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► **To cite this version:**

Bruno Danis, Olivier Cotret, Jean-Louis Teyssié, Scott W. Fowler, Paco Bustamante, et al.. Delineation of PCB uptake pathways in a benthic sea star using a radiolabelled congener. *Marine Ecology Progress Series*, 2003, 253, pp.155-163. 10.3354/meps253155 . hal-00336154

**HAL Id: hal-00336154**

**<https://hal.science/hal-00336154>**

Submitted on 2 Nov 2008

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1 **Delineation of PCB uptake pathways in a benthic sea star using a radiolabelled congener**

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1 **ABSTRACT**

2 *Asterias rubens*, a common sea star in North Sea waters, was selected to study the  
3 bioaccumulation of an important polychlorinated biphenyl congener, <sup>14</sup>C-labelled PCB#153,  
4 from two contrasted sources : sea water and sediments. After 4 weeks of acclimation to  
5 laboratory conditions, sea stars were exposed for 34 days to realistic concentrations (30 ng l<sup>-1</sup> in  
6 sea water and 9.5 ng g<sup>-1</sup> DW in sediments) of the contaminant during which time  
7 bioaccumulation of PCB#153 was followed in 6 body compartments. Results showed that (1)  
8 for each body compartment, PCB uptake kinetics were generally asymptotic and  
9 bioaccumulation was far greater when *A. rubens* was exposed via sea water than via sediments,  
10 (2) body wall and podia were the body compartments showing the greatest affinity for the PCB  
11 congener making them ideal tissues for biomonitoring purposes, and (3) the concentrations  
12 reached in body compartments were in the range of values reported in several field studies.  
13 Because radioisotopic techniques are extremely sensitive, they allow taking into account key  
14 organs which are sometimes too small for standard analysis of PCBs.

15

16 **KEYWORDS**

17 Polychlorinated biphenyls; PCB#153; bioaccumulation; kinetics; *Asterias rubens*; echinoderm

18

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20 **RUNNING HEADING**

21 PCB bioaccumulation in sea stars

22

## 1 INTRODUCTION

2 Polychlorinated biphenyls (PCBs) are strictly anthropogenic chemicals that constitute one of  
3 the most problematic and widespread group of contaminants. These xenobiotics, represented by  
4 209 congeners, are extremely resistant to degradation (physico-chemical or biological), are  
5 bioconcentrated by living organisms, and can cause various adverse effects depending on their  
6 pattern and degree of chlorine substitution (Metcalf 1994). For PCBs entering the marine  
7 environment, bottom sediments are the ultimate repository where they may become a source  
8 for uptake by marine organisms through direct or indirect contact or, for filter feeders, by  
9 ingestion; however, information about their impact on benthic species is relatively scarce  
10 (Chapman 1995, Carr *et al.* 1996, Wood *et al.* 1997).

11 According to different authors, the asteroid *Asterias rubens* qualifies as an excellent  
12 bioindicator organism for monitoring heavy metal contamination in the North Sea and NE  
13 Atlantic benthic ecosystems (Knickmeyer *et al.* 1992, den Besten *et al.* 1993, Everaarts *et al.*  
14 1998, Temara *et al.* 1998, Warnau *et al.* 1999). It is indeed a widely distributed and abundant  
15 key species (*sensu* Lewis 1978) that is easy to collect, identify and maintain in the laboratory.  
16 In addition, *A. rubens* is a top predator feeding mainly on mussels and living on or in the  
17 proximity to bottom sediments which are the main reservoir of many contaminants, including  
18 PCBs. The biological and ecological characteristics of *A. rubens* as well as its potential  
19 economic impact (as a predator of commercially important mussels) have lead some authors to  
20 use this species as a tool to assess the degree of PCB contamination in the North Sea (den  
21 Besten *et al.* 1989, 1993, Everaarts *et al.* 1998). However, to the best of our knowledge, no  
22 study has investigated PCB bioaccumulation processes in *A. rubens*. The only two  
23 experimental studies investigating PCB bioaccumulation in echinoderms concern sea urchins  
24 exposed to contaminated sediments (Weisberg *et al.* 1996, Schweitzer *et al.* 2000), and only  
25 Weisberg *et al.* (1996) examined the kinetic aspects of PCB uptake.

1 Such data are however needed to further assess the value of *Asterias rubens* as a bioindicator of  
2 PCB contamination. Therefore, in the present study, we have investigated the kinetics of PCB  
3 uptake in *A. rubens* exposed either to the contaminant in sea water or associated with  
4 sediments, i.e. the two extreme pathways of contamination from the viewpoint of absolute PCB  
5 concentrations. Indeed, the high hydrophobicity of PCBs result in a characteristic partitioning  
6 with concentrations in sea water typically in the range of pg to ng l<sup>-1</sup> while sediment  
7 concentrations are in the range of µg to mg kg<sup>-1</sup> (see Table 1). The PCB congener IUPAC #153  
8 (2,2',4,4',5,5' hexachlorobiphenyl) was selected because it is the most abundant in marine  
9 biota (Stebbing *et al.* 1992) and has been shown to be an excellent indicator of total PCB  
10 contamination (Atuma *et al.* 1996).

11

## 12 **MATERIALS AND METHODS**

13 **Sampling.** The sea stars *Asterias rubens* (Linnaeus 1758) were collected in April 1999 in the  
14 intertidal zone at Audresselles (Pas-de-Calais, France). Prior to experimentation, specimens  
15 were acclimated to laboratory conditions for 1 month in constantly aerated closed circuit  
16 aquaria (salinity: 36 ‰, T: 16 ± 0.5 °C, 12/12 h dark/light cycle).

17 In order to follow PCB#153 bioaccumulation under realistically simulated conditions, a <sup>14</sup>C-  
18 labelled congener was used and measured using highly sensitive β spectrometry.

19 **Radiotracer.** The <sup>14</sup>C-labelled 2,2',4,4',5,5' hexachlorobiphenyl (purity ≥ 95%) was purchased  
20 from Sigma Chemicals, USA. Specific activity was 925 MBq mmol<sup>-1</sup>. Stock solutions were  
21 prepared in acetone at a concentration of 1 µg ml<sup>-1</sup>.

22 **Sample treatment and liquid scintillation counting.** Water samples (2 ml) were directly  
23 transferred to 20 ml glass scintillation vials (Packard, USA) and 10 ml of Ultima Gold XR<sup>®</sup>  
24 (Packard Instruments) scintillation liquid were added. Samples of sediment and sea star tissue  
25 (previously crushed) were placed in a vial containing 2 ml of Acetonitrile<sup>®</sup> in an ultrasonic bath  
26 for 10 min. Acetonitrile<sup>®</sup> was then collected and replaced by another 2 ml of Acetonitrile<sup>®</sup> and

1 the ultrasonic operation was repeated a second time. This treatment gave 4 ml of liquid phase  
2 (*viz.* the extraction) and a residue. The residue was digested overnight at 70°C with 2 ml of  
3 Soluene<sup>®</sup>, and 10 ml of Hionic Fluor<sup>®</sup> scintillation liquid were then added. The liquid phase (4  
4 ml) was added to 16 ml of filtered seawater and extracted twice using 2 ml of n-Hexane  
5 (Sigma, USA) under constant agitation. The organic phase (4 ml) and the aqueous phase (20  
6 ml) were treated separately. The entire organic phase and 2 ml of the aqueous phase were each  
7 added separately to 10 ml of Ultima Gold XR<sup>®</sup> scintillation liquid.  
8 <sup>14</sup>C-radioactivity was then measured using a 1600 TR Liquid Scintillation Analyzer (Packard),  
9 compared to standards of known activities, and corrected for quenching, background and  
10 physical decay of the radiotracer. Counting times were adjusted to obtain counting rates with  
11 relative propagated errors less than 5 %. PCB concentrations were expressed on a total lipid  
12 content basis where lipids were determined according to the method of Barnes & Blackstock  
13 (1973). A schematic diagram of the sample treatment is shown in Figure 1.

#### 14 **Experimental procedures**

15 *Uptake from sea water:* Asteroids (n = 24) were placed for 34 d in a 70 l glass aquarium  
16 (constantly aerated closed circuit aquaria; salinity 36 ‰; 16 ± 0.5°C; 12/12 h dark/light cycle)  
17 containing natural sea water spiked with <sup>14</sup>C-labelled PCB#153. One day prior to the  
18 experiments, four 5 l glass beakers were filled with filtered sea water (36 ‰; 16 ± 0.5°C),  
19 spiked with the radiolabelled PCB stock solution, and constantly stirred using an orbital  
20 agitation plate. Contaminated water then was poured into the glass aquaria and uncontaminated  
21 sea water was added to obtain a final volume of 70 l. Sea water and radiotracer were renewed  
22 every second day during the entire experiment. Activity was checked before and after each  
23 renewal to assess the stability of the labelled PCB concentration in sea water (Table 1). The sea  
24 stars were fed unlabelled mussels (*Mytilus edulis*) every second day just before the seawater  
25 renewal. After 2 hours uningested mussels were removed to limit as much as possible PCB  
26 incorporation via the food. Periodically (after 2, 4, 7, 11, 14, 21 and 34 days), sea stars (n = 3)

1 were removed, dissected into seven body compartments (oral and aboral body walls, pyloric  
2 caeca, gonads, rectal caeca, central digestive system, and podia), and radioanalyzed to  
3 determine uptake kinetics and body distribution of the incorporated PCB.

4 ***Uptake from sediments:*** Sediments (2.5 kg dry wt) from the North Sea (Audresselles, Pas-de-  
5 Calais, France) were contaminated for 4 days with the <sup>14</sup>C-labelled PCB using the rolling jar  
6 method (Murdoch *et al.* 1997). Sea stars (n = 24) were placed in a 70 l glass aquarium  
7 (constantly aerated open circuit aquarium; salinity 36 ‰; 16 ± 0.5°C; 12/12 h dark/light cycle)  
8 containing a 10 cm layer of sea water running over a 2 cm layer of spiked sediments. A  
9 separate group of 5 sea stars were placed in the same aquaria, but in another compartment (not  
10 in contact with the sediments), to serve as a control for possible cross-contamination through  
11 sea water. The sea stars were fed every second day with mussels (*Mytilus edulis*). Uningested  
12 food was removed after 2 hours. The radioactivity of the labelled PCB was measured weekly in  
13 the sediments to check for possible leaching (Table 1). Periodically (after 2, 4, 7, 11, 14, 21,  
14 and 34 days), 3 individuals were removed, dissected as described above, and their tissues  
15 counted for radioactivity.

16 **Data analyses.** Uptake of the PCB congener from sea water and sediments was expressed as  
17 change in PCB concentration (ng g<sup>-1</sup> total lipids) over time. Uptake kinetics were described  
18 either by using a saturation exponential model (eq 1), a single component exponential model  
19 (eq 2), or a combined model (logistic and single component exponential) (eq 3):

20

21 
$$C(t) = C_{ss} (1 - e^{-k \cdot t}) \quad (\text{eq 1})$$

22

23 
$$C(t) = C(0) e^{k \cdot t} \quad (\text{eq 2})$$

24

25 
$$C_t = C_{ss} (1 - e^{-k \cdot t}) / 1 + e^{-k \cdot (t-I)} \quad (\text{eq 3})$$

26

1 where  $C(t)$ ,  $C(0)$ , and  $C_{ss}$  are the PCB concentrations ( $\text{ng g}^{-1}$  total lipids), respectively, at time  $t$   
2 ( $d$ ), at time 0 and at steady state,  $k$  is the rate constant ( $d^{-1}$ ), and  $I$  is the time ( $d$ ) at the inflexion  
3 point. The model showing the best fitting accuracy (based on the calculation of the  
4 determination coefficient,  $R^2$ , and examination of the residuals) was used.  
5 Constants of the different models and their statistics were estimated by iterative adjustment of  
6 the models and Hessian matrix computation, respectively, using the nonlinear curve-fitting  
7 routines in the Systat<sup>®</sup> 5.2.1 software (Wilkinson 1988). Differences between PCB  
8 concentrations in the different sea star body compartments were tested by 1-way ANOVA and  
9 the multiple comparison test of Tukey (Zar 1996). Changes in PCB body distribution were  
10 tested for significance using the G-test (adapted from the log-likelihood ratio test) for 2xk  
11 contingency tables (Zar 1996). Prior to the latter test, data were arcsin-transformed using the  
12 correction of Freeman-Tukey (1950) described by Zar (1996). The level of significance for  
13 statistical tests was always set at  $\alpha = 0.05$ .

14

## 15 **RESULTS**

16 The uptake of PCB#153 by *Asterias rubens* was investigated through separate exposures to  
17 contaminated sea water or sediments. As differences between accumulation kinetics in aboral  
18 and oral body walls were never found in any experiment ( $p$  always  $> 0.1$ ), these two  
19 compartments were pooled and are presented as a single compartment (body wall) throughout  
20 the text. The uptake kinetics of PCB congener #153 in 6 different body compartments (body  
21 wall, pyloric caeca, gonads, rectal caeca, central digestive system, podia) are shown in Figures  
22 2 and 3 for the sea water and sediment exposures, respectively.

23 ***Contamination via sea water.*** Depending on the body compartment, accumulation from sea  
24 water was best described by a combined (logistic and exponential) model (*viz.* uptake in body  
25 wall, pyloric caeca, gonads and podia) or a single component exponential model (*viz.* uptake in  
26 central digestive system and rectal caeca) (Fig. 2, Table 2A).



1 Body wall was the compartment that concentrated  $^{14}\text{C}$ -PCB#153 to the greatest degree, up to  
2 two orders of magnitude higher than the rectal caeca ( $p_{\text{Tukey test}} \leq 0.0001$ ; Table 3).

3 Body distribution of incorporated  $^{14}\text{C}$ -PCB#153 varied significantly along the timecourse of  
4 the experiment ( $p_{\text{G-test}} < 0.05$ ). Initially, the contaminant was mostly present in the podia ( $74 \pm$   
5  $5\%$  of total body load after 2 days of exposure) and secondarily in the body wall ( $26 \pm 5\%$ ).  
6 Progressively, the proportion of the PCB associated with body wall increased, reaching  $69 \pm 5$   
7  $\%$  of the total body burden after 34 days of exposure, while during the same time the podia  
8 proportion had decreased to  $7 \pm 2\%$  (Table 4).

9 ***Contamination via sediments.*** Frequent radioanalysis of the contaminated sediments indicated  
10 that the maximum difference between measured  $^{14}\text{C}$ -PCB#153 activities was 13.1% and that no  
11 significant decreasing trends occurred; therefore, concentrations in labelled PCB remained  
12 relatively stable throughout the 34 d-long experiment ( $9.5 \pm 1.1 \text{ ng g}^{-1}$  dry wt; see Table 1).  
13 Similarly, radioactivity in the sea water and in control sea stars remained below the detection  
14 limit, indicating that no significant  $^{14}\text{C}$ -PCB was incorporated from suspended sediments  
15 possibly ingested by the mussels on which they fed nor from sea water due to cross  
16 contamination.

17 Accumulation from contaminated sediments was best described either by a single component  
18 exponential model (gonads), a saturation exponential model (podia), or a combined model  
19 (body wall, rectal caeca, pyloric caeca and central digestive system) (Fig. 3, Table 2B). As  
20 noted during the seawater exposure, body wall and podia were the body compartments that  
21 accumulated  $^{14}\text{C}$ -PCB#153 to the highest levels when exposed to labelled sediments (Table 5).

22 The distribution of  $^{14}\text{C}$ -PCB in sea star tissues was determined at different times during the  
23 timecourse of the experiment. Relative transfers among body compartments appeared quite  
24 different from those observed during the seawater uptake experiment. Indeed, the proportion of  
25 contaminant in the body wall and podia remained relatively constant throughout the

1 experiment. Body wall and podia contained the major part (ca. 60%) of the total body burden  
2 of <sup>14</sup>C-PCB, while the lowest percentage was found in the rectal caeca ( $\leq 0.3\%$ ) (Table 4).

#### 4 **DISCUSSION**

5 The present study reports the first experimental data on the bioaccumulation kinetics of a key  
6 PCB congener in the sea star *Asterias rubens*, a common species widely distributed in the  
7 North Sea and NE Atlantic. The fact that organisms were also exposed to very low background  
8 concentrations of stable PCB#153 (Table 1), showed that they were actually exposed to a  
9 global concentration of PCB#153 that did not differ significantly from the <sup>14</sup>C-PCB  
10 concentrations added experimentally to sea water or sediments (Table 1). Experimental  
11 concentrations in sea water were higher than those usually reported for PCB#153 in the natural  
12 North Sea waters. However, the latter concentrations most generally concern the dissolved  
13 fraction whereas our measurements involve both dissolved and particulate fractions. Although  
14 available PCB data on bulk seawater samples mostly concern the sum of congeners or PCB  
15 mixture equivalents, it is noteworthy that the experimental concentrations used here are quite  
16 close (even much lower if considering extreme hot spots) to values reported for moderate to  
17 highly contaminated marine locations (Table 1). In addition, the ratio between seawater and  
18 sediment PCB concentrations added is similar to the ratio between the background PCB  
19 concentrations measured in sea water and sediments used in the experiments (Table 1).  
20 Therefore, the experimental exposures may be considered as acceptable simulations of field  
21 exposure situations that may actually occur in the field.

22 Data on PCB concentrations in *Asterias rubens* in the field are scarce, and even less are  
23 available when looking for congener-specific data (e.g. Everaarts *et al.* 1998, den Besten *et al.*  
24 2001). It is noteworthy that the total PCB#153 concentrations (background + incorporated)  
25 reached in the pyloric caeca at the end of the experiments matched the concentrations reported  
26 in the same organs of sea stars from moderate to highly contaminated North Sea locations

1 (Table 6). No field data were found concerning PCB concentrations in the body wall.  
2 Considering the whole body, PCB concentrations reached in experimentally-exposed sea stars  
3 were 2 to 10 times higher than the few data available from the literature (Everaarts & Fischer  
4 1989 ; Table 6). However, these comparisons should be made with caution, since the latter  
5 field values are derived from sea stars collected during the spawning period. Indeed, it has been  
6 shown that the whole-body content of extractable lipids is strongly dependent on the sexual  
7 state of individuals, and may fluctuate by a factor of 2 to 3, particularly during the spawning  
8 period. This may result in a similar range of variations of PCB concentrations occurring within  
9 a few weeks (Knickmeyer 1992 ; Everaarts *et al.* 1998 ; Table 6).

10 Whether sea water or sediments were considered as a contamination source, a steady-state was  
11 reached or tended to be reached in most body compartments during the course of the  
12 experiments. This suggests either that target sites are rapidly saturated, or that a metabolization  
13 mechanism is induced quite rapidly following PCB exposure. Although a MFO-like system has  
14 been described in pyloric caeca of *Asterias rubens* by den Besten *et al.* (1990, 1993, 1998), it is  
15 well documented that PCB#153 is quite resistant to biological degradation (Sipes &  
16 Schnellmann 1987, Letcher *et al* 2000) due to its specific structure lacking hydrogen atoms on  
17 the biphenyl molecule (Borlakoglu & Wilkins 1993). Therefore, the hypothesis regarding target  
18 site saturation is considered to be the most plausible explanation.

19 It is also noteworthy that when a steady-state in uptake was observed, equilibrium  
20 concentrations of PCB#153 were generally reached quite rapidly (around day 20), indicating  
21 that the sea star could be used as a bioindicator to pinpoint a PCB contamination event soon  
22 after its occurrence.

23 Concentrations of incorporated <sup>14</sup>C-PCB#153 at steady-state were much higher (up to 300  
24 times) in body wall and podia than in any other compartment. Being easily dissected and  
25 constituting 70-80% of the total body weight, body wall is of particular interest with respect to  
26 field surveys, and it should be recommended as a body compartment to monitor

1 complementarily to pyloric caeca which are the only body compartment that has been used in  
2 previous studies (*e.g.*, Everaarts *et al.* 1998, den Besten *et al.* 1993, 2001).

3 Concentrations incorporated into the rectal caeca were always low, between one and two orders  
4 of magnitude lower than all the other compartments. This is somewhat surprising but could be  
5 related to the functions of the rectal caeca which are well known to play an essential role in sea  
6 star digestion and excretion processes (Jangoux 1982, Warnau & Jangoux 1999).

7 Our results have shown that PCB uptake is far more efficient in sea stars exposed to spiked sea  
8 water than to labelled sediments when compared to exposure concentrations. For a given body  
9 compartment, calculated concentration factors (CFs) based on sea water were between 2 and 3  
10 orders of magnitude higher than transfer factors (TFs) from sediments (Tables 3 and 5).  
11 Therefore, over the long term, despite the fact that sediments constitute the main reservoir of  
12 PCBs in the marine environment and that seawater PCB concentrations are comparatively  
13 extremely low, sea water would be an important route for PCB bioaccumulation in this sea star  
14 as it has been suggested for certain benthic infauna (*e.g.* Fowler *et al.* 1978). However, this  
15 does not imply that sea water would be the predominant pathway for PCB uptake, since our  
16 results showed that final concentrations reached in the different body compartments following  
17 the two types of exposure were generally of the same order of magnitude. In addition, direct  
18 trophic transfer was not addressed here and could also contribute significantly to PCB  
19 bioaccumulation in the sea star.

20 While this work constitutes the first report on PCB bioaccumulation kinetics in a sea star,  
21 several previous studies have used radiolabelled  $^{14}\text{C}$ -PCB to examine bioaccumulation kinetics  
22 in other aquatic organisms (*e.g.*, Goerke *et al.* 1973, Gooch & Hamdy 1982, Schweitzer *et al.*  
23 1997). However, surprisingly, these studies mostly concern PCBs as Aroclor equivalents (see  
24 *e.g.* Butcher *et al.* 1997). The main advantage of the  $^{14}\text{C}$  approach to measure PCB fluxes and  
25 transfers in aquatic biota is obviously the high sensitivity and the rapidity of the detection,  
26 compared to analytical techniques using gas chromatography. It therefore constitutes an

1 interesting tool, since current research on the behaviour of PCBs in the environment tends to  
2 focus on congener-specific information (Safe 1990, Metcalfe 1994, Letcher *et al.* 2000).  
3 Furthermore, it allows working with low (realistic) PCB concentrations, and assessing uptake  
4 in organs which are often too small to be analyzed by classical chemical methodologies.

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## 7 **ACKNOWLEDGEMENTS**

8 The IAEA Marine Environment Laboratory operates under a bipartite agreement between the  
9 International Atomic Energy Agency and the Government of the Principality of Monaco. B.D.  
10 is holder of a FRIA doctoral grant; M.W. is a Honorary Research Associate of the National  
11 Fund for Scientific Research (NFSR, Belgium). Research was partially supported by a Belgian  
12 Federal Research Programme (SSTC, Contract MN/11/30) and a NFSR fellowship to M.W.

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**CAPTIONS TO FIGURES:**

**Figure 1.** Schematic representation of sample processing before  $\beta$ -spectrometry analysis

**Figure 2.** *Asterias rubens*-Seawater experiment. Uptake of  $^{14}\text{C}$ -PCB#153 from seawater in different body compartments of the sea star (mean concentration in  $\text{ng g}^{-1}$  total lipids  $\pm$  SD,  $n=3$ )

**Figure 3.** *Asterias rubens*-Sediment experiment. Uptake of  $^{14}\text{C}$ -PCB#153 from sediments in different body compartments of the sea star (mean concentration in  $\text{ng g}^{-1}$  total lipids  $\pm$  SD,  $n=3$ ).

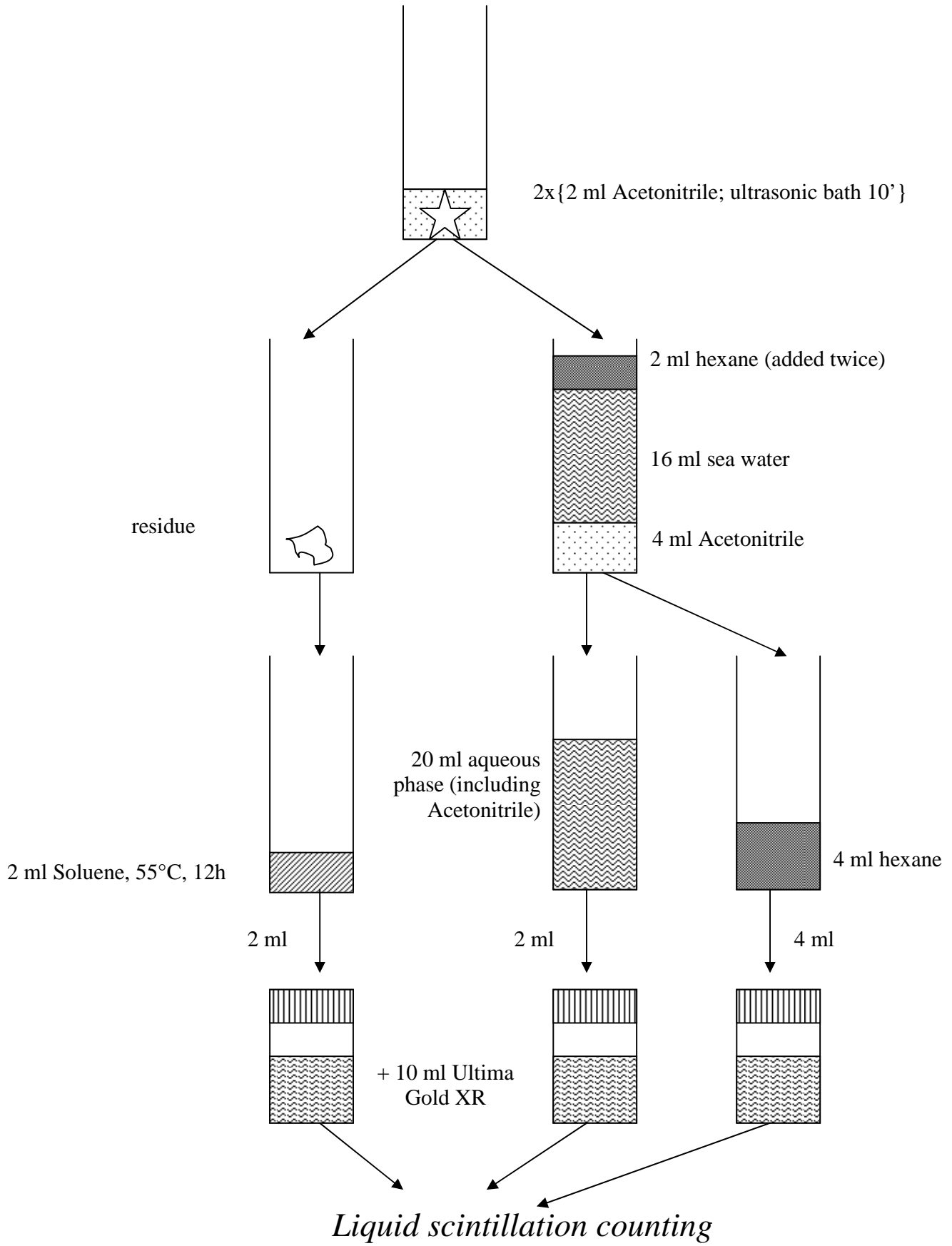


Figure 1

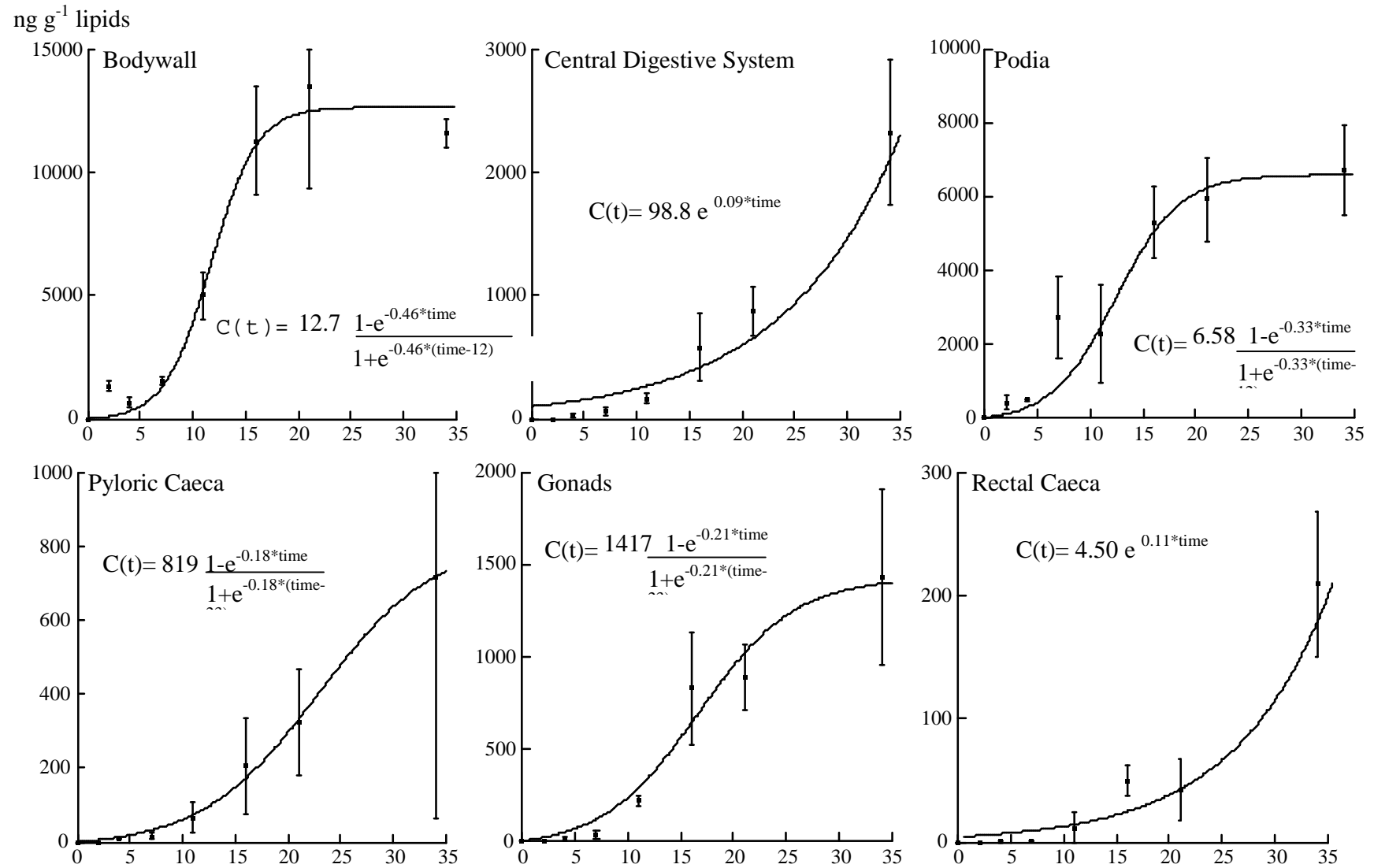


Fig. 2

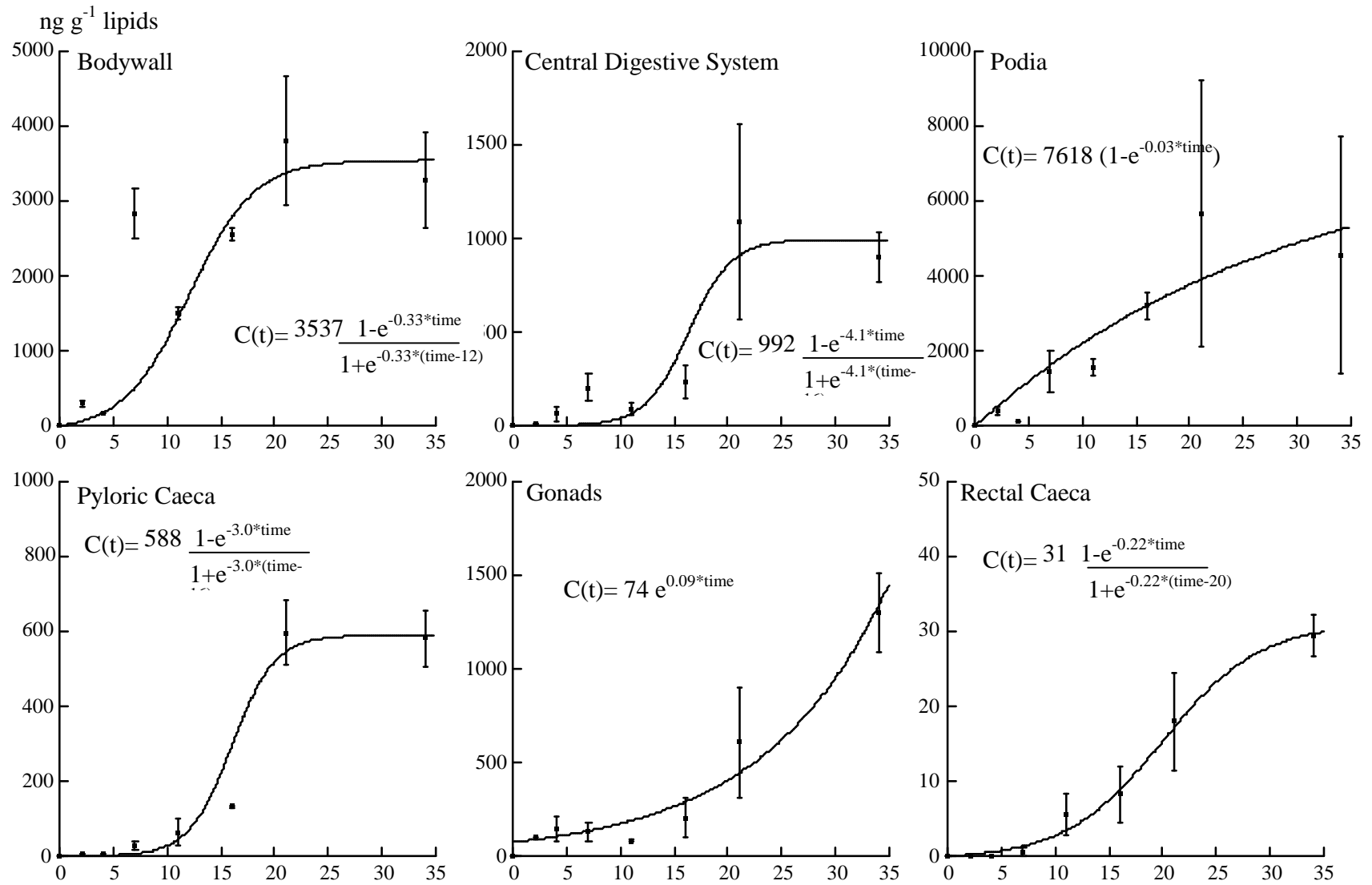


Fig. 3

Table 1. Characteristics of the background and added concentrations of PCB#153.

Background concentrations were measured in sediments, sea water and sea stars (body wall and pyloric caeca) the day before starting the experiment; added concentrations were measured in subsamples of sediments and sea water regularly collected in the experimental microcosms throughout the experiment. Ranges of values of PCB#153 (unless specified) reported for sediments and sea water in the field are given for comparison.

	Compartment	PCB concentration	Location	References
Background	Sediments	0.017 ng g <sup>-1</sup> dry wt (n = 6)		
	Sea water	0.026 ng l <sup>-1</sup> (n = 6)		
	Pyloric caeca	522 ± 167 ng g <sup>-1</sup> lipids (n = 6)		
	Body wall	559 ± 17 ng g <sup>-1</sup> lipids (n = 6)		
Added	Sediments	9.49 ± 1.14 ng g <sup>-1</sup> dry wt (n = 12)		
	Sea water (dissolved + particulate)	31.4 ± 15.6 ng l <sup>-1</sup> (n = 36)		
Field Values	Sediments	22 - 4,060 ng g <sup>-1</sup> dry wt	North Sea, German Bight	Stebbing <i>et al</i> 1992
		0.27 - 47 ng g <sup>-1</sup> dry wt (sum <sub>7</sub> PCB)	North Sea, Dutch coastal zone	Boon <i>et al.</i> 1985
		2.2 - 32 ng g <sup>-1</sup> dry wt (sum <sub>7</sub> PCB)	North Sea, Dutch coastal zone	Laane <i>et al.</i> 1999
	Sea water (dissolved)	0.1 - 67.2 pg l <sup>-1</sup>	Baltic Sea	Shultz-Bull <i>et al.</i> 1995
	Sea water (dissolved + particulate)	0.8 - 8.7 ng l <sup>-1</sup> (Aroclor 1260)	Atlantic	Harvey & Steinhauer 1976
		1.5 - 38.0 ng l <sup>-1</sup> (Phenoclor DP-5)	Mediterranean French coasts	Elder 1976
		0.2 - 370 ng l <sup>-1</sup> (Phenoclor DP-5/DP-6)	Med. and Atlantic French coasts	Marchand <i>et al.</i> 1990
		0.34 - 4.93 ng l <sup>-1</sup> (sum hexa-CB)	Marmara Sea	Telli-Karakoç <i>et al.</i> 2002
Sea water (extreme hot spot)	dissolved: 1.8 ± 0.3 µg l <sup>-1</sup> particulate: 14 ± 3.9 µg l <sup>-1</sup>	New Bedford Harbor, USA	Bergen <i>et al.</i> 1996	

Table 2. *Asterias rubens*. Parameters and statistics of the equations describing the uptake of <sup>14</sup>C-PCB #153 from sea water and sediments in the body compartments of the sea star.

E (exponential model):  $C(t) = C_0 \cdot e^{k \cdot t}$ ;

S (saturation model):  $C(t) = C_{ss} \cdot (1 - e^{-k \cdot t})$ ;

C (combined model):  $C(t) = C_{ss} \cdot (1 - e^{-k \cdot t}) / (1 + e^{-k \cdot (t-I)})$ ;

where  $C_0$ ,  $C(t)$ ,  $C_{ss}$ : <sup>14</sup>C-PCB #153 concentrations (ng g<sup>-1</sup> lipids) respectively at time 0, at time t (d) and at steady-state; k: rate constant (d<sup>-1</sup>); I: time (d) at the inflexion point; ASE: asymptotic standard error; R<sup>2</sup>: corrected determination coefficient.

#### 2A. Sea water

Body compartment	Model	C <sub>0</sub> (ASE)	C <sub>ss</sub> (ASE)	k (ASE)	I (ASE)	R <sup>2</sup>
Body wall	C		12,665 (691)	0.46 (0.13)	11.7 (0.67)	0.92
Central digestive system	E	98.8 (27.7)		0.093 (0.009)		0.77
Rectal caeca	E	4.5 (2.0)		0.11 (0.01)		0.91
Pyloric caeca	C		819 (398)	0.18 (0.17)	22.9 (8.2)	0.80
Gonads	C		1,417 (231)	0.21 (0.11)	23 (2.8)	0.90
Podia	C		6,584 (449)	0.33 (0.12)	12.4 (0.87)	0.93

#### 2B. Sediments

Body compartment	Model	C <sub>0</sub> (ASE)	C <sub>ss</sub> (ASE)	k (ASE)	I (ASE)	R <sup>2</sup>
Body wall	C		3,537 (206)	0.33 (0.08)	12 (0.92)	0.93
Central digestive system	C		992 (81)	4.1 (29)	16 (2.0)	0.81
Rectal caeca	C		31 (2.3)	0.22 (0.05)	20 (1.1)	0.94
Pyloric caeca	C		588 (18)	3.0 (11)	16 (1.5)	0.97
Gonads	E	74 (19)		0.085 (0.008)		0.89
Podia	S		7,618 (4266)	0.034 (0.029)		0.57



Table 3. *Asterias rubens*. Concentration factors (CF; maximum, minimum and mean values) in the body compartments of the sea star after 34 days of exposure via sea water. CFs are calculated as the ratio between PCB#153 concentration in the sea star body compartments (ng g<sup>-1</sup> total lipids) and its concentration in sea water (ng g<sup>-1</sup>).

	Body wall	Central dig. syst.	Gonads	Rectal caeca	Pyloric caeca	Podia
Max. CF	3.91 10 <sup>5</sup>	9.16 10 <sup>4</sup>	6.01 10 <sup>4</sup>	7.90 10 <sup>3</sup>	4.75 10 <sup>4</sup>	2.43 10 <sup>5</sup>
Min. CF	3.52 10 <sup>5</sup>	5.44 10 <sup>4</sup>	2.96 10 <sup>4</sup>	4.58 10 <sup>3</sup>	1.05 10 <sup>4</sup>	1.72 10 <sup>5</sup>
Mean CF	3.74 10 <sup>5</sup>	7.50 10 <sup>4</sup>	4.62 10 <sup>4</sup>	6.76 10 <sup>3</sup>	2.31 10 <sup>4</sup>	2.17 10 <sup>5</sup>

Table 4. *Asterias rubens*. PCB distribution (mean %  $\pm$  SD, n = 3) in the different body compartments of the sea star after 34 days of exposure via sea water or sediments.

Body compartments	<sup>14</sup> C-PCB-153 distribution (%)	
	Seawater exposure	Sediment exposure
Body wall	68.8 $\pm$ 1.4	20.7 $\pm$ 4.4
Central digestive System	13.9 $\pm$ 4.1	8.9 $\pm$ 2.3
Gonads	8.4 $\pm$ 2.5	12.7 $\pm$ 2.5
Rectal caeca	0.2 $\pm$ 0.1	0.3 $\pm$ 0.1
Pyloric caeca	1.8 $\pm$ 0.7	5.7 $\pm$ 1.4
Podia	6.8 $\pm$ 1.9	39.9 $\pm$ 14.6

Table 5. *Asterias rubens*. Transfer factors (TF; maximum, minimum, and mean values) in the body compartments of the sea star after 34 days of exposure via sediments.

TFs are calculated as the ratio between PCB#153 concentration in the sea star body compartments ( $\text{ng g}^{-1}$  total lipids) and its concentration in sediments ( $\text{ng g}^{-1}$  dry wt).

	Body wall	Central dig. syst.	Gonads	Rectal caeca	Pyloric caeca	Podia
Max. TF	417	109	150	3.43	70	863
Min. TF	286	81	111	2.91	55	258
Mean TF	343	94	137	3.10	61	479

Table 6. *Asterias rubens*. Comparisons among PCB #153 concentrations obtained in the present study (background + incorporated concentrations) and previous field studies in the North Sea.

Body compartment	PCB#153 concentration (ng g <sup>-1</sup> lipids)	Specifications	References
Pyloric caeca	608 - 1,111	Experimental conditions ; seawater uptake	Present study
	920 - 1,377	Experimental conditions ; sediment uptake	Present study
	41 - 1,054	Pre-spawning period 1995 ; southern North Sea	den Besten <i>et al.</i> 2001
	450 - 1,050	Pre-spawning period 1995 ; Dutch coastal zone	Everaarts <i>et al.</i> 1998
	40 - 125	Pre-spawning period 1995 ; southern North Sea	Everaarts <i>et al.</i> 1998
Bodywall	728 - 4,360	Experimental conditions ; seawater uptake	Present study
	1,215 - 14,068	Experimental conditions ; sediment uptake	Present study
Whole body	8,190 - 9,300	Experimental conditions ; seawater uptake	Present study
	2,330 - 2,810	Experimental conditions ; sediment uptake	Present study
	550 - 940	Spawning period 1986 ; Dutch coastal zone	Everaarts & Fischer 1989
	100 - 235	Spawning period 1986 ; southern North Sea	Everaarts & Fischer 1989
	4,300 (sum <sub>35</sub> PCB)	Spawning period 1989 ; German Bight	Knickmeyer <i>et al.</i> 1992
	2,400 (sum <sub>35</sub> PCB)	Post-spawning period 1989 ; German Bight	Knickmeyer <i>et al.</i> 1992