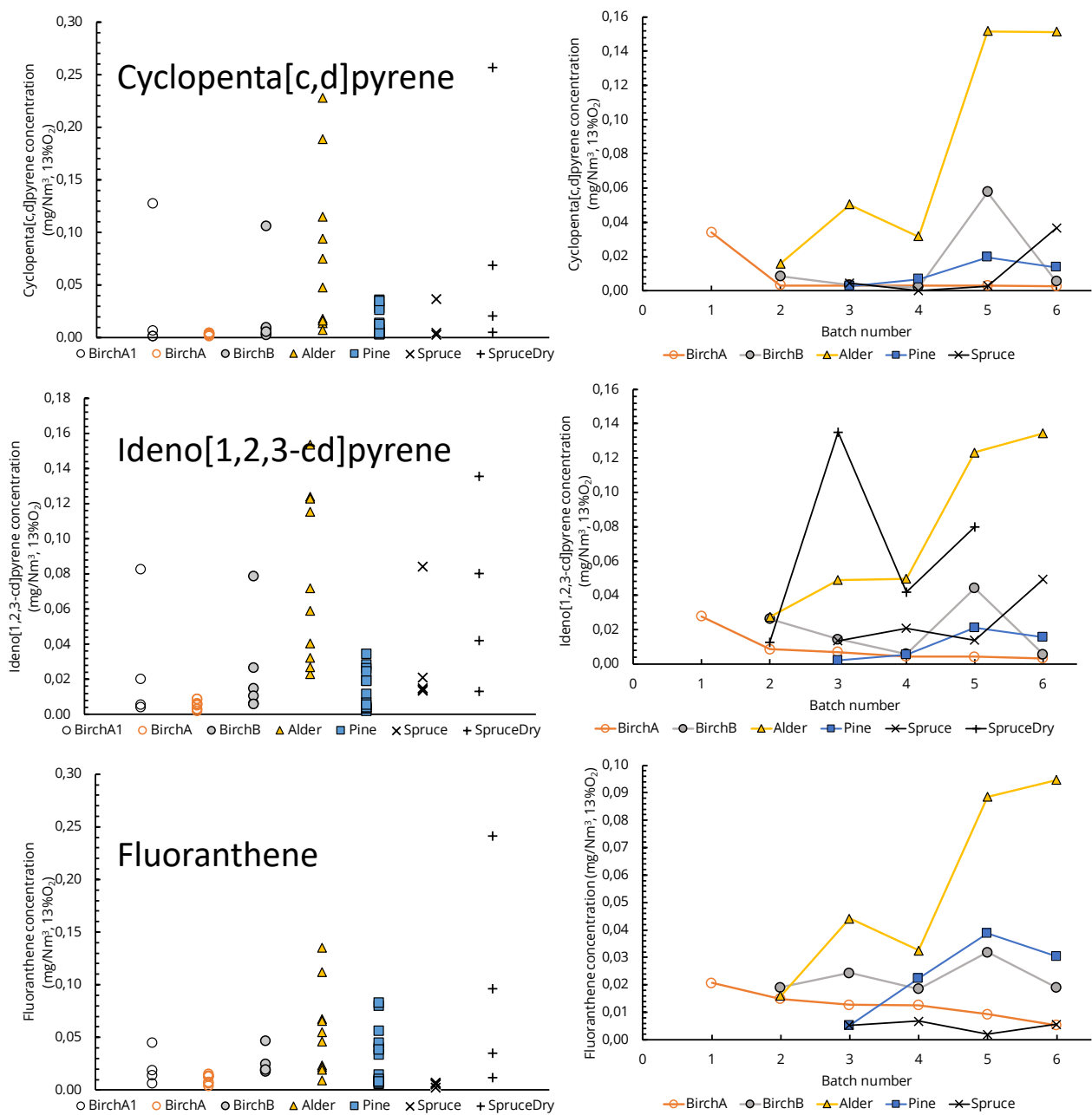


Figure S11C. Average PAH concentrations from each investigated batches (left) and evolution of PAH concentrations from batch to batch (right) of cyclopenta[c,d]pyrene, ideno[1,2,3-cd]pyrene and fluoranthene.

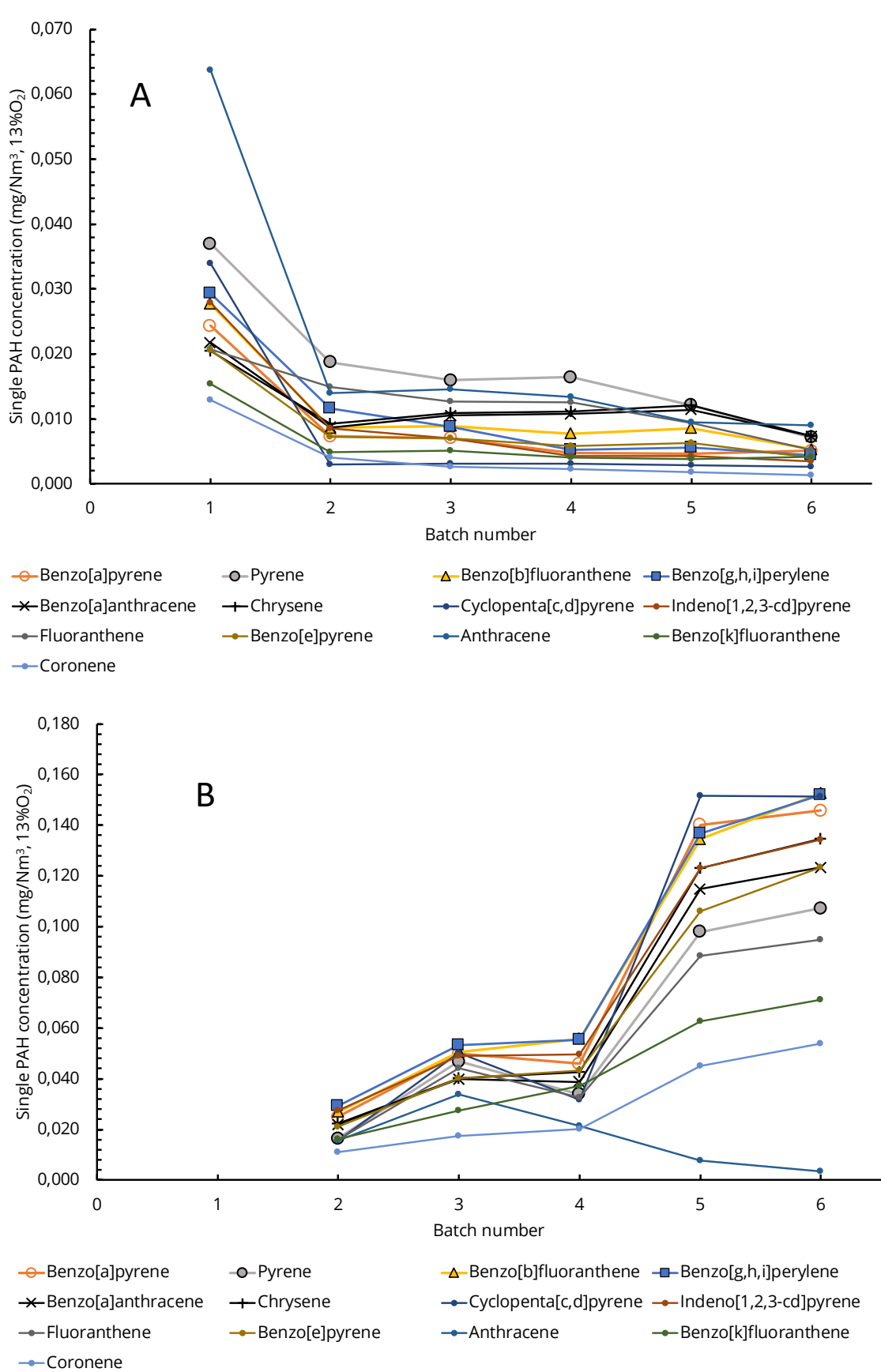


Figure S12. Evolution of concentrations (mg/m³, normalized to 1 atm, 20 °C, 13% O₂) of selected PAH compounds from batch to batch with BirchA (A) and Alder (B).

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Figure S13. A figure of the wood stove used in the experiments.

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