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Modelling growth and bioaccumulation of Polychlorinated biphenyls in common sole (*Solea solea*)

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ABSTRACT

Experiments were performed on juvenile sole in controlled conditions in the aim of understanding how the biology of common sole may affect the accumulation and dilution of Polychlorinated biphenyls (PCBs). The fish were raised in optimal conditions and divided into two tanks: one control tank and one PCB tank. 4 PCB congeners were added to food for 3 months in the PCB tank; the soles were subsequently fed unspiked food for 3 months. Growth (length and weight) and PCB concentrations were monitored in both tanks and juvenile sole growth was not significantly affected by PCBs in our experimental conditions. We used the Dynamic Energy Budget (DEB) theory to model sole biology and paid special attention to model calibration through the wide use of data from the literature. The model accurately reproduced fish growth in both tanks. We coupled a bioaccumulation model to reproduce the concentration dynamics of the 4 PCB congeners used. This model did not require additional calibration and was dependent solely on the growth model and PCB concentrations in food. The bioaccumulation model accurately simulated PCB accumulation in fish, but overestimated PCB concentrations in fish during the dilution phase. This may suggest that in addition to PCB dilution due to growth, PCB concentrations decreased due to other PCB elimination mechanisms. Finally, we discussed potential improvements to the model and its future applications.

1. Introduction

The use of mechanistic models to evaluate and predict individual responses of living organisms to environmental disturbances and the impact of these disturbances on population dynamics is of considerable interest (Alunno-Bruscia et al., 2009). These models are already used for various marine research purposes, such as the reconstruction of food conditions for bivalve species (Freitas et al., 2009), the prediction of anchovy spawning duration according to environmental conditions (Pecquerie et al., 2009) and the analysis of contamination levels in hake from various study zones due to dietary evolution, according to hake length and various hake bolus contamination levels in each zone (Bodiguel et al., 2009). Mechanistic models can thus be used to resolve issues relating to organism feeding, growth, reproduction and contamination from the individual to the trophic level, and specifically for persistent and bioaccumulable contaminants in living organisms, like PCBs.

Polychlorinated biphenyls (PCBs) are synthetic organic chemicals forming a family of 209 congeners used for numerous industrial applications and in particular in the electrical power industry. PCBs are characteristic of chronic contamination from urban and industrial sources. They are highly stable, hydrophobic and persistent. They thus represent typically bioaccumulable compounds. They have been detected in all environmental compartments at concentrations ranging from picograms per litre in oceanic water to milligrams per kilogramme in the fatty tissue of marine mammals (Abarnou and Loizeau, 1994). These compounds provoke a wide range of toxicological responses depending on the position of their chlorine atoms (Ahlborg and Hanberg, 1994). In Europe, the use of PCBs for everyday applications has been prohibited since 1979. Recent studies have shown that the concentrations of seven PCB congeners have decreased in five fish species since 1997 in the Baltic Sea, with different patterns according to congeners and fish species (Szlinder-Richert et al., 2009). However, results of a chemical contamination monitoring program of the French coastline (RNO — French mussel monitoring network) highlighted the high levels of persistent organic contaminants in estuaries. Coastal and estuarine ecosystems are highly productive areas and contribute largely to the economic value of marine environments (Costanza et al., 1997).

Flatfish use coastal habitats during the critical juvenile period, when their movements are limited (Koutsikopoulos et al., 1995; Riou et al., 2001). Their benthic lifestyle and the fact that their nurseries are located in coastal estuarine zones make them particularly vulnerable to chronic and accidental pollution (Mole and Norcross, 1998; Able, 1999; Smith and Suthers, 1999). Common sole (*Solea solea L.*) are found from the coasts of Norway to Mauritania. This highly-

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commercial benthic species is present throughout the coasts of France, including the English Channel and Mediterranean coasts. Various investigations have reported the effects of oil exposure on juvenile sole (Claireaux et al., 2004) and of specific PCB congeners on larvae (Foekema et al., 2008), but, to the best of our best knowledge, no studies to date have focused on the bioaccumulation patterns of PCBs and their effects on juvenile sole.

Empirical approaches in aquatic systems often use the bioaccumulation factor (BAF), defined as being the ratio between compound concentrations in the organism and in its food (Hofelt and Shea, 1997; Ivanciuc et al., 2006). However, this method does not provide any insight into how these factors will evolve during the organism's lifetime, or how bioaccumulation processes differ according to species. Modelling is therefore necessary to understand how bioaccumulation differs according to organism physiology. Several authors have developed bioaccumulation models describing PCB behaviour in aquatic food webs (Thomann and Connolly, 1984; Loizeau et al., 2001; Bodiguel et al., 2009, Rashleigha et al., 2009). However, this approach requires adequate knowledge of the environment, which impacts growth and reproduction. This often proves difficult, especially if we are unfamiliar with the study organism food to which the PCBs are bound. We therefore performed our experimental study in controlled conditions, using measured food and PCB inputs, in order to assess juvenile sole growth and PCB bioaccumulation.

The main purpose of this study was to calibrate a mechanistic model of sole growth and couple it to a PCB bioaccumulation model in order to understand how growth may affect PCB accumulation. This phase is necessary (1) if the model is to be used for subsequent *in situ* investigations, to assess nursery quality, or for predicting PCB elimination from the environment and (2) to incorporate the impact of contaminants on physiological responses. We chose the Dynamic Energy Budget (DEB) theory (Kooijman, 2000) to describe sole growth, in view of its genericity and mechanistic rules. This theory has been widely applied to and validated on an individual level for various marine organisms, ranging from bacteria (Eichinger et al., 2009) to bivalves (Pouvreau et al., 2006; Bourlès et al., 2009) and fish (van der Veer et al., 2001; Bodiguel et al., 2009; Pecquerie et al., 2009) and on the ecosystem level for a number of organisms (Maury et al., 2007; Grangeré et al., 2009). This model was calibrated and used for the study of sole by van der Veer et al. (2001). However, various uncertainties remain as regards its calibration, in particular as the study focused only on females and the majority of model parameters were deduced from plaice (*Pleuronectes platessa*) biology. We paid specific attention to model calibration, which was performed using large amounts of data from the literature. Model simulations were compared to juvenile growth data from our experiments and to published *in situ* growth curves, covering the entire sole life cycle. The bioaccumulation model was coupled to the energy allocation model. This approach was first used for the *in situ* study of PCB bioaccumulation by Bodiguel et al. (2009) and showed promising results. We compared PCB concentrations measured in sole throughout the course of the experiment to bioaccumulation model predictions. In our conclusion, we put forward various assumptions that may explain the discrepancies found between model simulations and measurements, and presented future improvements and applications for the model.

2. Materials and methods

2.1. Experiment design

Our experiments were performed on juvenile sole (G0) obtained from a farm (Solea BV, Netherlands). The fish showed very low levels of PCB at the outset: [CB105] = 0.8 ng g^{-1} of wet weight, [CB118] = 1.9 ng g^{-1} of wet weight, [CB149] = 2.0 ng g^{-1} of wet weight and [CB153] = 4.1 ng g^{-1} of wet weight.

The sole were raised in optimal conditions in terms of temperature (19 °C), oxygenation (>80%), fish density (~2 kg m^{-2}), photoperiod (12:12) and food (*ad libitum*) (Table 1) (Imsland et al., 2003; Schram et al., 2006). PCBs were artificially added to fish food (DAN-EX 1362, Dana Feed®, Horsens, Denmark) in order to investigate the bioaccumulation properties of PCBs and their potential effects on sole. In view of the very low solubility of PCBs in water, we were obliged to coat them with solvent (iso-octane: 160 ml for every 4 kg of food granules) before incorporating them in the food. After coating, the granules were evaporated under a nitrogen jet to remove the maximum amount of solvent. Contamination efficiency was then measured for each congener (measured concentration vs theoretical concentration). The initial group of sole was separated into 2 tanks with equivalent fish densities (Table 1): one control tank (C) and one PCB tank. Mean initial lengths were 12.4 ± 1.4 cm and 12.0 ± 1.3 cm for the C and PCB tanks respectively; mean initial weights were 19.2 ± 6.1 g and 16.0 ± 4.6 g for the C and PCB tanks respectively (Table 1). We selected the four PCB congeners most commonly found in the environment: CB105, CB118, CB149 and CB153. Concentrations in food were measured for each congener (see Table 1). The experiment lasted 6 months overall, comprising a 3-month contamination period and a 3-month non contamination period in the PCB tank: after feeding the sole with spiked granules, we subsequently studied their decontamination dynamics by feeding them unspiked granules coated with the same amount of solvent.

2.2. Measurements

We monitored sole growth in both tanks through individual biometric measurements of total length (L in cm) and total wet weight (W_W in g) on sampling days 0, 4, 8, 28, 56, 84 (last day of feeding with spiked food), 88, 91, 98, 112, 140 and 168 (Table 1).

We divided the fish from the PCB tank into 3 groups of 4 to 11 fish on each sampling day due to analytical constraints. We then took liver, gonad and muscle samples from each group. We quantified PCB

Table 1
Conditions in each experimental tank and concentrations of each PCB congener included in sole food. C and PCB are control and Polychlorinated biphenyl tanks respectively.

Tank name	C	PCB
Initial conditions		
Fish density (kg m^{-2})	2.3	1.8
Initial length (cm)	12.4 ± 1.4	12.0 ± 1.3
Initial total wet weight (g)	19.2 ± 6.1	16.0 ± 4.6
Physico-chemical parameters		
Temperature	19 °C	19 °C
[O_2]	>80%	>80%
Photoperiod light:dark (h)	12:12	12:12
Food		
Amount	*ad libitum*	*ad libitum*
Composition	No solvent, no PCB	+ Solvent + PCB
[PCB] ng g^{-1} of food		
[CB105]	0	228
[CB118]	0	454
[CB149]	0	420
[CB153]	0	888
Measurements		
Biometry		
Total length L (cm)	x	x
Total wet weight W_W (g)	x	x
Number of fish per sample	33 ± 14	34 ± 13
Sampling days	0, 4, 8, 28, 56, 84, 88, 91, 98, 112, 140, and 168	
Chemical analyses in muscle		
CB* (ng)		x
Number of fish per sample		Triplicates (3 groups) 4 to 11 fish/measurement