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Free concentrations and activated carbon amendments

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Bioaccumulation of native PAHs from sediment by a polychaete and a gastropod: Freely dissolved concentrations and activated carbon amendment

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Abstract

The present paper describes a study on the bioaccumulation of native PAHs from three harbors in Norway in the polychaete *Nereis diversicolor* and the gastropod *Hinia reticulata.* First, BSAFs were measured for the original sediments. Median BSAFs were 0.004-0.01 (ten PAHs; six organism-sediment combinations), which was a factor of 89-240 below the theoretical BSAF based on total sediment contents (which is around one). However, if BSAF-values were calculated on the basis of measured freely dissolved PAH concentrations in the porewater (measured with polyoxymethylene passive samplers), it appeared that these "$BSAF_{free}$" values were much closer to the actually measured BSAF values, within a factor of 1.7-4.3 (median values for ten PAHs and six organism-sediment combinations). This means that freely dissolved porewater concentrations are a much better measure for bioaccumulation than total sediment contents.

Second, we tested the effect of 2 wt-% activated carbon (AC) amendments on BSAF. BSAFs were significantly reduced (factor 6-7) for *N. diversicolor* in two sediments, i.e. two out of six organism-sediment combinations, while no significant reduction was observed for *H. reticulata.* This implies that site-specific evaluations of AC amendment are necessary, using several site-relevant benthic organisms.

Key words:

Sediment, Bioaccumulation, PAH, Freely Dissolved Concentrations, Activated Carbon Amendment

Introduction

A steadily growing volume of studies has shown that carbonaceous geosorbents (CG) can show much stronger sorption of hydrophobic organic chemicals (HOCs) than amorphous organic carbon (AOC) [1-3]. Examples of CG include unburned coal particles, kerogen, and soot and charcoal (the residuals of incomplete combustion, commonly termed "black carbon" or BC). Strong sorption to CG carbon, CGC (exceeding sorption to AOC by one to three orders of magnitude) has been shown for PAHs, PCBs, polychlorinated dibenzo-*p*-dioxins and -furans (PCDD/Fs), polybrominated diphenylethers (PBDEs), diuron, benzene, chlorobenzenes and chlorinated short-chain aliphatic compounds [3].

Because bioaccumulation of HOCs is regarded as an equilibrium situation between sediment, porewater and organisms' lipids, strong sorption to CGC will reduce concentrations of these compounds in aquatic and benthic organisms. Thus, with variation in geosorbent quality (e.g., CGC and AOC contents), the bioaccumulation of organic compounds can be expected to vary. This has led to the notion that freely dissolved concentrations provide a better measure for uptake in organisms and thus environmental risk than total sediment contents [3-6]. From an engineering perspective, an interesting consequence of strong CGC sorption is that amendment of such materials to HOC-contaminated sediments should reduce the *in situ* freely dissolved concentrations [7-9] and thus the actual risk of contaminated sediments. In some cases, activated carbon (AC) amendment has been shown to effectively reduce the uptake by benthic organisms of especially PAHs [10] and PCBs from sediments [11,12]. However, in another case, lipid-normalized contents in organisms were not reduced by amendment of coal and charcoal [13]. In the latter study, the overall contents in the test organisms were lowered by the amendments (factor 1.2-8.5), but this effect was completely offset by reductions in lipid contents hypothesized to be caused by adverse effects of coal and charcoal on habitat quality.

48 In the present study, native PAHs were studied in sediments from three contaminated and
49 CGC-rich harbors in Norway, and the tested organisms were the gastropod *Hinia reticulata*
50 and the polychaete *Nereis diversicolor*. The following two aims were pursued: i) comparison
51 of BSAFs based on total sediment contents with ones based on freely dissolved
52 concentrations, in order to evaluate the effect that CGC has on bioaccumulation from CGC-
53 rich sediments and ii) testing the effect of AC amendments on bioaccumulation, and
54 comparing this with their effect on freely dissolved concentrations as measured in a previous
55 study [9]. This is the first study in which these aims are simultaneously pursued, and the one
56 employing most simultaneous sediment-organism combinations on either aim. The obtained
57 results will be useful in the contexts of improved risk assessment (freely dissolved
58 concentrations and bioaccumulation) and of novel *in situ* remediation strategies (AC
59 amendments).
60
61 **Methods**
62 **Sediments.** Samples were taken from three Norwegian harbors with variable degrees of
63 native PAH pollution (sum-PAH 8.9-161 mg/kg dry weight, dw; Table 1): Oslo (OS), Bergen
64 (BG) and Tromsø (TR). Sampling locations and characteristics of the sediments (Table 1)
65 have been described in detail earlier [9,14]. The sediments contain significant amounts of
66 carbonaceous materials: BC is 6-12% of TOC [14], and total contents of CGC (unburned +
67 partly combusted carbonaceous carbon) amount to 28-56% of TOC [9]. Due to the presence
68 of these strongly sorbing materials, total sorption of the native PAHs is much stronger than
69 according to linear free energy relationships (LFERs) that are based on AOC sorption only
70 and do not take into account this strong sorption: for example, PHE showed TOC-water
71 partitioning coefficients (K_{TOC}) almost two orders of magnitude above the LFER-K_{TOC} value

(Table 1). Similar observations were made for the other PAHs that showed sorption 10-100 times stronger than predicted by LFER-values [9].

AC amendments. Pilot experiments showed that the currently used AC (Sigma-Aldrich "untreated powder 100-400 mesh", i.e. 37-149 μm) would sink in water at 22 °C within 10 min [9]. In contrast to methods described in [7,8,11,12], where the AC was boiled in water prior to use, we therefore added dry AC to our experimental systems, as boiling the AC is probably cumbersome and cost-increasing for field applications. AC (2% of sediment dry weight) was added to 5-kg sediment batches. Water was added until slurries were obtained (30-50% dry matter) that could be well-mixed by end-over-end shaking (6 rpm; 20 ± 1°C). These slurries were shaken for 78 d. In our previous study, a time series experiment showed that 31 d was long enough for redistribution of native PAHs between sediment and AC [9].

Bioaccumulation studies. These experiments were carried out exactly according to the procedures described in [15]. The test organisms were the netted dog whelk *Hinia reticulata* (Gastropoda) and the ragworm *Nereis diversicolor* (Polychaeta). In addition to being important prey to several bottom-dwelling fish species [16], both organisms are common in large parts of Europe [17] and able to live in aquaria for extended periods [15]. In spite of the gastropod's siphon ventilating to the overlying water, the mode of living of these organisms is such that they are intimately associated with the sediment so that equilibrium between organism and pore water can be expected [15]. *H. reticulata* is a scavenger and predator, but it can also utilize OM in the sediment. *N. diversicolor* uses OM as its sole food source [15]. There are to our knowledge no specific studies regarding the ability of *H. reticulata* to metabolize PAHs. *N. diversicolor* has been shown to metabolize PAHs to a certain extent; however, the metabolization rate constants are most likely considerably lower than the uptake rate constants so that PAH biotransformation does not influence steady-state uptake [15,18].

96 In addition, *N. diversicolor* is one of the most studied marine invertebrates with regard to
97 bioaccumulation [15,18,19].
98 All of the test organisms were collected in May 2005 at a fixed location in the outer Oslofjord
99 where concentrations of metals and organic pollutants are on background levels for
100 Norwegian fjord and coastal sediments. PAH contents in the reference sediment (16-PAH)
101 were ~ 100 µg/kg dw, about 2-3 orders of magnitude lower than the PAH concentrations in
102 the test sediments. Adult organisms (both sexes) were picked to avoid growth dilution. The
103 size of the *H. reticulata* individuals was approximately 15 mm in length and 1.3 g in weight
104 (0.3 g without the shell); the employed specimens of *N. diversicolor* were 40-80 mm long.
105 The organisms were acclimatized in the laboratory for ≥ 14 d in an aquarium with flowing
106 clean seawater.
107 Briefly, homogenized sediments were placed in 5-L all-glass aquaria. Twenty-one aquaria
108 each holding 1.5 kg sediment were deployed: aquaria for the original sediments (three
109 triplicates), for the three AC-amended ones (three triplicates) and for the reference sediment
110 (one triplicate). This reference sediment originated from the place where the organisms were
111 collected. *H. reticulata* (10 individuals) and *N. diversicolor* (22 individuals) were added to
112 each aquarium after 24 h. To provide oxygen, clean seawater (as described above) was
113 circulated over the sediment in each aquarium at a rate of 150 mL/min. Temperature (7.2 ±
114 0.2°C), salinity (34.8 ± 0.2 practical salinity units), pH (8.00 ± 0.05) and oxygen (83 ± 3%
115 saturation) in the water were monitored and found to vary little throughout the experiment.
116 At the termination of the experiment (28 days), all *H. reticulata* and on average 14 out of the
117 22 individuals of *N. diversicolor* could be retrieved from the aquaria. No significant
118 differences in mortality were observed between the 18 test sediments and the three reference
119 sediments (t-test, 95%), so the mortality of *H. reticulata* was probably not caused by the
120 contamination of the test sediments. The soft parts of the gastropods were separated from

121 their hard shell, and rinsed in seawater. The polychaetes were held in seawater for 12 h to
122 empty all sediment remnants from their guts. All individuals from one species in each
123 aquarium were pooled into one sample (3-6 g wet weight). An exposure time of 28 d results in
124 steady-state tissue residues [20].
125 **Analysis of organism tissue.** To obtain measurable amounts of lipid, small aliquots of the
126 organism quantity from the triplicate aquaria were pooled into one sample for lipid analysis.
127 Lipids were determined gravimetrically following Folch et al [21].
128 PAH analysis of the organisms was accomplished as described previously [15]. Briefly,
129 samples (about 3-6 g wet weight) were homogenized, six deuterated PAHs were added as
130 internal standards and the mixture was subsequently saponified. The PAHs were extracted
131 with *n*-pentane and the extracts were dried over sodium sulfate. The extraction volume was
132 reduced, solvent-exchanged to dichloromethane, and the extracts were cleaned by gel
133 permeation chromatography and solvent-exchanged to cyclohexane. The extracts were
134 analyzed by GC-MS (Agilent GC 6890 with MSD 5973) in selected ion monitoring mode.
135 Measured PAH contents in organisms exposed to the test sediments were not corrected for
136 initial PAH contents (i.e., the PAH contents in organisms exposed to the reference sediment),
137 as it was assumed that the organisms in the test sediments would have reached a new steady
138 state independent of their initial PAH body burden, provided that these initial internal
139 concentrations were relatively low. Therefore results are reported on the condition that PAH
140 contents in organisms exposed to test sediment were more than twice the PAH contents in
141 organisms exposed to the reference sediment.
142
143 **Results and discussion**
144 **BSAF of original sediments based on free vs. total concentrations.** Measured BSAFs were
145 calculated from the data as

$$BSAF_{measured} = \frac{C_{lipid}}{C_{TOC}} \quad (1)$$

where C_{lipid} (mg/kg lipid) is the lipid-normalized concentration in the organisms and C_{TOC} the TOC-normalized concentration in the sediment (mg/kg organic carbon). Median $BSAF_{measured}$ values were 0.004-0.01 for all PAHs in both organisms in all three sediments (Table 2), around two orders of magnitude lower than the "theoretical" value ($BSAF_{theoretical}$ being slightly above one because lipids are usually a bit more hydrophobic than AOC [22,23]). It should be noted that the effects of strong PAH sorption to CGC are not considered in this theory. As indicated in the Methods section as well as in Table 1 and Cornelissen et al. [9], the presence of CGC caused K_{TOC} of our sediments to be more than two orders of magnitude higher than LFER-K_{OC} values based on AOC sorption only.

To compare measured BSAFs to theoretical ones, ratios between these two values are reported (Table 2). Median $BSAF_{theoretical}$: $BSAF_{measured}$ ratios were as high as 89-240. We hypothesize that strong sorption (to CGC) is the reason for the low observed BSAFs. To test this hypothesis, BSAFs were also estimated on the basis of the freely dissolved aqueous concentrations for the same sediment batches, $C_{w,free}$ (determined using the polyoxymethylene passive sampler method and reported in Cornelissen et al. [9]). This way, overall TOC sorption (to AOC and CGC) is taken into account. Such $BSAF_{free}$ values were determined as

$$BSAF_{free} = \frac{K_{lipid} \cdot C_{w,free}}{C_{TOC}} \quad (2)$$

where K_{lipid} is the lipid–water partition coefficient (L/kg; approximated as equal to octanol–water partition coefficient (K_{ow}) values from Mackay et al. [24]). It should be pointed out that equation (2) is no attempt to correct $BSAF_{measured}$ to the theoretical value. Instead it provides an independent chemical method for estimating BSAF that takes into account strong sorption. $BSAF_{free}$ was compared to the empiric $BSAF_{measured}$ by calculating $BSAF_{free}$: $BSAF_{measured}$ ratios. These appeared to be close to one (medians 1.7-4.3; Table 2), although estimations for

170 K_{lipid} were used (estimated as being equal to K_{OW}). In our previous paper [9], we showed that
171 the low freely dissolved PAH concentrations (used in eqn. 2) in these sediments could be
172 explained by strong sorption to CGC. Thus, strong sorption to CGC is probably the reason for
173 the low BSAF values observed for these sediments. This implies that BSAFs are better
174 described by freely dissolved aqueous concentrations than by total sediment contents.
175 In addition, biological/ecological factors can influence the magnitude of BSAF. For example,
176 K_{lipid} can vary among organisms, and sediment ingestion and gut fluid characteristics may
177 influence the uptake kinetics and thus the rate at which steady-state is reached [25]. In
178 addition, the trophic structure of the ecological system can influence BSAFs [26]. However, it
179 is not likely that variations in ecological factors can explain the observed 100-fold deviations
180 from $BSAF_{theoretical}$ such as observed here. In addition, the two tested organisms showed very
181 similar $BSAF_{measured}$ for the original sediments. Therefore strong sorption rather than
182 biological/ecological factors most likely explains the low $BSAF_{measured}$. Any noteworthy PAH
183 biotransformation has likely not influenced our results because of i) the similar findings for
184 different organisms, and ii) the good agreement between $BSAF_{free}$ and $BSAF_{measured}$ (Table 2).
185 Theoretically, it would be expected that significant PAH biotransformation would lead to
186 $BSAF_{free}$ being higher than $BSAF_{measured}$. In fact, it was observed that $BSAF_{free}$ slightly
187 exceeded $BSAF_{measured}$ by a factor of 1.7-4.3 (Table 2). One possibility is that this difference
188 can be attributed to (limited) biotransformation, but it is also possible that the "real" K_{lipid} for
189 the organisms is below K_{OW} (in the calculation of $BSAF_{free}$, eqn. 2, it was assumed that K_{lipid}
190 = K_{OW}).
191 The present findings are in agreement with earlier observations by Kraaij et al. [27] who
192 observed that $C_{W,free}$ measured by Solid-Phase Micro-Extraction (SPME) was a good
193 predictor for BSAFs of laboratory-added PAHs and PCBs in one specific sediment and for
194 one particular organism (the oligochaete *Tubifex sp.*). Other observations where strong

195 sorption to CGC probably explained variations in BSAF-values include e.g. i) variation in
196 BSAFs of organic compounds for deposit-feeders in New York Harbor sediments [26], ii)
197 BSAFs for mussels being lower for pyrogenic PAHs than for petrogenic ones [28,29], iii)
198 improved BSAF data modeling for PAH uptake in invertebrates through the inclusion of CGC
199 [30], iv) K_{TOC} values being higher [31] and BSAFs being lower [32] in the rainy season than
200 in the dry period due to higher surface runoff of BC, and v) BSAF values of native PAHs in
201 six sediments decreasing by approximately a factor of 20 when native BC contents increased
202 from 0.1 to 0.45% [33].
203 **Effect of AC amendment.** Lipid contents did not show a clear difference between organisms
204 in the original sediments and in the AC-amended ones (Table 3). Neither were there any clear
205 differences between organisms exposed to the clean reference sediment and the tested
206 contaminated ones, with the exception of *H. reticulata*, where the lipid contents were higher
207 in the test sediments. Unfortunately no statistical analysis can be offered to substantiate the
208 above comparisons due to the manner in which lipids were quantified (samples for the three
209 replicate aquaria per sediment had to be pooled in order to obtain enough lipid mass for an
210 accurate analysis). In spite of this, it can be stated that our results are not in agreement with
211 those of Jonker et al. [13], who observed that individuals of the aquatic oligochaete
212 *Limnodrilus sp.* exposed to sediments amended with 1.5 wt-% coal or charcoal for 28 d
213 possessed an order of magnitude lower lipid contents than worms exposed to original
214 sediment. We did not see this adverse effect on habitat quality of our AC (charcoal) additions.
215 Our previous chemical study of the current sediments [9] showed that the presently used AC
216 was very effective in reducing freely dissolved PAH concentrations in the porewater ($C_{W,free}$)
217 for these sediments: $C_{W,free}$ was reduced 17-fold (OS), 33-fold (BG) and 55-fold (TR) by 2 wt-
218 % AC amendment (medians for all PAHs; Table 4 and ref. [9]). The present measurements
219 showed that bioaccumulation (BSAF) was less strongly reduced by AC amendment than

220 $C_{W,free}$ (Table 4; significant difference for 44 out of 49 comparisons; t-test on individual
221 PAHs, 95%). BSAFs were significantly reduced for *N. diversicolor* in two of the sediments
222 (OS and TR; median reduction factor 6 and 7, respectively; Table 4). A t-test (95%) showed
223 that the reductions in BSAF for *N. diversicolor* in these two sediments were significant for 9
224 out of 14 comparisons of individual PAHs. For the other four sediment-organism
225 combinations (*N. diversicolor* in BG sediment, *H. reticulata* in all three sediments)
226 amendment of 2 wt-% AC resulted in significant BSAF reductions in 4 out of 30 cases (Table
227 4; t-test on individual PAHs, 95%), so AC amendment appeared hardly effective in those
228 cases.
229 These results show that differences in the effectiveness of AC amendment probably exist
230 between sediments and organisms. One must, however, consider the possibility that the
231 absence of an effect of AC amendment for the snail *H. reticulata* may partly be accounted for
232 by foldings in its body surface [34]: fine AC particles could adhere in these foldings and
233 inadvertedly be analyzed as taken up by the organism. PAHs sorbed to such particles would
234 be quantified as bioaccumulated, but in fact they are present in a nonbioavailable form, likely
235 also for organisms that prey on *H. reticulata*. Unfortunately no organism material was left
236 after the chemical analyses to test this hypothesis. To a lesser extent, this process of AC
237 sorbing to the organisms' surface could have played a role for *N. diversicolor* as well. That
238 leaves, however, unexplained why reduction factors in BSAF were so different between the
239 three sediments for this organism.
240 Earlier studies provide contradicting information on the effect of amendment of carbonaceous
241 materials. For example, the addition of 1.5% coal and charcoal led to a seemingly extensive
242 reduction (factor 1.5-8) of total concentrations of sediment-bound PCBs in *Limnodrilus sp.*
243 (aquatic worms) [13]; however, when normalizing the results on lipid contents, actually an
244 increase of BSAFs was observed as the organisms' lipid contents were drastically reduced

upon coal/charcoal amendment. Other studies indicate that BSAF is lowered by CGC and AC additions: i) BSAFs of PCBs were reduced by factors of 3 and 7 for *Neanthes arenaceodentata* (polychaeta) and *Leptocheirus plumulosus* (amphipoda), respectively, upon the addition of 3.4% AC [11]; ii) the carbonaceous resin Ambersorb was observed to significantly reduce the bioaccumulation of native PAHs in *Lumbriculus variegatus* (oligochaeta) [10]; iii) the amendment of 3.4% AC lowered PCB uptake by factors of 14 and 10 for *N. arenaceodentata* and *L. plumulosus*, respectively [12]; iv) uptake of benzo[*a*]pyrene (BaP) by *Macoma baltica* (bivalvia) was lower from coke, char, anthracite and activated carbon than from wood and diatoms [36], AC-bound HOCs being up to 60 times less bioavailable than coke, char and anthracite-bound HOCs; v) BSAFs for sediment amended with BC-bound pyrogenic PAHs were six times lower than those of the same sediment amended with BC-bound petrogenic PAHs [35].

The present study is the most extensive one so far on the effect of native CGC and amended AC on bioaccumulation, with three sediments, two organisms and native compounds. In addition, it is the first one where these two processes are simultaneously studied. In the first part of the study, it was shown that the effect of CGC on BSAFs very closely follows its effect on sorption for all organism-sediment combinations, so that freely dissolved concentrations are accurate predictors of actual bioaccumulation in all cases. In contrast, the effects of AC amendments on BSAFs were observed to be site- and organism-specific (significant reductions of BSAFs upon 2% AC amendments for two out of six tested organism-sediment combinations). This implies that site-specific evaluations of the effect of AC amendment are necessary, for several benthic organisms that are relevant to the potentially remediated site.

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Table 1: Sediment characteristics of Oslo (OS), Bergen (BG) and Tromsø (TR) sediments. Chemical parameters are presented for the example compound PHE. Chemical data for the other PAHs are in [9].

	OS	BG	TR
Latitude	59° 54′ 21″ N	60° 23′ 26″ N	69° 39′ 03″ N
Longitude	10° 45′ 01″ E	05° 18′ 15″ E	18° 15′ 42″ E
Total Organic Carbon (TOC;%)[a]	4.2	7.4	1.7
Total Organic Nitrogen (TON;%)[a]	0.26	0.27	0.13
Black Carbon (BC;%)[a]	0.25	0.90	0.12
BC:TOC[a]	6.1	12.1	6.7
CGC:TOC[b]	50.9	55.8	27.9
Total-PAH (mg/kg dw[c]**)**	31.1 ± 1.5	161 ± 31	9.0 ± 1.1
C_{SED} (PHE; mg/kg dw)[d]	1.10 ± 0.06	6.2 ± 2.4	1.1 ± 0.4
$C_{W,free}$ (PHE; ng/L)[e]	16.8 ± 2.5	128 ± 21	59 ± 12
log K_{TOC} (PHE; L/kg)	6.19 ± 0.09	5.79 ± 0.17	6.13 ± 0.12
log K_{AOC} (PHE; L/kg)[f]	4.2	4.2	4.2

[a] from [14]
[b] CGC, Carbonaceous Geosorbent Carbon, i.e., the total carbonized OM + the unburned coal carbon, derived from organic micropetrography [9].
[c] dw, dry weight
[d] total PHE concentration in the sediment [9]
[e] Freely dissolved PHE concentration [9]
[f] AOC, amorphous organic carbon. Value derived from a Linear Free Energy Relationship for PAHs: log K_{OC} = 0.98 log K_{OW} – 0.32 [36], with log K_{OW} from [23].

Table 2: BSAF of original Oslo (OS), Bergen (BG) and Tromsø (TR) sediments (kg_{OC}/kg_{lipid}), as well as ratios between theoretical and empiric BSAFs ($BSAF_{theory}$ / $BSAF_{measured}$) and between BSAFs calculated on the basis of freely dissolved concentrations and empiric ones ($BSAF_{free}$ / $BSAF_{measured}$).

		Nereis diversicolor (Polychaeta)			*Hinia reticulata* (Gastropoda)		
		$BSAF_{measured}$	Ratio $BSAF_{theory}$ / $BSAF_{measured}$	Ratio $BSAF_{free}$ / $BSAF_{measured}$	$BSAF_{measured}$	Ratio $BSAF_{theory}$ / $BSAF_{measured}$	Ratio $BSAF_{free}$ / $BSAF_{measured}$
OS	PHE	b.d.[a]	x[b]	x	b.d.	x	x
	FLU	b.d.	x	x	0.0115 ± 0.0038	87 ± 29	1.9 ± 0.6
	PYR	0.095 ± 0.010	10.5 ± 1.1	0.30 ± 0.02	0.077 ± 0.009	13 ± 2	0.40 ± 0.02
	CHR	b.d.	x	x	b.d.	x	x
	BBF	0.0057 ± 0.0019	175 ± 57	2.3 ± 0.6	0.0067 ± 0.0038	150 ± 85	2.0 ± 1.0
	BEP	0.038 ± 0.015	26 ± 10	1.5 ± 0.4	0.052 ± 0.021	19 ± 8	1.1 ±0.3
	BAP	0.0042 ± 0.0015	240 ± 86	3.4 ± 1.0	0.0064 ± 0.0037	156 ± 89	2.2 ± 1.1
	PER	0.0041 ± 0.0011	241 ± 62	1.8 ± 0.4	0.0075 ± 0.0038	133 ± 67	1.0 ±0.5
	IND	0.0022 ± 0.0005	450 ± 106	10 ± 2	0.008 ± 0.007	119 ± 96	3 ± 2
	BGP	0.0036 ± 0.0014	274 ± 105	6 ± 2	0.012 ± 0.009	81 ± 59	1.8 ± 1.3
	Median	**0.0042**	**240**	**2.3**	**0.010**	**103**	**1.8**
	IQR[c]	**0.0038-0.021**	**100-258**	**1.6-4.7**	**0.006-0.018**	**66-137**	**1.1-2.0**
BG	PHE	b.d.	x	x	0.010 ± 0.006	96 ± 56	2.5 ± 0.5
	FLU	0.008 ± 0.004	115 ± 53	3.1 ± 0.6	0.007 ± 0.003	143 ± 67	3.8 ± 0.8
	PYR	0.11 ± 0.04	9 ± 4	0.36 ± 0.05	0.032 ± 0.012	31 ± 11	1.3 ± 0.1
	CHR	0.002 ± 0.002	474 ± 420	6 ± 4	0.002 ± 0.001	473 ± 225	6.0 ± 1.1
	BBF	0.010 ± 0.008	94 ± 70	1.2 ± 0.4	0.007 ± 0.002	138 ± 68	1.7 ± 0.2
	BEP	0.06 ± 0.02	16 ± 7	0.7 ± 0.2	0.032 ± 0.012	31 ± 12	1.4 ± 0.2
	BAP	0.006 ± 0.003	167 ± 72	2.2 ± 0.7	0.006 ± 0.002	156 ± 46	2.1 ± 0.4
	PER	0.010 ± 0.002	99 ± 21	0.9 ± 0.2	0.012 ± 0.002	85 ± 19	0.8 ± 0.1
	IND	0.007 ± 0.006	155 ± 145	5 ± 2	0.016 ± 0.010	63 ± 40	2.0 ± 0.3
	BGP	0.009 ± 0.006	114 ± 72	2.5 ± 0.9	0.018 ± 0.007	56 ± 22	1.2 ± 0.2
	Median	**0.0094**	**107**	**1.7**	**0.011**	**90**	**1.8**
	IQR	**0.0070-0.051**	**35-145**	**0.8-2.9**	**0.007-0.017**	**58-142**	**1.3-2.4**
TR	PHE	b.d.	x	x	b.d.	x	x
	FLU	0.028 ± 0.008	36 ± 5	1.0 ± 0.2	0.016 ± 0.004	62 ± 14	1.7 ± 0.1
	PYR	0.058 ± 0.013	17 ± 6	0.45 ± 0.03	0.015 ± 0.004	69 ± 21	1.8 ± 0.3
	CHR	b.d.	x	x	b.d.	x	x
	BBF	0.011 ± 0.002	93 ± 25	2.8 ± 0.5	0.0057 ± 0.0028	174 ± 85	5 ± 2
	BEP	0.024 ± 0.008	42 ± 13	1.7 ± 0.2	0.011 ± 0.005	85 ± 39	3.4 ± 0.8
	BAP	0.011 ± 0.007	86 ± 50	6 ± 2	0.008 ± 0.007	120 ± 96	8 ± 5
	PER	0.0029 ± 0.0013	347 ± 161	3.0 ± 0.6	0.006 ± 0.007	181 ± 253	1.6 ± 1.8
	IND	0.010 ± 0.008	97 ± 74	11 ± 7	0.012 ± 0.007	85 ± 51	10 ± 5
	BGP	0.007 ± 0.004	146 ± 86	8 ± 4	0.010 ± 0.006	96 ± 56	5 ± 2
	Median	**0.011**	**89**	**2.9**	**0.0094**	**91**	**4.3**
	IQR	**0.0077-0.027**	**36-109**	**1.4-6.2**	**0.006-0.012**	**81-133**	**1.8-5.9**

[a] b.d., below detection, defined as the situation where C_{biota} was less than twice the C_{biota} in the reference sediment.

[b] x, cannot be calculated because C_{biota} was below detection.

[c] IQR, Interquartile range.

Table 3: Lipid contents in the presence and absence of AC, of Oslo (OS), Bergen (BG) and Tromsø (TR) sediments as well as clean reference sediment.

Sediment	Lipid content (%)			
	N. diversicolor (Polychaeta)		*H. reticulata* (Gastropoda)	
	No AC	2% AC	No AC	2% AC
Reference sediment[a]	0.73		0.78	
OS	1.3	0.51	1.3	1.2
BG	0.68	0.94	1.2	1.2
TR	0.82	0.62	1.3	1.6

[a] clean sediment from outer Oslofjord (see text).

Table 4: BSAF-values after AC addition (2%), and reduction factors of $C_{W,free}$ and BSAF due to 2% AC amendment, for Oslo (OS), Bergen (BG) and Tromsø (TR) sediments. For example, $C_{W,free}$ of PHE in OS sediment was reduced 17-fold by the addition of 2% AC.

			N. diversicolor		*H. reticulata*	
		Reduction factor $C_{w,free}$[a]	**$BSAF_{AC}$**[b]	**Reduction factor $C_{biota,lipid}$**[c]	**$BSAF_{AC}$**	**Reduction factor $C_{biota,lipid}$**
OS	PHE	17	x[d]	x	x	x
	FLU	53	x	x	0.011 ± 0.003	1.6 ± 0.9
	PYR	46	0.0048 ± 0.0033	29 ± 20	0.010 ± 0.002	11 ± 2
	CHR	31	x	x	x	x
	BBF	18	0.0012 ± 0.0008	7 ± 6	0.0071 ± 0.0017	1.4 ± 0.4
	BEP	17	0.006 ± 0.003	9 ± 5	0.022 ± 0.005	3.4 ± 1.2
	BAP	11	0.0023 ± 0.0016	2.5 ± 2	0.007 ± 0.002	1.3 ± 0.8
	PER	9	0.0043 ± 0.0004	1.4 ± 0.4	0.0095 ± 0.0013	1.1 ± 0.6
	IND	3	0.0030 ± 0.0007	1.1 ± 0.4	0.012 ± 0.002	1.0 ± 0.9
	BGP	3	0.0006 ± 0.0002	9 ± 6	0.014 ± 0.003	1.3 ± 1.1
	Median	**17**	**0.0030**	**7**	**0.010**	**1.3**
	IQR[e]	**9-28**	**0.0018-0.0045**	**2-9**	**0.009-0.012**	**1.2-2.0**
BG	PHE	33	x	x	0.018 ± 0.017	0.7 ± 0.6
	FLU	127	0.009 ± 0.009	1 ± 1	0.008 ± 0.008	1.1 ± 1.1
	PYR	113	0.008 ± 0.006	19 ± 14	0.009 ± 0.008	4 ± 3
	CHR	61	0.003 ± 0.003	0.9 ± 1.1	0.003 ± 0.003	0.8 ± 0.6
	BBF	32	0.008 ± 0.008	1.7 ± 1.2	0.009 ± 0.008	1.0 ± 0.7
	BEP	39	0.018 ± 0.015	4 ± 3	0.025 ± 0.017	1.6 ± 1.0
	BAP	30	0.007 ± 0.006	1.1 ± 1.2	0.007 ± 0.005	1.1 ± 0.8
	PER	16	0.013 ± 0.008	1.0 ± 0.7	0.014 ± 0.009	1.0 ± 0.7
	IND	8	0.02 ± 0.03	0.4 ± 0.5	0.018 ± 0.018	1.1 ± 0.7
	BGP	8	0.014 ± 0.012	0.8 ± 0.7	0.018 ± 0.014	1.2 ± 0.7
	Median	**33**	**0.010**	**1.2**	**0.012**	**1.1**
	IQR	**19-56**	**0.008-0.014**	**0.9-3.7**	**0.008-0.018**	**1.0-1.2**
TR	PHE	27	x	x	x	x
	FLU	236	x	x	0.03 ± 0.04	1.2 ± 1.8
	PYR	147	0.003 ± 0.002	43 ± 33	0.02 ± 0.03	2 ± 2
	CHR	76	x	x	x	x
	BBF	64	0.005 ± 0.003	5 ± 3	0.03 ± 0.03	0.4 ± 0.6
	BEP	46	0.005 ± 0.001	11 ± 2	0.02 ± 0.02	1.1 ± 1.3
	BAP	66	0.010 ± 0.004	2.0 ± 1.2	0.05 ± 0.06	0.4 ± 0.6
	PER	25	0.0012 ± 0.0003	5.0 ± 1.1	0.012 ± 0.011	1 ± 2
	IND	20	0.0032 ± 0.0005	7 ± 4	0.06 ± 0.07	0.4 ± 0.6
	BGP	18	0.009 ± 0.001	1.5 ± 0.7	0.04 ± 0.04	0.6 ± 0.8
	Median	**55**	**0.0046**	**6**	**0.03**	**0.9**
	IQR	**25-74**	**0.0031-0.0070**	**4-19**	**0.02-0.04**	**0.4-1.2**

[a] from [9]; [b] BSAF after AC amendment; [c] reduction factor in C_{biota} (lipid weight basis); [d] x, cannot be calculated because C_{biota} was below detection (less than twice the concentrations in reference organisms); [e] IQR, Interquartile range.