Alkyl-phenanthrenes in early life-stage fish: differential toxicity in Atlantic haddock (*Melanogrammus aeglefinus*) embryos

SUPPLEMENTAL INFORMATION

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Part I: Exposure Study

Table S1 Retention time (RT) and multiple reaction monitoring (MRM) transitions.. Alkylation varies between no alkyl carbons (C0) on phenanthrene, to 4 alkyl groups (C4) on retene.

Alkyl-ation	Abbrev.	Name	RT (min)	Molar mass (g/mol)	MRM quant	MRM qual
		Phenanthrene-*d10* (internal standard)	15.77	188.3	188 → 160	188 → 184
C0	PHE	phenanthrene	15.84	178.2	178 → 176	178 → 177
C1	3-MP	3-methylphenanthrene	18.06	192.3	192 → 191	191 → 189
	2-MP	2-methylphenanthrene	18.10			
	4-MP 9-MP	4-methylphenanthrene 9-methylphenanthrene	18.54			
	1-MP	1-methylphenanthrene	18.63			
C2	3-EP	3-ethylphenanthrene	19.83	206.3	206 → 191	191 → 189
	3,6-DMP	3,6-dimethylphenanthrene	20.17		206 → 189	206 → 191
	2,7-DMP	2,7-dimethylphenanthrene	20.41			
	1,7-DMP	1,7-dimethylphenanthrene	20.89		206 → 191	206 → 189
	2,3-DMP	2,3-dimethylphenanthrene	21.01			
	1,4-DMP	1,4-dimethylphenanthrene	21.13			
C3	3-PP	3-propylphenanthrene	21.57	220.3	191 → 189	191 → 165
C4	RET	retene (1-methyl-7-isopropylphenanthrene)	23.93	234.1	219 → 202	219 → 189

Table S2 Complete results from Batches 1 and 2. . Mean (± SD). Because we used the Bonferroni method to correct for multiple comparisons, the effect of including dilution treatments groups lowered several endpoints to below the threshold for significance, explaining small discrepancies between Fig 3 and these data. *Water concentrations are the average of all days, all replicates.

	batch	Batch 1 (2018)												Batch 2 (2018)		
	compound	**PHE**					**4-MP**				**1,4-DMP**			**3-EP**	**3-PP**	**RET**
	dilution	S	S/3	S/9	S/27	S/81	S	S/3	S/9	S/27	S	S/3	S/9	S	S	S
	alkylation	C0	C0	C0	C0	C0	C1	C1	C1	C1	C2	C2	C2	C2	C3	C4
µg/L	**water conc.* Mean (st dev)**	184 (77)	105 (38.8)	30.0 (11.5)	10.8 (3.20)	3.40 (1.26)	177 (106)	117 (17.1)	43.2 (26.8)	7.75 (4.71)	43.1 (21.39	18.3 (9.68)	5.95 (3.53)	38.2 (21.0)	7.01 (3.04)	2.30 (0.974)
	n, body burden	2	2	3	3	3	3	3	1	3	2	2	3	1	1	1
ng/ind.	**body burden (st dev)**	155 (31.7)	111 (25.3)	38.0 (3.83)	17.9 (5.64)	4.60 (0.577)	245 (23.2)	176 (4.93)	111 (na)	25.1 (0.835)	107 (3.14)	49.9 (1.58)	17.7 (4.19)	57.9 (na)	21.1 (na)	2.80 (na)
µg/g ww	**body burden (st dev)**	71.1 (14.6)	51.1 (11.6)	17.4 (1.76)	7.78 (2.58)	2.11 (0.264)	113 (10.6)	80.7 (2.26)	51.0 (na)	11.5 (0.383)	48.9 (1.44)	22.9 (0.725)	8.13 (1.92)	26.5 (na)	9.69 (na)	1.28 (na)
µmol/ g ww	**body burden (st dev)**	0.400 (0.082)	0.287 (0.065)	0.098 (0.010)	0.044 (0.015)	0.012 (0.001)	0.586 (0.055)	0.420 (0.012)	0.266 (na)	0.060 (0.002)	0.237 (0.007)	0.111 (0.004)	0.039 (0.009)	0.129 (na)	0.044 (na)	0.005 (na)
	cypla expression (st dev)	1.02 (0.345)	1.37 (0.0582)	1.41 (0.360)	1.20 (0.068)	1.42 (0.200)	1.01 (0.112)	1.06 (0.394)	1.13 (0.0918)	1.48 (0.316)	1.39 (0.295)	2.14 (0.264)	2.17 (0.202)	no data	no data	no data
	Mortality	signif.	signif.	--	--	--	--	--	--	--	--	--	--	signif.	signif.	signif.
body	Finfold	--	--	--	--	--	--	--	--	--	--	signif.	signif.	signif.	signif.	--
body	Length	signif.	signif.	--	--	--	signif.	signif.	--	--	signif.	--	--	signif.	--	signif.
body	Yolk area	signif.	--	--	--	--	signif.	signif.	signif.	--	signif.	--	--	--	--	--
body	Yolk sac edema	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
body	Body axis defor.	signif.	signif.	--	--	--	signif.	--	--	--	--	--	--	--	--	--
face	Eye area	signif.	signif.	signif.	signif.	--	signif.	signif.	signif.	--	signif.	--	--	--	signif.	signif.
face	Eye nose distance	--	--	--	--	--	signif.	signif.	signif.	--	signif.	signif.	--	--	--	--
face	Jaw length	signif.	--	--	--	--	signif.	signif.	signif.	--	signif.	signif.	--	signif.	--	signif.
face	Jaw angle	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
face	Eye deformity	--	signif.	--	--	--	signif.	--	--	--	--	--	--	--	--	signif.
face	Jaw deformity	signif.	signif.	--	--	--	signif.	signif.	signif.	--	signif.	--	--	--	--	--
heart	Ventricle area	--	--	--	--	--	signif.	signif.	signif.	--	--	--	--	signif.	--	signif.
heart	AFS	--	--	--	--	--	signif.	--	--	--	--	--	--	--	--	--
heart	VFS	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
heart	silent ventricle	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
heart	Heart rate	--	signif.	--	--	signif.	signif.	signif.	--	--	signif.	signif.	--	signif.	--	signif.

Table S3 Complete results from Batches 3, PD1 and PD2. . Mean (± SD). Because we used the Bonferroni method to correct for multiple comparisons, the effect of including dilution treatments groups lowered several endpoints to below the threshold for significance, explaining small discrepancies between Fig 3 and these data. *Water concentrations are the average of all days, all replicates. Asterisks by *cyp1a* expression values indicate significance from control.

	batch	Batch 3 (2018)								PD1 (2019)						PD2 (2019)			
	compound	**1-MP**	**3-MP**	**9-MP**	**1,7-DMP**	**2,3-DMP**	**2,7-DMP**	**3,6-DMP**	**Si-free Ctrl**	**PHE**			**1,4-DMP**		**Si-free Ctrl**	**2-MP**	**4-MP**		**Si-free Ctrl**
	Dilution	S	S	S	S	S	S	S	--	S	S/3	S/9	S	S/3	--	S	S	S/3	--
	alkylation	C1	C1	C1	C2	C2	C2	C2	QC	C0	C0	C0	C2	C2	QC	C1	C1	C1	QC
µg/L	**water conc.* Mean (st dev)**	22.4 (9.41)	109 (61.3)	37.5 (19.4)	23.8 (13.5)	29.1 (13.9)	10.1 (7.89)	5.20 (3.86)	--	194 (14.9)	59.6 (11.4)	19.0 (2.95)	18.1 (0.617)	16.9 (23.2)	--	197 (21.4)	204 (21.8)	46.1 (5.05)	--
	n, body burden	3	3	3	2	2	3	2	2	3	3	3	3	3	3	3	3	3	3
ng/ind.	**body burden (st dev)**	67.3 (4.76)	224 (37.0)	109 (2.43)	75.8 (6.33)	90.6 (15.8)	46.7 (1.87)	15.6 (4.29)	--	190 (40.2)	53.9 (0.578)	24.4 (1.48)	55.7 (1.39)	24.4 (4.99)	--	146 (16.9)	150 (6.08)	32.7 (2.90)	--
µg/g ww	**body burden (st dev)**	30.9 (2.18)	103 (17.0)	50.0 (1.12)	34.8 (2.90)	41.5 (7.25)	21.4 (0.860)	7.18 (1.87)	--	87.3 (18.4)	24.7 (0.265)	11.2 (0.679)	25.6 (0.636)	11.2 (2.29)	--	66.9 (7.77)	68.6 (2.79)	15.0 (1.33)	--
µmol/g ww	**body burden (st dev)**	0.161 (0.011)	0.535 (0.088)	0.260 (0.006)	0.169 (0.014)	0.202 (0.035)	0.104 (0.004)	0.035 (0.010)	--	0.490 (0.104)	0.139 (0.001)	0.063 (0.004)	0.124 (0.003)	0.124 (0.003)	--	0.349 (0.040)	0.358 (0.105)	0.078 (0.007)	--
	cypla expression (st dev)	3.41 (0.631)	1.92 (0.980)	1.98 (0.494)	2.34 (1.71)	3.01 (0.196)	1.79 (0.556)	4.00 (0.815)	--	1.13 (0.590)	1.56 (1.11)	2.70* (1.24)	2.56* (0.673)	3.17* (1.47)	3.02* (0.96)	1.11 (0.218)	0.876 (0.232)	1.471* (0.289)	1.94* (0.31)
	Mortality	no data	no data	no data	no data	no data	no data	no data	no data	--	--	--	--	--	--	--	--	--	--
body	Finfold	signif.	--	--	signif.	signif.	signif.	--	--	--	--	--	--	--	--	signif.	--	--	signif.
body	Length	--	signif.	--	signif.	signif.	signif.	--	--	signif.	--	--	signif.	signif.	--	signif.	signif.	--	--
body	Yolk area	--	--	--	signif.	--	--	signif.	signif.	--	signif.	signif.	signif.	signif.	signif.	signif.	signif.	signif.	--
body	Yolk sac edema	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
body	Body axis defor.	--	signif.	--	--	--	--	--	--	signif.	--	--	--	--	--	--	signif.	--	--
face	Eye area	--	signif.	--	signif.	signif.	signif.	--	--	signif.	--	--	--	--	--	signif.	signif.	signif.	--
face	Eye nose distance	--	--	--	signif.	signif.	--	--	--	--	--	--	--	--	--	signif.	signif.	--	--
face	Jaw length	signif.	signif.	--	signif.	signif.	--	--	--	--	--	--	--	--	--	signif.	signif.	signif.	--
face	Jaw angle	signif.	signif.	--	signif.	--	--	--	--	--	--	signif.	--	--	signif.	signif.	signif.	--	--
face	Eye deformity	--	--	--	--	signif.	--	--	--	--	--	--	signif.	signif.	--	signif.	signif.	--	--
face	Jaw deformity	--	signif	--	signif	signif	--	--	--	--	--	--	--	--	--	signif	signif	--	--
heart	Ventricle area	--	--	--	signif.	signif.	signif.	--	--	--	signif.	--	--	--	--	signif.	signif.	--	--
heart	AFS	--	signif.	--	signif.	--	--	--	--	--	--	--	--	--	--	--	--	--	--
heart	VFS	--	signif.	--	signif.	signif.	--	--	--	--	--	--	--	--	--	signif.	--	--	--
heart	silent ventricle	--	--	--	--	signif.	--	--	--	--	--	--	--	--	--	signif.	--	--	--
heart	Heart rate	signif.	signif.	signif.	--	--	--	--	signif.	--	--	--	--	--	--	--	--	--	--

Table S4 Dilution exposure concentrations (average days 0-3 and jars A-C), expressed as µg L^{-1} and as a percent of the above concentration. The dosing scheme aimed to have each subsequent concentration be 33% of the above concentration. Values are the mean of all days. Asterisks indicate samples lost in laboratory error.

	PHE		4-MP		1,4-DMP	
Dilution 2018	µg L^{-1}	% of above concentration	µg L^{-1}	% of above concentration	µg L^{-1}	% of above concentration
S	184	-	177	-	43.1	-
S/3	105	57%	117	66%	18.3	42%
S/9	30.0	29%	43.2	37%	5.95	33%
S/27	10.8	36%	7.75	18%	-	-
S/81	3.4	31%	-	-	-	-
Dilution 2019						
S	194	-	203	-	--*	-
S/3	59.7	31%	46.1	23%	16.9	--*
S/9	19.0	32%	-	-	-	-

Table S5 Water concentration percent decrease from day 0 . Averages are only of the S exposure level. Asterisk indicate sample lost in laboratory error.

Exposure year	PAH	Average, day 0	Averages, day 1-3	Percent decrease after day 0
2018	PHE	306	143	53 %
	1-MP	37	18	51 %
	3-MP	202	78	61 %
	4-MP	347	120	65 %
	9-MP	67	28	59 %
	1,4-DMP	83	33	60 %
	1,7-DMP	46	16	64 %
	2,3-DMP	50	22	56 %
	2,7-DMP	23	5.9	74 %
	3,6-DMP	11	3.1	72 %
	3-EP	70	28	60 %
	3-PP	8.9	6.4	28 %
	RET	3.2	2.0	38 %
2019	PHE	235	199	15 %
	2-MP	214	192	10 %
	4-MP	237	196	17 %
	1,4-DMP	--*	18	na*

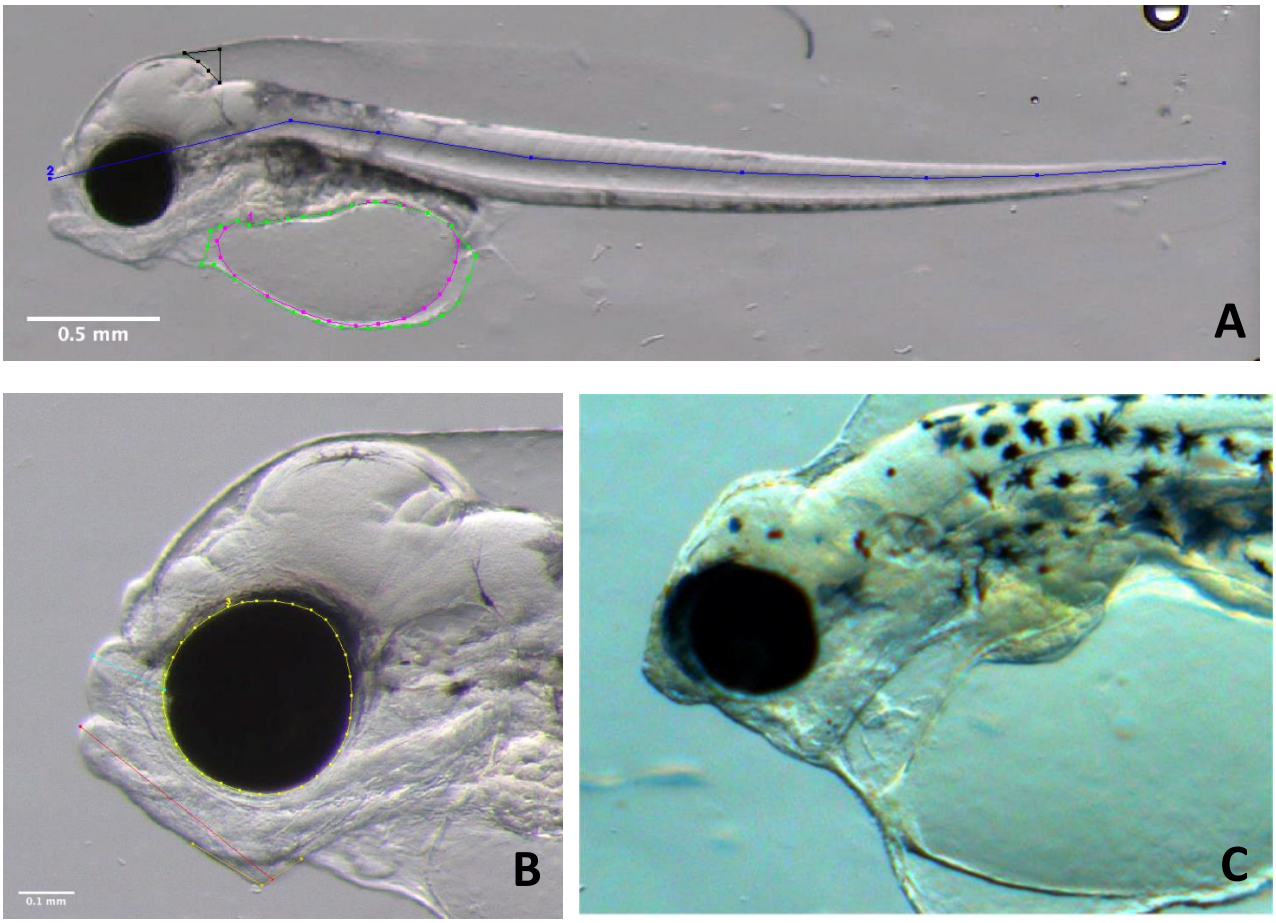


Fig S1 Biometric endpoints (A) Whole body endpoints measured at 1.6X magnification included: length (blue), finfold (black), net yolk (pink) and total yolk (green). (B) Face endpoints measured at 6.3X included eye area (yellow), eye-nose length (turquoise), length of jaw (red), and jaw angle (orange). (C) Representative phenotype of an early embryonic oil-exposed haddock from Sørhus et al. 2021, "high surface" with 7500 ng/g ww measured PAH body burden

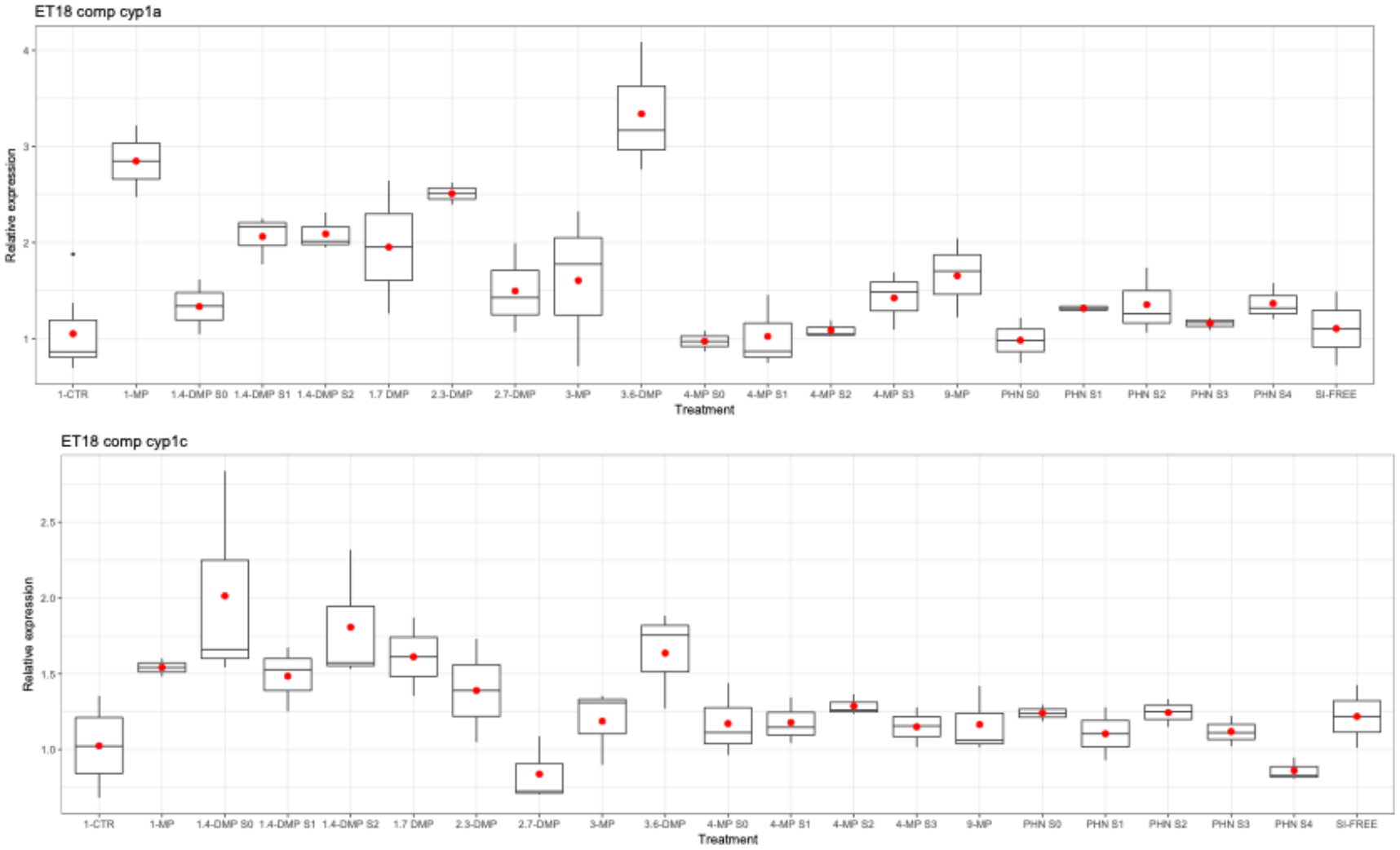


Fig S2 Trends in expression of *cyp1a* and *cyp1c*. The similar trends between the two CYP genes serve as additional quality control in lieu of having expression data for RET, which was originally intended to be a positive control. *Cyp1a* and *cyp1c* have been observed to follow each other in the analagous exposures in Sørhus et al. (2021).

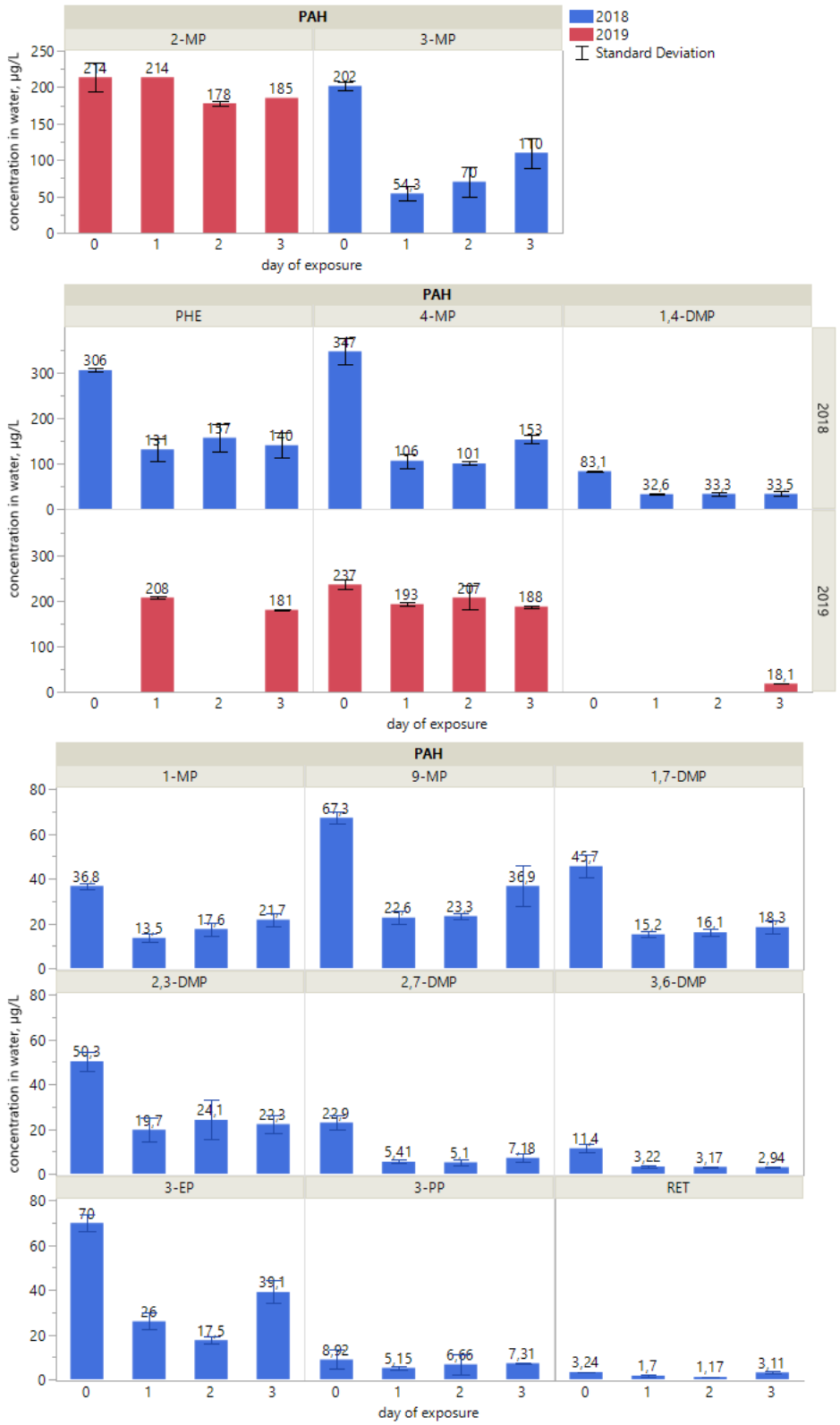


Fig S3 Concentrations in water on different exposure days. Levels of most compounds dropped after day 0 and the addition of eggs. Levels in 2018 (blue) tended to drop after day 0 and the addition of eggs, while levels over time in 2019 (red) were more stable. Missing bars indicate all replicates were lost to laboratory error. Error bars are standard deviation.

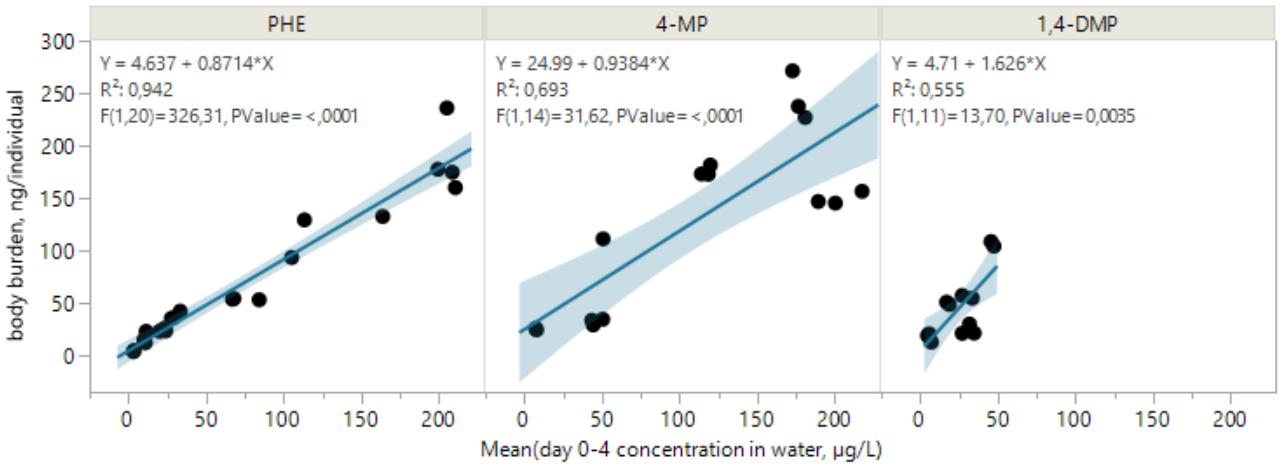


Fig S4 Linear regressions between body burden in the embryo and PAH concentration in water. Water concentrations are averaged for each replicate jar across days 0-4. Each data point represent a unique body burden sample plotted against the average water concentration from the jar it was sampled from.

Comments on expected and actual water concentrations.

Passive dosing is a suitable method for determining the solubility of solid, hydrophobic substances (Birch et al. 2019). Our experiments were not performed at standard conditions, but can be compared to known values to examine the efficiency of the dosing scheme intended to conduct aquatic toxicity tests at the solubility limit. Many of the compounds tested do not have reliable published solubility values, and any available literature values must first be adjusted to experimental conditions before comparing to the present study. Water temperature was recorded every day and measured 8.2 ± 0.1°C, and the seawater was 34.6‰ before autoclaving. Lower temperature has a large effect on solubility, and higher salinity will lead to lower solubility to a lesser degree. A study by Whitehouse (1984) measured solubility of PHE and other PAHs over a range of temperatures and salinity that encompasses our conditions. A multiple linear regression of the PHE data ($p < 0.001$, $R^2 = 0.97$) show a collective significant effect of temperature, salinity, and an interaction. Inputting our conditions into this model, we would expect PHE solubility to be 301 µg/L. The average PHE S (all days, all jars, both years) of 187 µg/L (95% confidence interval: 158-216) was lower than the expected value. We attempted to extend the multiple linear regression, but no additional satisfactory predictive variables (molar volume, molecular weight, melting point) were found that would allow solubility predictions beyond PHE to include the six other PAHs presented in Whitehouse (1984).Such a model might have allowed us to estimate the solubilities of the various alkylated homologues. As such, we have only compared our experimental values for PHE against adjusted estimates of literature values.

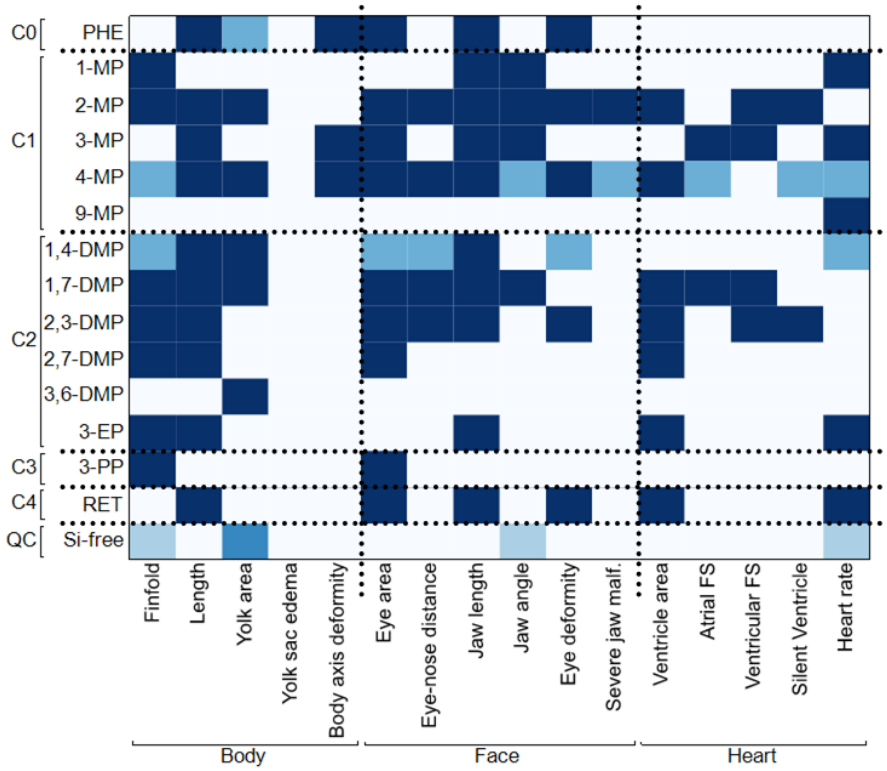


Fig S5 Significant endpoints sorted by type, and phenanthrenes sorted by degree of alkylation. Dark boxes indicate the endpoint was significantly different from control. Lighter boxes indicate the endpoint significant in only one of the repeated experiments, when tested. Yolk area = Net yolk, as defined in the main text

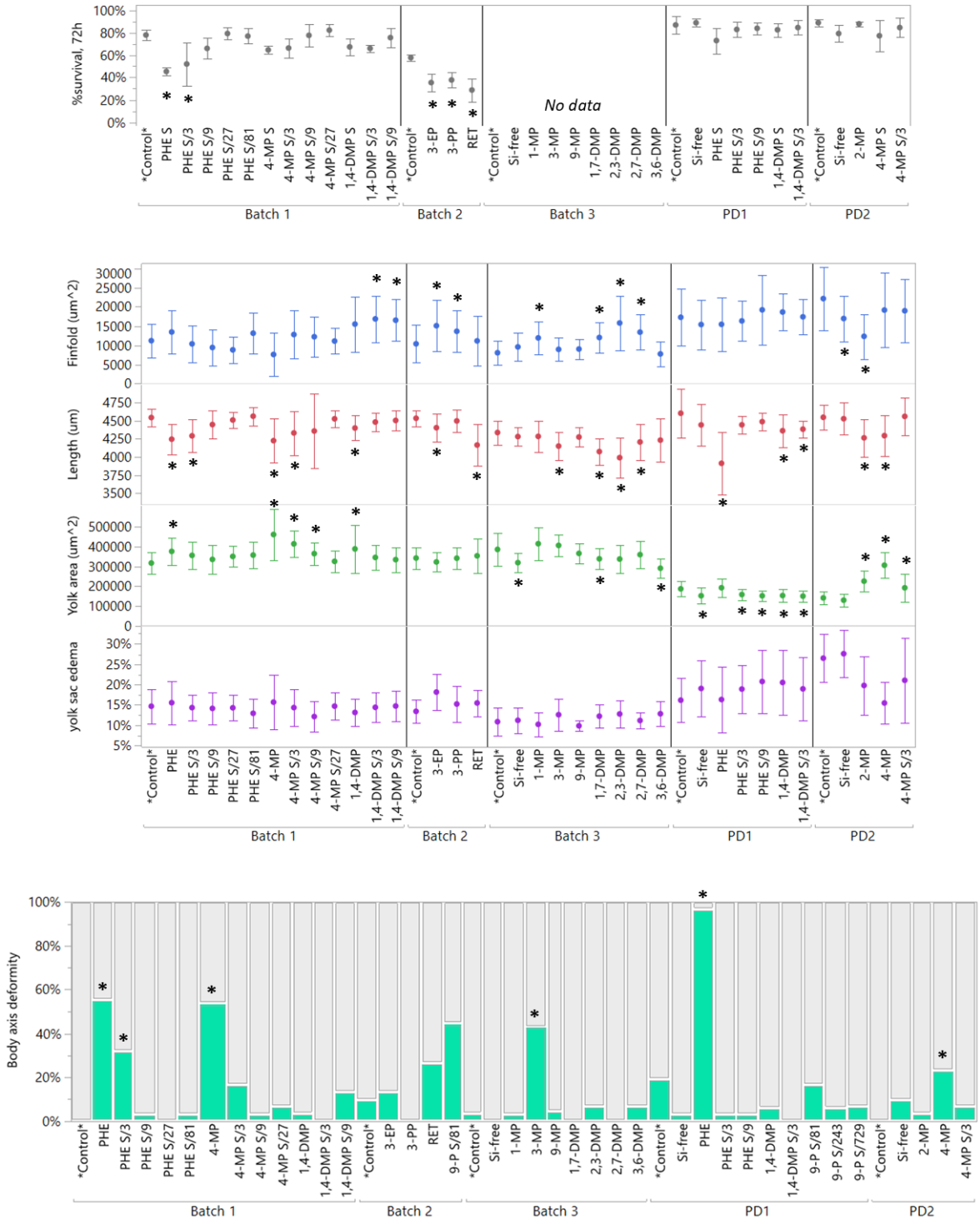


Fig S6 Mortality and body endpoints. Mann-Whitney tests (continuous data, shown as mean and standard deviation) and Fisher's exact tests (categorical data, shown as bar graphs) were performed to compare treatments against respective batch controls (labelled as *Control*). Significant differences are given in Tables S2 and S3 and are noted with asterisks in the plots. Yolk area = Net yolk, as defined in the main text

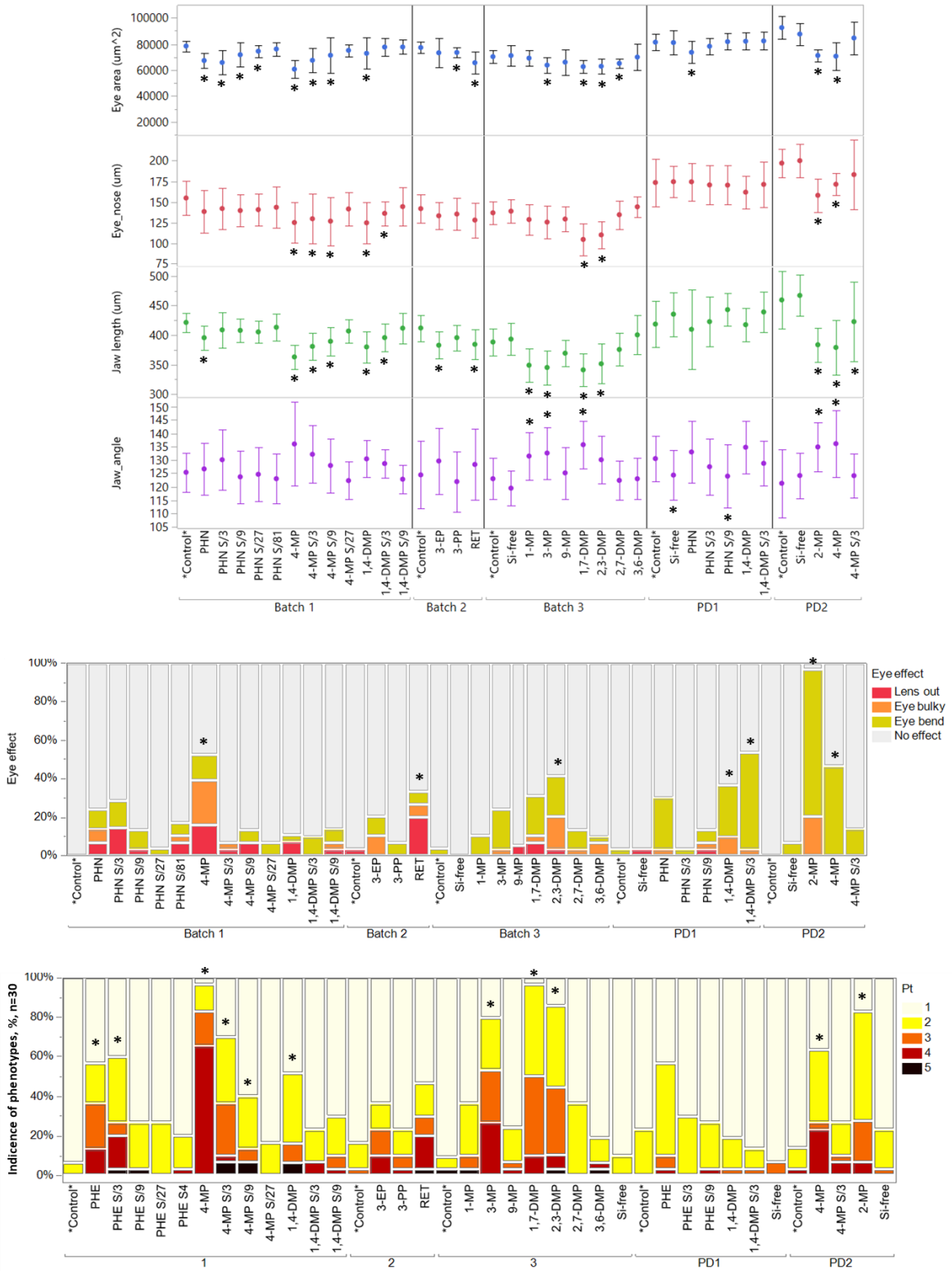


Fig S7 Face endpoints. Mann-Whitney tests (continuous data, shown as mean and standard deviation)) were performed to compare treatments against respective batch controls (labelled as *Control*). For eye effects and jaw phenotypes, Fisher's exact tests compared the incidence of any of the effects (bend, bulky, or lens out) to control. Significant differences are given in Tables S2 and S3 and are noted with asterisks in the plots. The incidence of eye shape deformity was scored according to 4 categories of phenotypes, severity-dependent: 1) No effect, 2) Eye bend (one protrusion from circular), 3) Eye bulky (two or more protrusions from circular), and 4) Lens out.(Lie et al., 2019) Jaw deformities (lowest plot) were scored by severity from 1) No effect, 2) Slight deformity, often with a thicker, shortened lower jaw, 3) Moderate deformity, often with twisted jaw structure 4) Severe deformity with straight jaw hanging open, to 5) No lower jaw structures

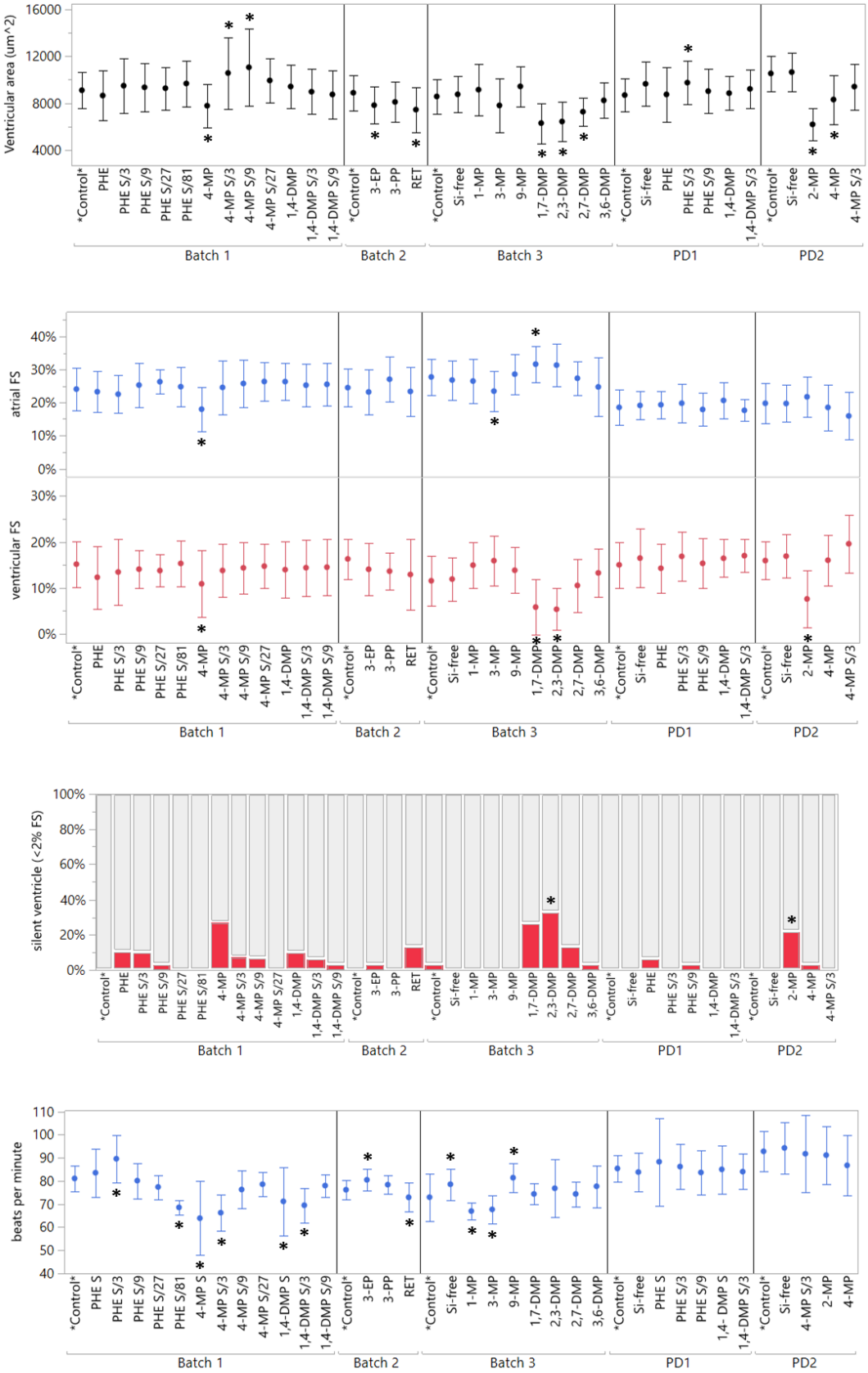


Fig S8 Heart endpoints. Mann-Whitney tests (continuous data, shown as mean and standard deviation) and Fisher's exact tests (categorical data, shown as bar graphs) were performed to compare treatments against respective batch controls (labelled as *Control*). Significant differences are given in Tables S2 and S3 and are noted with asterisks in the plots

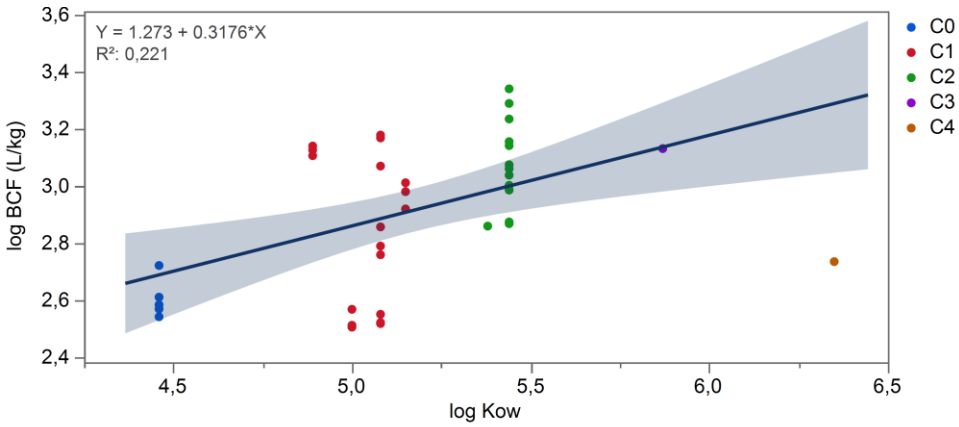


Fig S9 Bioconcentration factor (BCF) increased with octanol-water coefficient (K_{ow}). Compounds are *not* expected to be at equilibrium

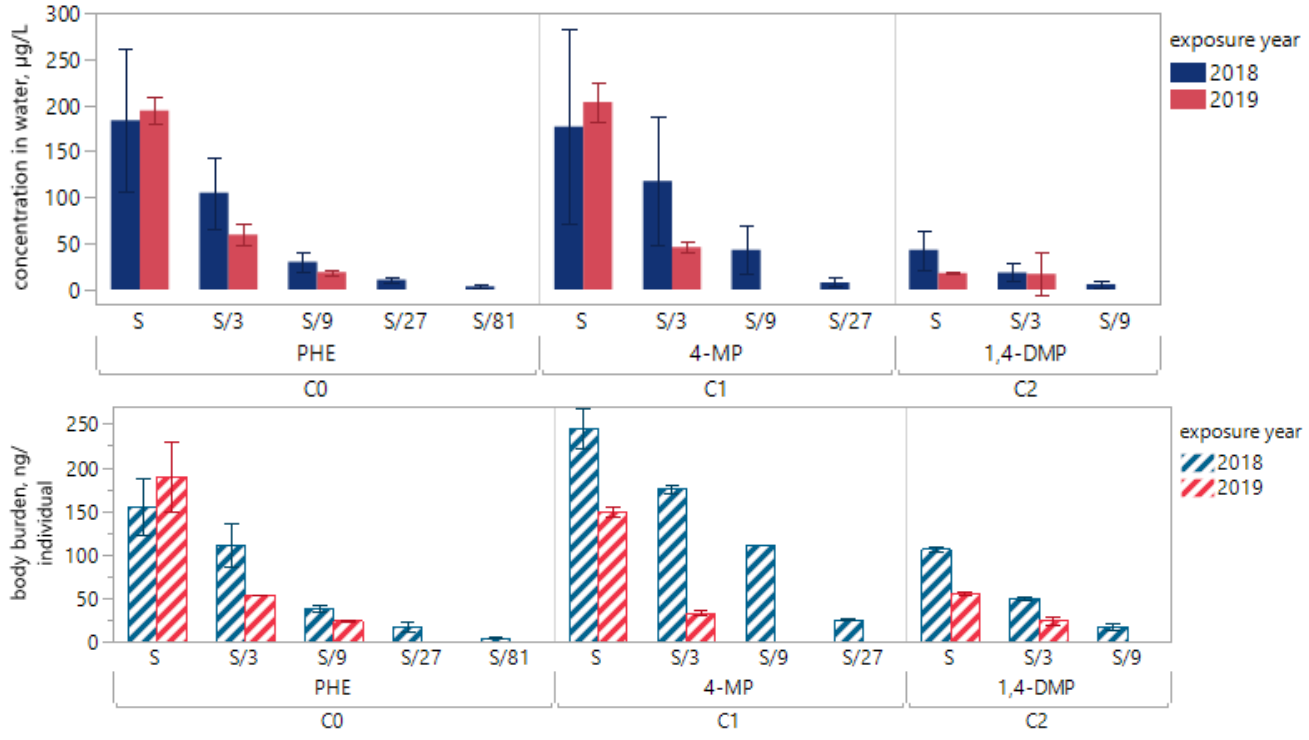


Fig S10 Comparison between years in water concentrations (top) and body burden concentrations (bottom)

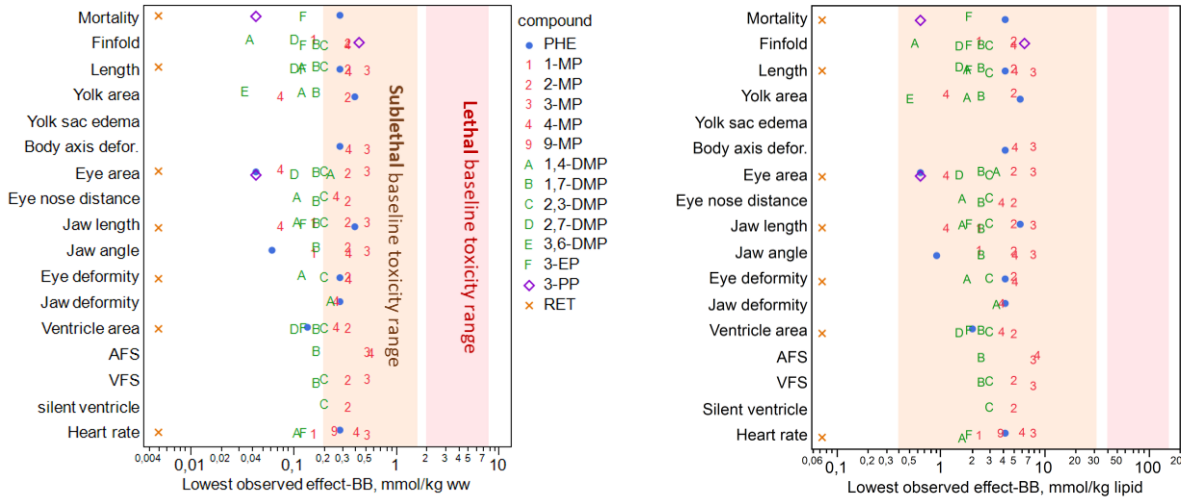


Fig S11 Lowest observed effect levels with significant toxicity versus control, with all compound information. Sublethal effects were observed below and within the range of expected sublethal base toxicity. Units are presented with wet weight (left) and lipid (right). Mortality occurred at concentrations well below the range of lethal baseline toxicity. Significant mortality was observed in only 4 of the 7 compounds where mortality was measured.

Part I References:

Birch, H.; Redman, A. D.; Letinski, D. J.; Lyon, D. Y.; Mayer, P., Determining the water solubility of difficult-to-test substances: A tutorial review. *Anal. Chim. Acta* **2019**, 1086, 16-28.

Sørhus, E.; Donald, C. E.; Silva, D. d.; Thorsen, A.; Karlsen, Ø.; Meier, S., Untangling mechanisms of crude oil toxicity: linking gene expression, morphology and PAHs at two developmental stages in a cold-water fish. *Sci. Total Environ*. **2021**, 757, 143896.

Whitehouse, B. G., The effects of temperature and salinity on the aqueous solubility of polynuclear aromatic hydrocarbons. *Mar. Chem.* **1984**, 14, 319-332.

Part II: Synthesis

General Information

Photocyclizations were performed with a 400W medium pressure Mercury vapor lamp in a quartz immersion well from Photochemical Reactors Ltd. The lamp was fitted with a pyrex glass filter, and the setup was protected with a water-stop unit turning the lamp off in case of cooling water failure. Maximum reactor volume was 1200 mL, and gas were bubbled through the reactor from the bottom through a glass tube. When other reactions were performed under nitrogen atmosphere the glassware were equipped with a septum and a balloon with nitrogen. Anhydrous solvents were purchased as anhydrous from the supplier. Flash columns were made with silica gel (40-63 μm particle size). NMR-spectra were obtained on a Bruker 400 MHz Advance III spectrometer. The ppm scale was set to 0 ppm from TMS in ^{1}H-NMR and 77 ppm from the solvent peak of $CDCl_3$ in ^{13}C-NMR. Splitting patters are assigned as s=singlet, d=doublet, t=triplet, q=quartet, sept.= septet, br.=broad. IR were recorded on a Perkin Elmer Spectrum One FTIR spectrometer using KBr-pellets of solids or NaCl-tablets for liquids. Strong peaks are assigned with (s). Melting points were measured in open capillary tubes on a Bibby SMP3 Mp apparatus. HRMS were obtained from the University of Bergen or Tromsø by electron impact (EI) or electrospray ionization (ESI) on time-of-light mass analyzers.

Abbreviations:

DCM= dichloromethane
EtOAc= ethyl acetate
THF= tetrahydrofurane
TEMPO= 2,2,6,6-tetramethylpiperidine 1-oxyl.
An overview of the synthesis and numbering of compounds are given in Fig S11.

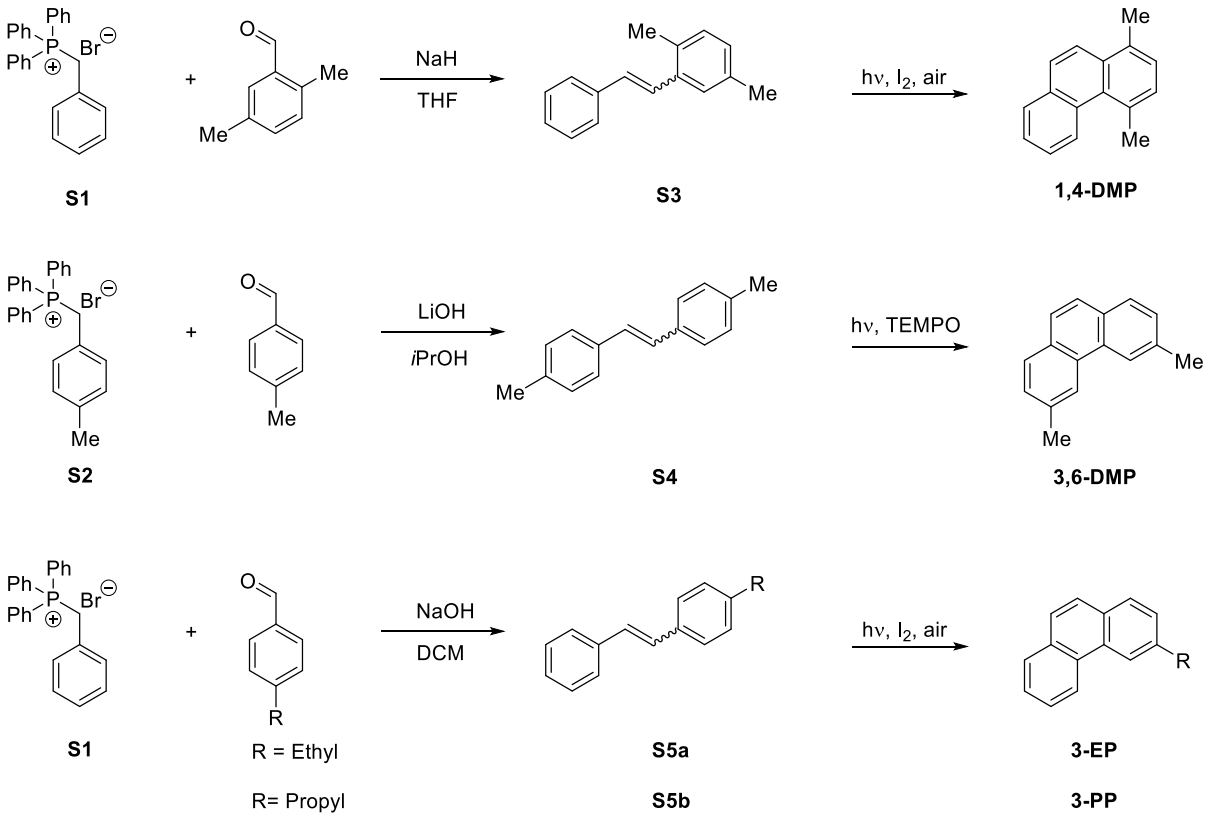


Fig S12 Photochemical synthesis of Phenanthrenes

Experimental procedures

*Synthesis of benzyltriphenylphosphonium bromide (**S1**).*

A mixture of triphenylphosphine (29.62 g, 114.0 mmol) and benzylbromide (19.62 g, 114.7 mmol) in toluene (100 mL) was stirred under reflux at 120 °C under nitrogen atmosphere for 40 hrs. The mixture was then evaporated to dryness and washed with diethyl ether (5 x 100 mL). The remaining solids were dried under reduced pressure to yield 48.98 g (99%) of **S1** as a white solid.

NMR data was in accordance with those reported by Cvengros *et al.*[S1]

*Synthesis of 4-methylbenzylphosphonium chloride (**S2**).*

A mixture of triphenylphospine (14.3 g, 54.0 mmol) and 4-methylbenzylchloride (7.65 g 54.0 mmol) in toluene (50 mL) was stirred under reflux at 120 °C under nitrogen atmosphere for 48 hrs. The mixture was then evaporated to dryness and washed with diethyl ether (4 x 40 mL). The remaining solids were dried under reduced pressure to yield 17.8 g (81%) of **S2** as a white solid.

^{1}H-NMR (400 MHz, $CDCl_3$) δ: 2.22 (d, *J*=2.5 Hz, 3H), 5.36 (d, *J*=14.2 Hz, 2H), 6.88(d, *J*=8.3 Hz, 2H), 6.93 (dd, *J*= 8.3, 2.3 Hz, 2H), 7.57-7.62 (m, 6H), 7.68-7.75 (m, 9H) ppm.

^{13}C-NMR (100 MHz, $CDCl_3$) δ: 21.2, 30.4 (d, J_P= 46.2 Hz), 118.1 (d, J_P= 85.1 Hz), 129.5 (d, J_P= 3.0 Hz), 130.2 (d, J_P= 12.5 Hz), 131.4 (d, J_P= 5.2 Hz), 133.8 (d, J_P= 19.2 Hz), 134.5 (d, J_P= 10.4 Hz), 134.9 (d, J_P= 3.0 Hz), 138.3 (d, J_P= 4.4 Hz) ppm.

^{1}H-NMR spectrum was in accordance with that reported by Cui *et al*.[S2]

*Synthesis of 1,4-dimethyl-2-styrylbenzene (**S3**).*

2,5-Dimethylbenzaldehyde (1.88 g, 14.01 mmol) and **S1** (7.29 g, 16.8 mmol) were dissolved in anhydrous THF (140 mL), and slowly added NaH (0.84 g, 21 mmol, 60% dispersion in paraffin) at 0 °C. The reaction mixture was heated up and refluxed for 4 hrs. After complete reaction by TLC, the mixture was cooled down and quenched with ice-cold water (75 mL). The mixture was extracted with diethyl ether (2 x 75 mL), the ether phases dried over anhydrous $MgSO_4$ and concentrated *in vacuo*. The crude product was purified by column chromatography (1% EtOAc in heptane) to afford 2.47 g (85%) of **S3** as a white solid as a micture of Z and E isomers in a 1:2 ratio (measured by NMR).

Characterization data were in accordance with those reported by Barder *et al*.[S3]

*Synthesis of 1,2-di-p-tolylethene (**S4**).*

4-Methylbenzaldehyde (2.88 g, 24.0 mmol), **S2** (10.6 g, 26.4 mmol) and LiOH (1.27 g, 52.8 mmol) in 2-propanol (300 mL) under nitrogen atmosphere was refluxed at 87 °C for 24 hrs. After completion by TLC (petroleum ether: EtOAc 19:1) the solvent was removed under reduced pressure. The remains were partitioned between DCM (300 mL) and water (150 mL). The DCM phase was washed with brine (150 mL), dried over anhydrous $MgSO_4$ and concentrated in vacuo. The crude was purified by flash chromatography (petroleum ether : EtOAc 19:1) to obtain 4.87 g (97%) of **S4** as a mixture of E/Z isomers in an approx. 1:1 ratio.

Characterization data were in accordance with those reported by Chen and Chen.[S4]

*Synthesis of 1-ethyl-4-styrylbenzene (**S5a**).*

4-Ethylbenzaldehyde (2.01 g, 15.0 mmol) and **S1** (7.80 g, 18.0 mmol) was dissolved in DCM (120 mL), added 50% aqueous NaOH (15 mL) and vigorously stirred under nitrogen atmosphere for 4 hrs until completion by TLC (Petroleum ether: EtOAc 7:1). The reaction mixture was washed with water (300 mL), and the water phase extracted with DCM (100 mL). The combined DCM-phases were dried over anhydrous $MgSO_4$ and concentrated under reduced pressure. The product was purified by flash column chromatography (Petroleum

ether : EtOAc, 95:5) to afford 2.77 g (89%) **S5a** as a colorless amorphous solid (undetermined *E*/*Z*-mixture 1.2:1).

^{1}H-NMR (400 MHz, $CDCl_3$) δ: 1.21(t, *J*= 7.6 Hz, 3H, major), 1.25 (t, *J*=7.6 Hz, 3H, minor), 2.61 (q, *J*= 7.6 Hz, 2H, major), 2.66(q, *J*=7.6 Hz, minor), 6.55 (s, 2H), 7.05(d, *J*=8.3 Hz, 2H, major), 7.08(d, *J*= 3,3 Hz, 2H, minor), 7.16-7.28(m, 10 H), 7.33-7.36(m, 2H), 7.43-7.45(m, 2H), 7.49-7.52(m, 2H)

^{13}C-NMR(100 MHz, $CDCl_3$) d: 15.4, 15.5, 28.56, 28.63, 126.4, 126.5, 126.9, 127.4, 127.7, 127.8, 128.17, 128.19, 128.6, 128.8, 129.5, 130.2, 134.5, 134.8, 137.5, 143.2, 143.9 ppm.

*Synthesis of 1-propyl-4-styrylbenzene (**S5b**).*

4-Propylbenzaldehyde (1.16 g, 8.67 mmol) and **S1** (4.53 g, 10.5 mmol) were treated as for **S5a** to afford 1.487 g (77%) of **S5b** as a colorless amorphous solid (undetermined E/Z-mixture 1.2:1).

^{1}H-NMR (400 Hz, $CDCl_3$) δ: 0.93(t, *J*= 7.4 Hz, 3H, major), 0.95(t, *J*=7.4 Hz, 3H, minor), 1.52-1.70(m, 2H), 2.54(t, *J*=7.8 Hz, 2H, major), 2.59(t, *J*=7.8 Hz, 2H, minor), 6,55(s, 2H), 7.02(d, *J*= 8.1 Hz, 2H major), 7.08(d, *J*= 2.7 Hz, 2H, minor), 7.15-7.28 (m, 10 H), 7.33-7.37 (m, 2H), 7.43(d, *J*= 8.1 Hz, 2H), 7.50(d, *J*= 7.8 Hz, 2H) ppm.

^{13}C-NMR (100MHz, $CDCl_3$) δ: 13.8, 24.4, 24.5, 37.77, 37.80, 126.4, 126.9, 127.4, 127.7, 128.16, 128.26, 128.6, 128.7, 128.80, 128.82, 129.5, 130.2, 134.5, 134.8, 137.51, 137.53, 141.7, 142.4 ppm.

General procedure for the Mallory-reaction (G1)

The required stilbene and 5 mol% I_2 was dissolved in toluene* and transferred to the photoreactor. A slow stream of air was bubbled through the reactor while the mixture was irradiated. The R_f-values of starting material and products on TLC were close, and the reaction had to be monitored by ^{1}H-NMR (5 mL aliquots were evaporated *in vacuo* and dissolved in $CDCl_3$ for NMR-analysis). When the reaction was complete, 2/3 of the toluene was removed by reduced pressure. The remaining reaction mixture was washed with 10% aq $Na_2S_2O_3$ (100 mL), brine (100 mL) and dried over anhydrous $MgSO_4$. The organic solvent was removed *in vacuo*, and the crude product purified by flash chromatography or vacuum distillation.

*) Although these reactions were made in toluene, later experience with the Mallory-reaction indicate that cyclohexane gives a bit better yields and slightly purer products. Thus, we will recommend using cyclohexane in these reactions.

*Synthesis of 1,4-dimethylphenanthrene (**1,4-DMP**).*

Following the general procedure G1, **S3** (3.33 g, 16.0 mmol) and I_2 (0.41 g, 1.6 mmol) in toluene (900 mL) was irradiated for 48 hrs. After workup the crude was purified by distillation under reduced pressure to obtain 1.41 g (43%) **1,4-DMP** as a white solid.

MP: 42.1–46.9 °C(MeOH)

^{1}H-NMR(400 MHz, $CDCl_3$) δ: 2.76 (s, 3H), 3.14 (s, 3H), 7.43 – 7.37 (m, 2H), 7.66–7.59 (m, 2H), 7.78 (d, *J*= 9.0 Hz, 1H), 7.96-7.93 (m, 1H), 7.98 (d, *J*= 9.1 Hz, 1H), 8.92 (dd, *J* = 1.8, 7.4 Hz, 1H) ppm

^{13}C-NMR (100 MHz, $CDCl_3$) δ: 20.3, 27.4, 123.4, 125.3, 125.7, 126.8, 127.3, 127.7, 128.5, 130.3, 130.7, 131.9, 132.2, 132.8, 133.1, 133.3 ppm

FTIR (KBr): 1448, 1432, 1032, 864, 820, 747, 711 cm^{-1}.

HRMS (ESI) m/z $[M + H]^+$ for formula $C_{16}H_{15}$: calcd 207.1169; found 207.1168.

Characterization data are in accordance with those reported by Jung and Koreeda.[S5]

*Synthesis of 3,6-dimethylphenanthrene (**3,6-DMP**).*

S4 (3.00 g, 14.4 mmol) and TEMPO (6.75 g, 43.2 mmol) was dissolved in degassed cyclohexane (1000 mL) and bubbled through with nitrogen gas during the reaction. The mixture was irradiated for 96 hrs. The reaction mixture was washed with 0.1 M aqueous NaOH (3 x 300 mL) and brine (300 mL), dried over $MgSO_4$ and concentrated under reduced pressure. The crude was purified by flash column chromatography (petroleum ether: EtOAc 19:1) and recrystallized from methanol to yield 1.63 g (55%) of **3,6-DMP** as white crystals.

MP: 144-145 °C(methanol) (Lit. 142-144 °C[S6])

^{1}H-NMR (400 MHz, $CDCl_3$) δ: 2.63 (s, 6H), 7.41 (dd, *J*=8.2, 1.3 Hz, 2H), 7.64 (s, 2H), 7.77 (d, *J*=8.1 Hz, 2H), 8.47 (br. s, 2H) ppm.

^{13}C-NMR (100 MHz, $CDCl_3$) δ: 22.1, 122.4, 125.8, 128.1, 128.4, 130.14, 130.07, 136.0 ppm.

IR (KBr): 3054, 2857, 1609, 1517, 1452, 840 cm^{-1}.

HRMS (EI) m/z $[M]^+$ for formula $C_{16}H_{14}$: calcd 206.10955; found 206.10933.

Spectral data are in accordance with those reported by Moussa *et al.*[S7]

*Synthesis of 3-ethylphenanthrene (**3-EP**).*
Following the general procedure G1, **S5a** (2.058 g, 9.88 mmol) and I_2 (0.14 g, 0.55 mmol) was dissolved in toluene (1200 mL) and irradiated for 18 hrs. The crude product was purified by flash column chromatography (gradient from pure petroleum ether to 5% EtOAc) to yield 1.39 g (68%) of **3-EP** as a colorless oil.

^{1}H-NMR(400 MHz, $CDCl_3$) d: 1.36(t, *J*= 7.6 Hz, 3H), 2.89(q, *J*= 7.6 Hz, 2H), 7.43(dd, *J*=8.1, 1.5 Hz, 1H), 7.55(ddd, *J*= 7.4, 7.4, 1.4 Hz, 1H), 7.60(ddd, *J*= 8.1, 8.1, 1.4 Hz, 1H), 7.64(d, *J*= 8.9 Hz, 1H), 7.68(d, *J*=8.9 Hz, 1H), 7.78(d, *J*= 8.1 Hz, 1H), 7.84(dd, *J*= 7.9, 1.1 Hz, 1H), 8,47(s, 1H), 8.67(d, *J*= 8.2 Hz, 1H) ppm.

^{13}C-NMR(100 MHz, $CDCl_3$) d: 15.9, 29.5, 121.2, 122.6, 126.0, 126.3, 126.4, 126.7, 127.2, 128.49, 128.51, 130.1(C), 130.2(C), 130.4(C), 132.2(C), 142.6(C) ppm.

IR(NaCl): 3054, 3021, 2959(s),2924, 2868, 1453, 838 (s), 745(s) cm^{-1}.

^{1}H-NMR were in accordance with that reported by Bartle and Smith.[S8]

*Synthesis of 3-propylphenanthrene **(3-PP)**.*

Following general procedure G1, **S5b** (1.12 g, 5.04 mmol) and I_2 (0.11 g, 0.43 mmol) dissolved in toluene (1200 mL) was irradiated for 19 hrs. The crude product was purified by flash column chromatography (gradient from pure petroleum ether to 5% EtOAc) to yield 0.624 g (56%) of **3-PP** as a colorless oil.

^{1}H-NMR(400 MHz, $CDCl_3$) δ: 1.00 (t, *J*= 7.5 Hz, 3H), 1.78(p, *J*= 7.5 Hz, 2H), 2.84(t, *J*= 7.5 Hz, 2H), 7.42(dd, *J*= 8.1 , 1.5 Hz, 1H), 7.55 Hz, ddd, *J*= 7.1, 7.1, 1.2 Hz, 1H), 7.61(ddd, *J*= 8.1, 7.1, 1.4 Hz, 1H), 7.65(d, *J*= 8.9 Hz, 1H), 7.69 (d, *J*= 8.9 Hz, 1H), 7.78(d, *J*= 8.1 Hz, 1H), 7.85(dd, *J*= 7.5, 0.9 Hz, 1H), 8.46(s, 1H), 8.68(d, *J*= 8.1 Hz, 1H) ppm.

^{13}C-NMR(100 MHz, $CDCl_3$) δ: 14.0, 24.9, 38.7, 122.0, 122.7, 126.1, 126.35, 126.43, 126.8, 127.7, 128.5, 128.6, 130.2(C), 130.3(C), 130.4(C), 132.3(C), 141.1(C) ppm.

IR(NaCl): 3052, 3021, 2963, 2929, 2870, 1453, 839(s), 743(s) cm^{-1}.

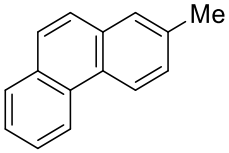
*2-methylphenanthrene (**2-EP**)*

^{1}H-NMR(400 MHz, $CDCl_3$) δ: 2.58(s, 3H), 7.49(dd, *J*= 8.4, 1.7 Hz, 1H), 7.57(ddd, *J*= 7.7, 7.2, 1.2 Hz, 1H), 7.64(ddd, *J*= 7.2, 7.3, 1.4 Hz, 1H), 7.67(d, *J*= 8.8 Hz, 1H), 7.68(s, 1H), 7.75(d, *J*= 8.8 Hz, 1H), 8.59(d, 8.4 Hz, 1H), 8.66(d, *J*= 8.4 Hz, 1H) ppm.

*4-methylphenanthrene (**4-MP**)*

^{1}H-NMR (400 MHz, $CDCl_3$) δ: 3.17(s, 3H), 7.48-7.52(m, 2H), 7.58-7.66(m, 2H), 7.73(s, 2H), 7.76-7.80(m, 1H), 7.91-7.93(m, 1H), 8.93(d, *J*= 8.6 Hz, 1H) ppm.

Spectra



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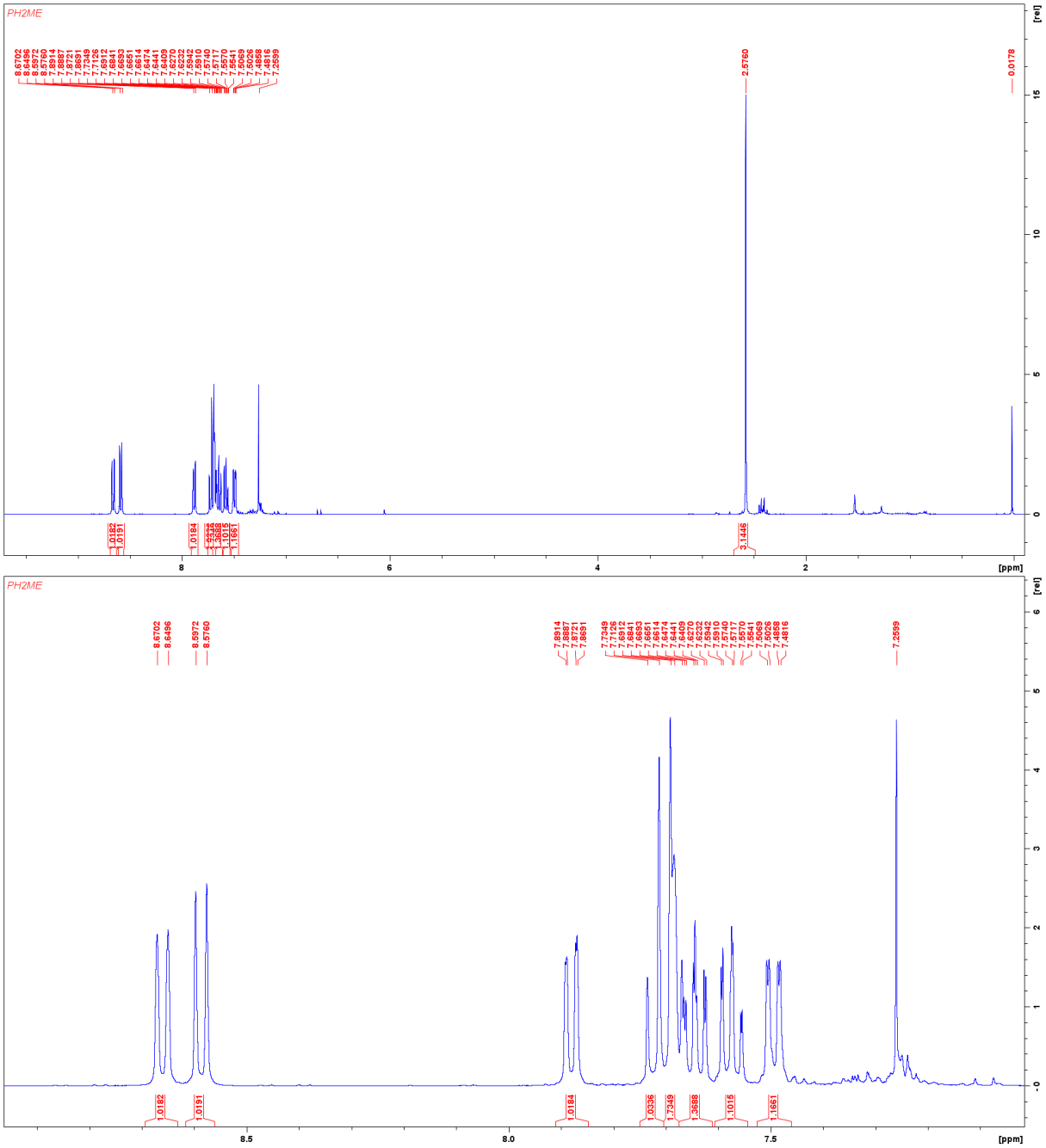

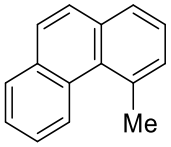
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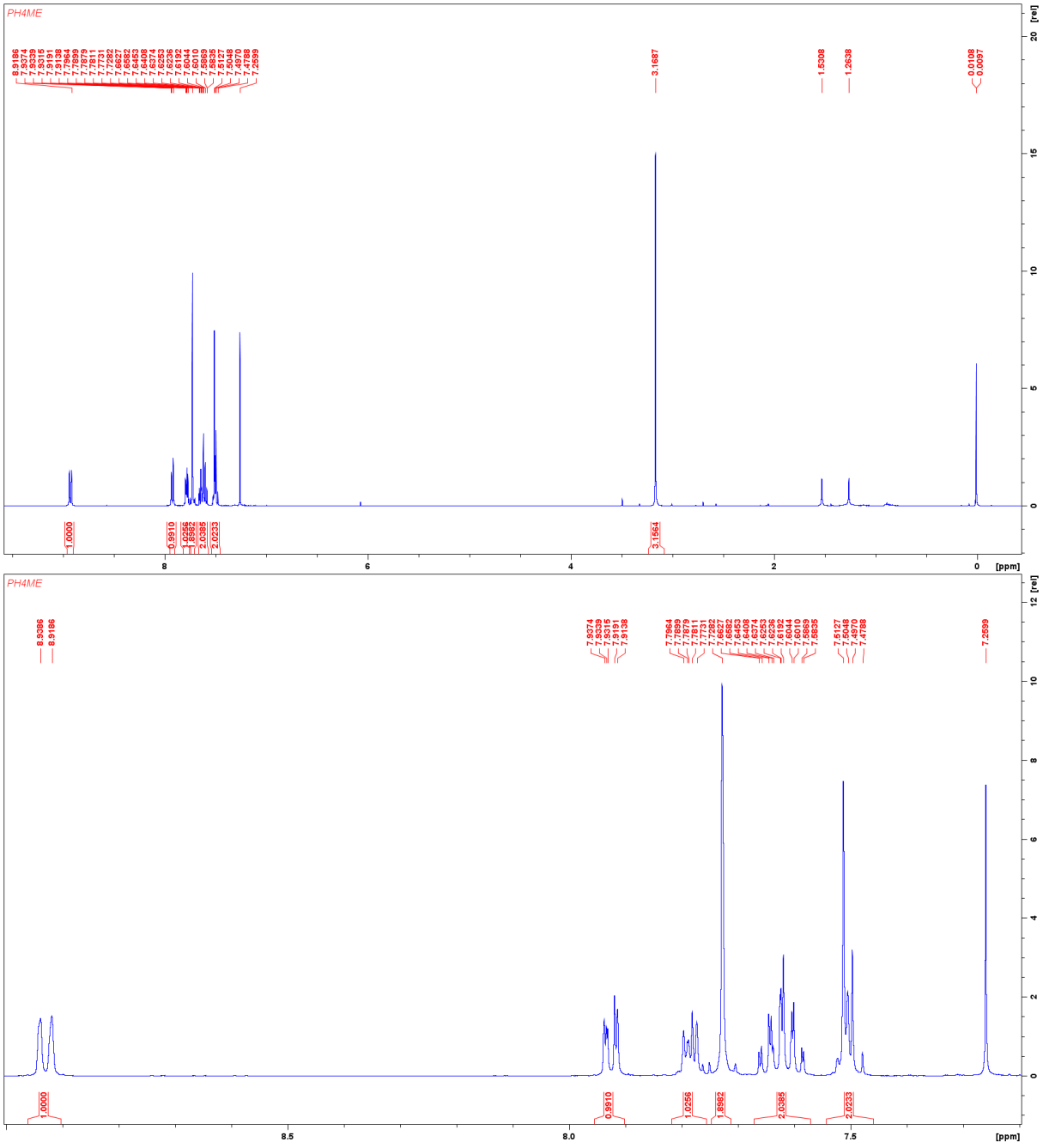
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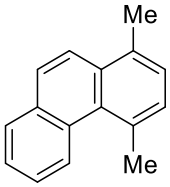

1,4-DMP,

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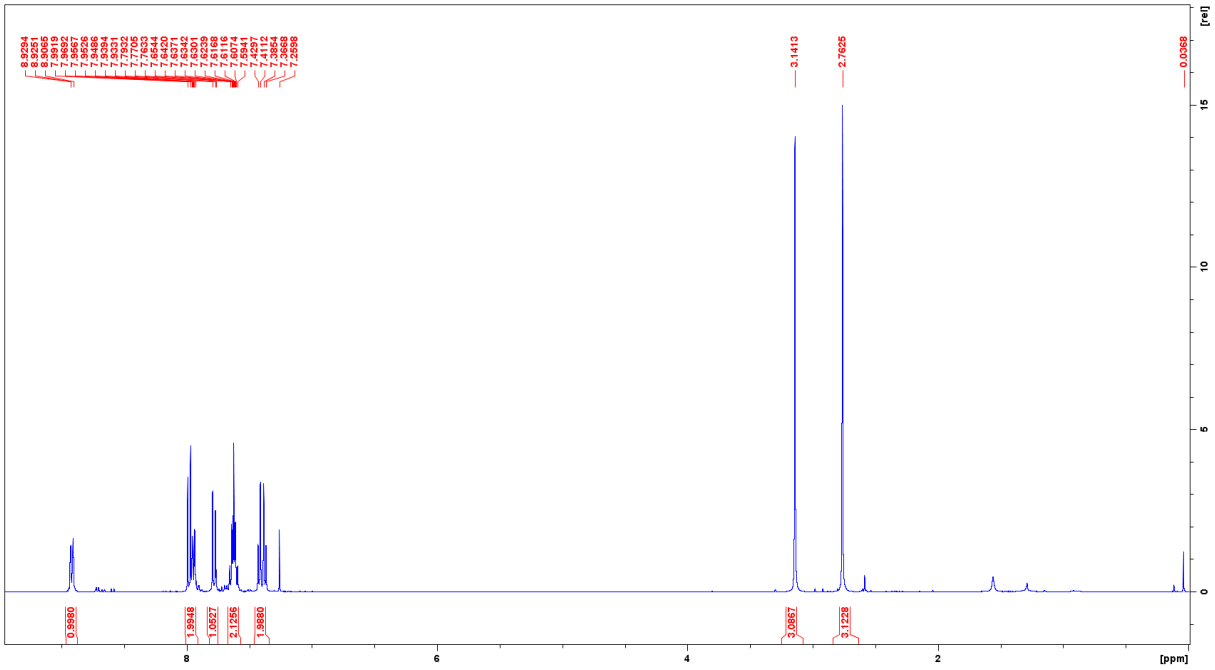

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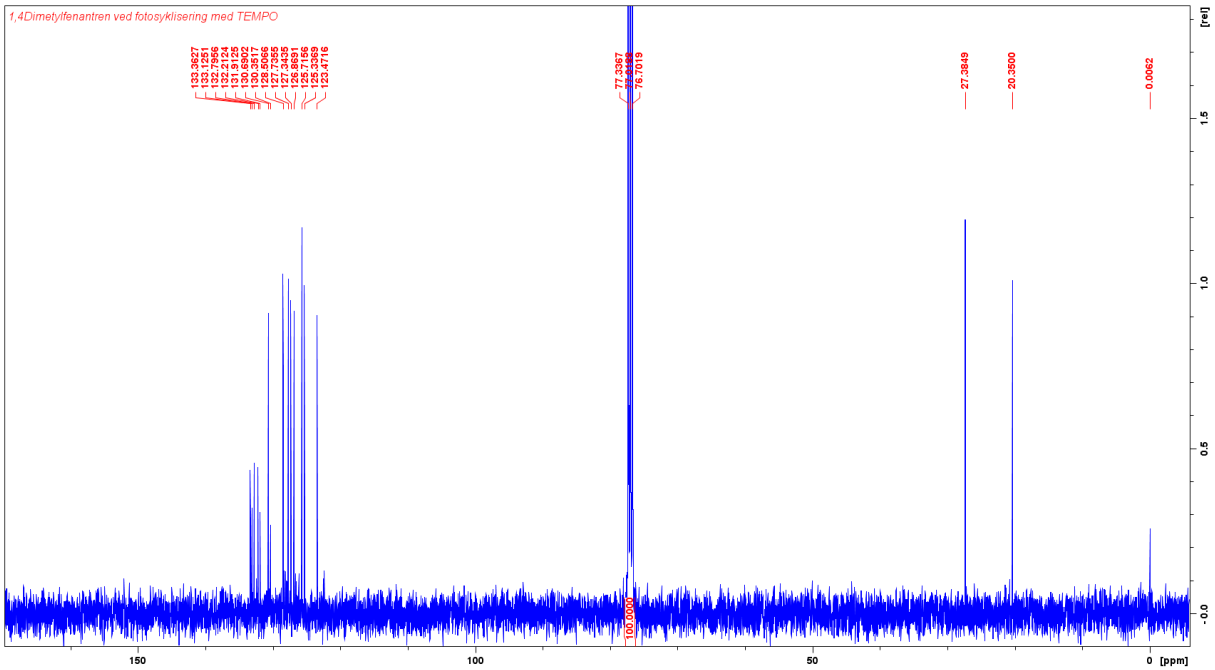
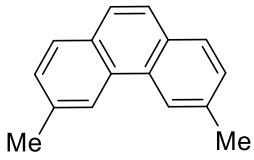


3,6-DMP, 

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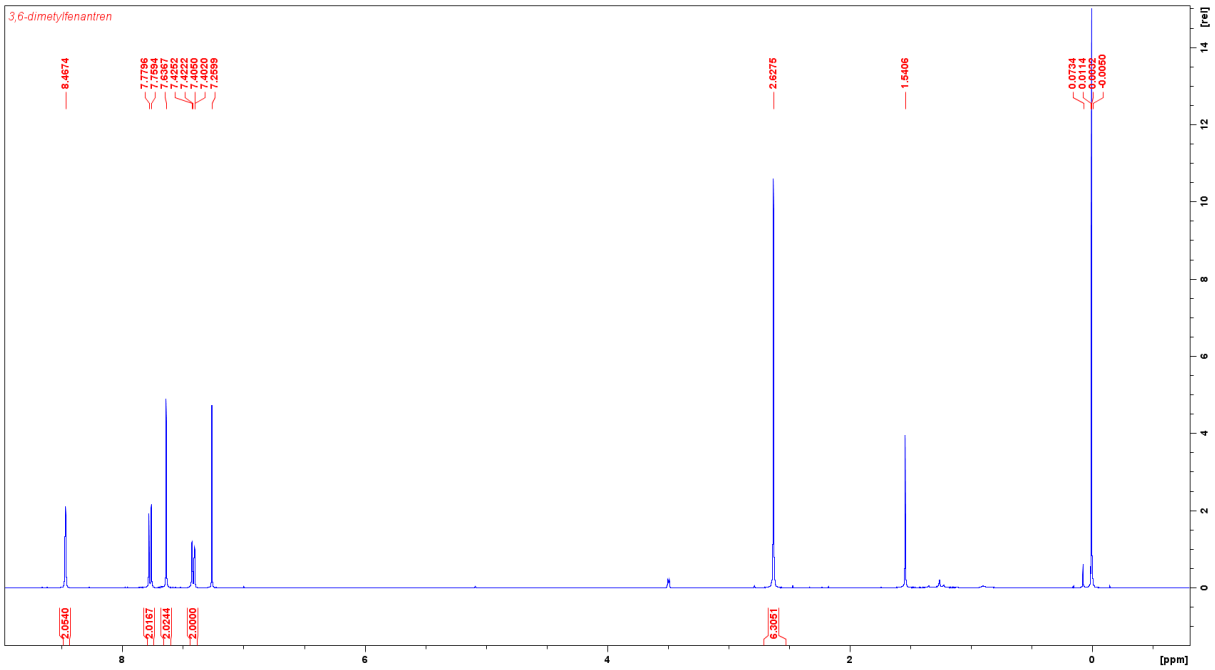

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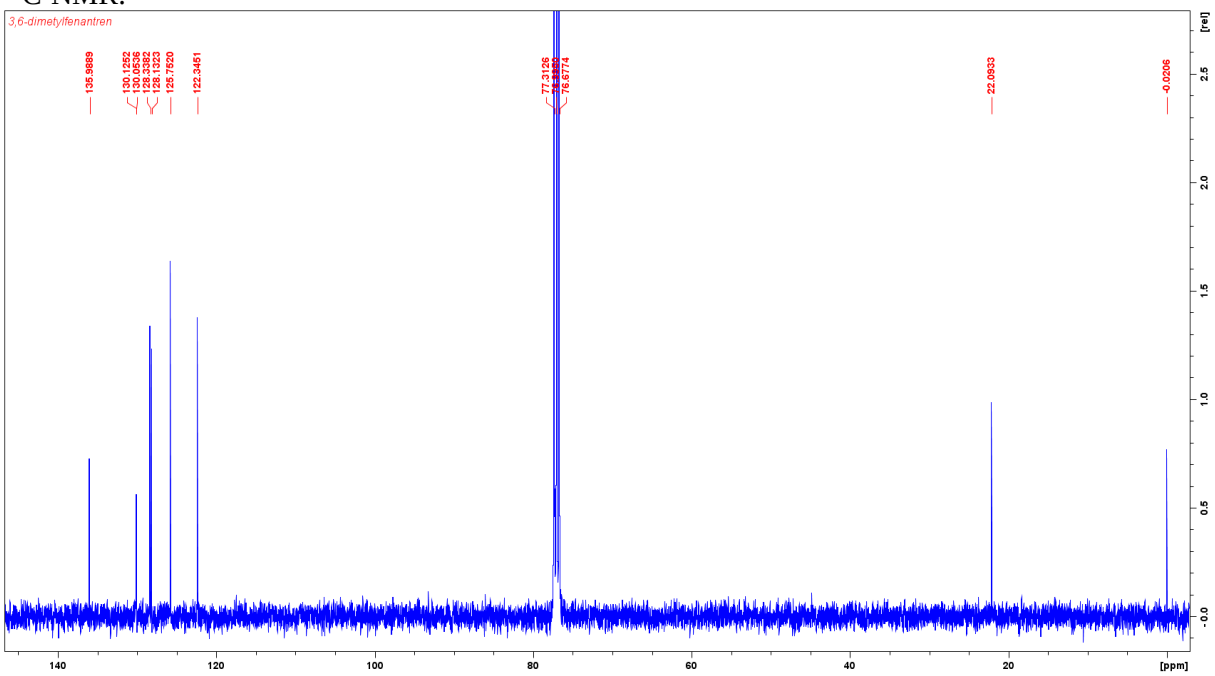
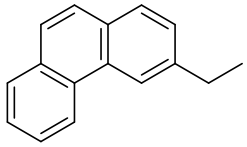
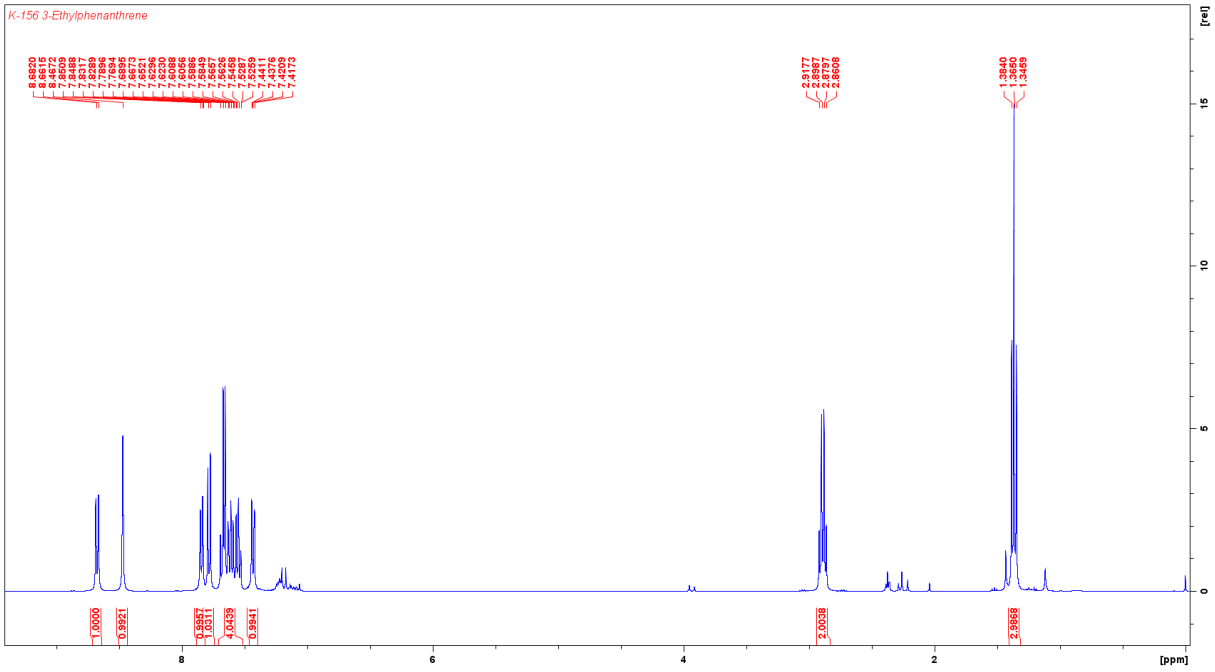


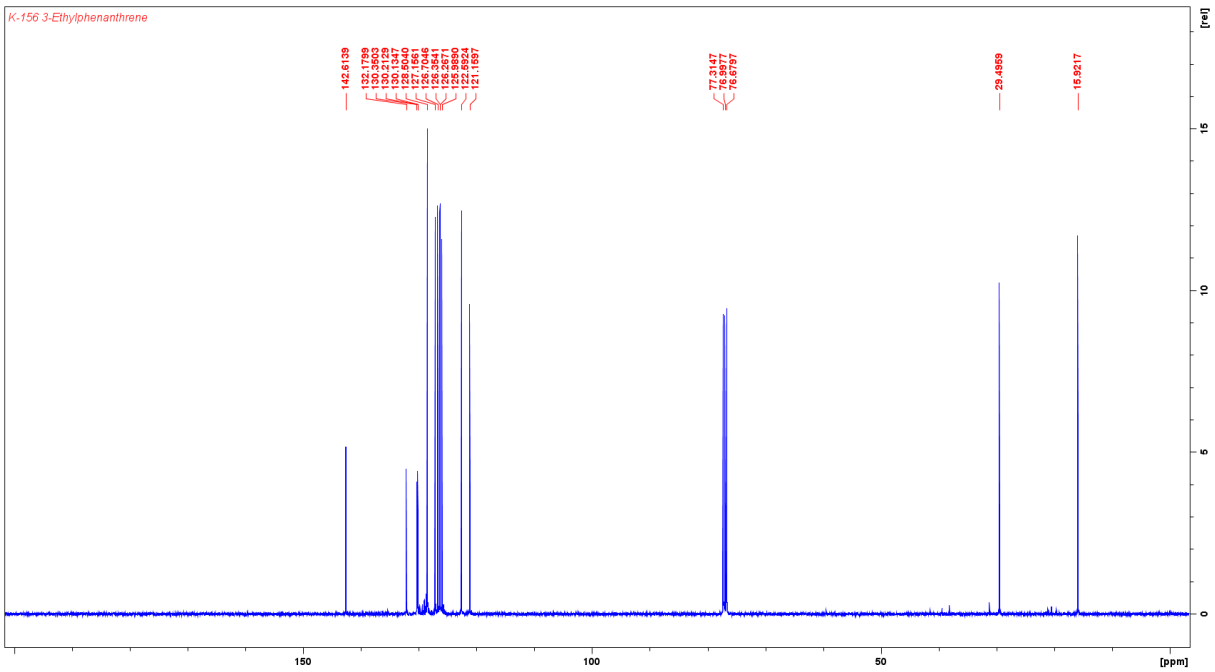


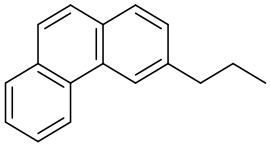
3-EP,

^{1}H-NMR:



^{13}C-NMR:





3-PP,

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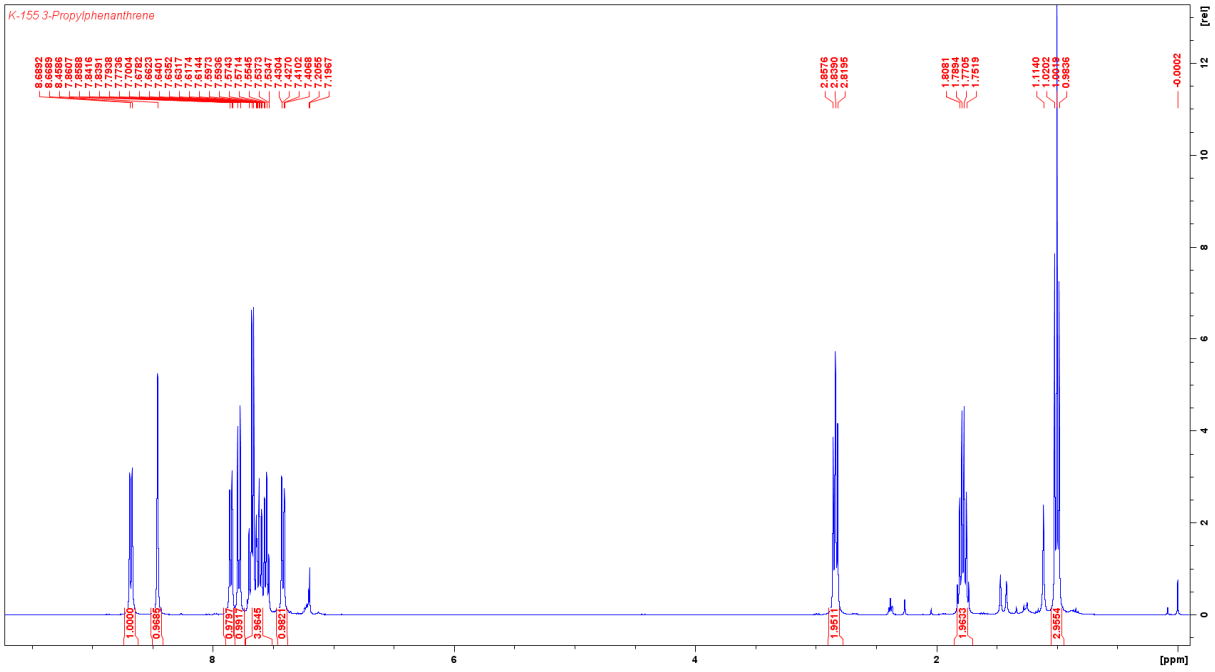

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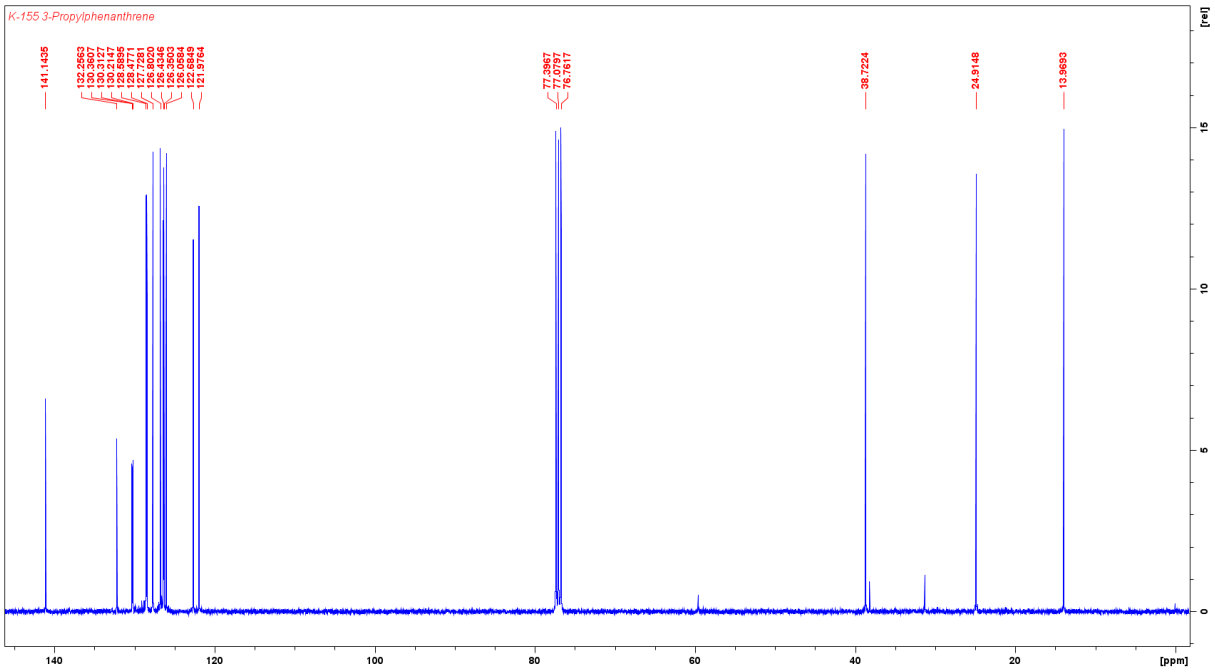

Part II References:

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