Fish, Fishing, and Pollutant Reduction in the Baltic Sea

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The Baltic Sea is heavily polluted yet supports major commercial fisheries for cod (Gadus morhua), herring (Clupea harengus), and sprat (Sprattus sprattus). Emissions of persistent organic pollutants, such as polychlorinated biphenyls (PCBs) and DDT, were high during the 1960s and 1970s, and concentrations in fish and other fauna are still significant. Several models of the fluxes of these pollutants among the water, sediment, and atmosphere have been developed, but these generally omit the roles of fish and fisheries. We show that the standing stock of the most abundant fish species in the Baltic Sea was a sink for 260 kg of PCBs in the late 1980s to early 1990s and that the fishery removed as much or more PCB (31 kg yr⁻¹) than other budget components (e.g., degradation in the water column). Accounting for fish and fisheries could increase our understanding of the fluxes of pollutants and banning the discard of highly contaminated organs such as cod liver could be part of the pollutant management.

Introduction

The Baltic Sea is one of the largest brackish water areas in the world. It is shallow (average depth 56 m), and the surface salinity ranges from 1 psu in the northernmost area to ~20 psu in the Danish belts. The water exchange with the North Sea is slow and infrequent; the average residence time of the water exchange, in combination with ca. 85 million inhabitants, has made the Baltic Sea one of the most heavily polluted seas in the world (3). This pollution includes persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs) and other hydrophobic organochlorine compounds (e.g., dioxins, DDT). PCBs enter the Baltic Sea via atmospheric deposition (73% of total inputs) and rivers (27%; 4). Because of their hydrophobic characteristics, POPs tend to partition into the organic phases of suspended particles and bottom sediment, and the lipid fraction of aquatic biota. They are efficiently transferred to consumers from lower trophic levels and readily biomagnified (5), which often results in higher concentrations in top consumers and in fat-rich species (5–7). The fate of PCBs in aquatic environments depends on a range of physical processes and interactions among water, sediment, atmosphere, and biota (5, 7).

Several budget models have been constructed to quantify the sinks and flows of POPs in aquatic ecosystems (see, e.g., refs 8 and 9), including the Baltic Sea (10). The significance of fish and fisheries in pollutant budgets is often omitted from these models either because the necessary data (e.g., concentrations, biomasses) are not available or because the influence of fish and fisheries on the budget and fluxes is assumed to be negligible. However, because fish occupy upper levels of trophic food webs and have longer lifespans and therefore greater exposure to contaminants, their tissues usually have higher contaminant concentrations than lower trophic levels and potentially could have important effects on POP dynamics. As a natural consequence of ignoring the fish from budgets and fluxes, such models also generally ignore the removal of POPs through fishing or the import of POPs via fish migration (11). These assumptions might be valid if the fish biomass or landings are small, but in an ecosystem such as the Baltic Sea where ~800 000 tonnes of fish are caught annually (average 1990–1998 (12)), the removal of toxic substances by the fishery may be substantial.

The fish fauna in the Baltic is a mixture of freshwater and marine species, where the freshwater species inhabit coastal and northern areas and marine species dominate offshore and southern areas (13). The most abundant species are sprat, herring, and cod; these species are also the most important economically and represent 80–90% of the total annual catch (12). Salmon (Salmo salar) represents only a small fraction of the biomass and catch in tons, but is nevertheless considered an important target species (12). Although other species are present, particularly in coastal areas, the trophic interactions in the fish community are dominated by cod, herring, and sprat: adult cod are predators of juvenile and adult herring and sprat (14). Salmon are also predators of herring and sprat (15).

The objectives of this study were to calculate the removal of PCBs by commercial fishing and the population-level PCB burden in Baltic fish populations and to assess the significance of fish and fisheries in the flows of pollutants in this ecosystem. The study area is that part of the Baltic Sea encompassing International Council for the Exploration of the Sea (ICES) subdivisions 22–32 (Figure 1). Most of the fish captured in this region are taken from subdivisions 25–28. This area also has the most intensive monitoring programs for measurements of contaminant levels in fish (3, 16).

Methods

Contaminant Sampling and Measurements. Our objective is to demonstrate the potential role that fisheries can have on PCB export from the Baltic Sea. To meet this objective, we preferentially used datasets which were long, had large numbers of samples, and/or were based on consistent sampling and measuring methods. Most of the measurements of PCB concentration used in this study come from major contaminant monitoring programs in Sweden and Denmark; additional data for individual years and species have been compiled in other national monitoring programs (Estonia, Finland, Poland). The data sources are summarized in Table 1 and cover different areas and time periods.

The technique to analyze pollutants in biota has improved since the first analyses were made in the 1960s (16, 17). The older type of gas chromatography with a packed column was used until the end of the 1980s and gave a quantification of total PCB. Since the beginning of the 1990s, congeners-specific analysis of PCB with capillary columns is the standard.
technique. The total PCB values, as measured by the older methods, and the ∑PCB values (the sum of the analyzed congeners) are not directly comparable because of these analytical differences. There is, however, a good correlation between the PCB congener CB-153 and total PCB, with CB-153 constituting about 10% of the total PCB (18, 19). For the years from 1990 to the present in the Swedish Monitoring Programme data, we assumed that total PCB concentrations were equivalent to CB-153 concentrations multiplied by 10. For years prior to 1990, we used the total PCB concentrations as reported by the Swedish Monitoring Programme (17).

Data Analyses. We conducted four sets of calculations to quantify and compare the roles of fish and different fisheries on PCB removals. These estimates were made by combining fish landings, biomasses, and PCB concentration data.

The first calculation estimates the amount of PCB removed by commercial fisheries for herring, sprat, and salmon, given the observed landings of these species and their measured PCB concentrations. Nearly all measurements were based on muscle lipid concentrations (Table 1). When necessary, PCB concentrations were converted to the fat basis from the wet weight basis by applying tissue lipid fractions measured in individual studies or a species-specific average from the literature. For herring PCB data, spring and summer measurements from several sites in the eastern Baltic (subdivisions 25–32) are available (16). We calculated mean values from these data because the Baltic fishery captures herring year-round and throughout the Baltic (12). For herring in the western Baltic (subdivisions 22–24), we used the mean concentration from several sites and sampling seasons as given by ref 17. The two sets of PCB measurements were then applied to corresponding area-disaggregated catch data (i.e., western and eastern Baltic).

Similar time series with standard sampling and processing do not exist for either sprat or salmon. In the case of sprat we used compiled (20) and original data from the literature. These data were usually obtained from sprat muscle (20, 21) or whole body weights (22).

We also estimated the removal of PCB associated with the landings of cod in the eastern Baltic Sea (ICES subdivisions 25–32). This calculation was based on the PCB content in cod muscle. However, the amount removed annually during 1980–1995 was negligible, primarily due to the very low lipid content of cod muscle. Additional details of these estimates

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**TABLE 1. Data Sources and Sampling Information (Location, Year, Season of the Year) for PCB Concentrations in Fish from the Baltic Sea Used in This Study**

<table>
<thead>
<tr>
<th>species</th>
<th>analyzed tissue</th>
<th>years</th>
<th>notes</th>
<th>ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>cod</td>
<td>liver</td>
<td>1980–1996</td>
<td>subdivisions 25, 27, 29,</td>
<td>16, 38</td>
</tr>
<tr>
<td>cod</td>
<td>liver</td>
<td>1971–1985, 1989</td>
<td>subdivision 26, Polish coast</td>
<td>29</td>
</tr>
<tr>
<td>cod</td>
<td>liver</td>
<td>1989–1996</td>
<td>subdivisions 22–24</td>
<td>17</td>
</tr>
<tr>
<td>herring</td>
<td>muscle</td>
<td>1965–1985</td>
<td>southern Baltic proper</td>
<td>38, 39</td>
</tr>
<tr>
<td>herring</td>
<td>muscle</td>
<td>1972–1995</td>
<td>subdivisions 25, 27, 29,</td>
<td>16</td>
</tr>
<tr>
<td>herring</td>
<td>whole body (wet weight basis)</td>
<td>1993–1996</td>
<td>Swedish coast, spring and fall sampling</td>
<td>17</td>
</tr>
<tr>
<td>sprat</td>
<td>muscle</td>
<td>1994, 1995</td>
<td>subdivisions 24–26</td>
<td>21</td>
</tr>
<tr>
<td>sprat</td>
<td>whole body (wet weight basis)</td>
<td>1994, 1995</td>
<td>subdivision 29</td>
<td>22</td>
</tr>
<tr>
<td>salmon</td>
<td>muscle</td>
<td>1979, 1985, 1992</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>salmon</td>
<td>muscle</td>
<td>1996</td>
<td></td>
<td>41</td>
</tr>
</tbody>
</table>

* Most measurements were reported on a lipid weight basis.
are available in the Supporting Information. The landings data used for calculations of PCB removal for each species were obtained from ICES (12, 23).

A second set of calculations used landings of cod liver by Danish commercial fishermen on the island of Bornholm (Figure 1). These data were used to estimate the amount of PCB removed from the Baltic by this segment of the Baltic fishery. The cod livers landed by Danish fishermen are primarily from subdivisions 24–25 for the years 1986–1999; these data were extracted from the official Danish fishery statistics database. We applied in separate analyses the Swedish (subdivision 25) and Danish (subdivisions 22–24) PCB concentration data to the cod liver landings data because cod livers probably originate from cod captured in both areas.

Our third calculation was an estimate of the potential removal of PCBs that could have been achieved if all livers of captured cod were landed instead of returned to the sea as fish offal. This calculation applies the time series of liver concentrations to commercial cod catch data for subdivisions 22–32.

The final calculation estimated the amount of PCBs in the standing stock of fish biomass in the Baltic Sea, as represented by cod, herring, and sprat. This calculation used the biomasses of all age groups (12) for the same subdivisions as were used for the PCB removal estimates due to the fishery. This analysis used a series of years (late 1980s to early 1990s) which corresponded to the time period represented by an existing budget of PCB concentrations and fluxes in the Baltic Sea (10). This choice of years enabled us to compare the fish PCB pool with other budget components.

**Removal of PCB through Fisheries.** For herring, salmon, sprat, and cod muscle, the removal of PCB (R, kg) was calculated as

\[
R = CFL \times L \times M
\]

where C is the concentration of PCB (kg of lipid)\(^{-1}\) in the body tissue (e.g., muscle, liver), F is the fat content (kg of lipid) (kg of fresh weight)\(^{-1}\) in the tissue, L is the annual landings (kg), and M is the proportion of whole body weight associated with the tissue used for measurement of PCB concentration. In the case of muscle tissue measurements, we assumed muscle weight was equivalent to fillet yield (expressed as weight of skinless fillets relative to whole body weight). Mean fillet yield data for each species were obtained from literature compilations (24, 25).

The remaining portion of the fish was excluded from the calculations, due to the lack of contaminant time series data for viscera, skin, and bone tissue. Our calculated removal rates are therefore underestimates because some fish species in the Baltic are often landed ungutted (e.g., sprat, herring), and these body parts often have higher fat and PCB concentrations than muscle tissue (22).

In the case of sprat for 1994–1995, we used the whole body values of PCB concentrations (22). These values were multiplied by the total sprat landings for these years. For cod liver, the removal of PCB was calculated as

\[
R = CFL \times L \times M
\]

where C is the concentration of PCB (kg of liver lipid)\(^{-1}\), F is the lipid content (kg of lipid) (kg of fresh weight)\(^{-1}\) of the liver, and L is the annual landings of cod liver on Bornholm (kg).

The potential removal of PCB that could have been achieved by landing all cod livers in fishing ports instead of discarding them as fish offal was calculated retrospectively as

\[
R = CFL \times L \times M
\]

where C is the concentration of PCB (kg of liver)\(^{-1}\), F is the fat content in the liver (kg of fresh weight)\(^{-1}\), L is the landings (kg), and M is the liver weight relative to total body weight (26). We used literature data for the removal estimates to quantify this uncertainty. The cases considered for analysis (see the Results) represent most of the different types of calculations we have conducted. They also correspond to the major fishery-related removal components close to or during the period represented by the PCB budget for the Baltic (10).

The analysis assumes independence of the variance estimates for each input used in our calculation. The estimated variance of our removal rates is given by

\[
S_R^2 = FLM^2 + CLM^2 + CFM^2 + CFL^2
\]

Although the commercial landings data are known to be uncertain, this uncertainty has not been quantified (12) and cannot be included in our analysis. As a result the third term was deleted:

\[
S_R^2 = FLM^2 + CLM^2 + CFL^2
\]

There are several levels of variance associated with most of the inputs to our removal calculation (e.g., variance between individuals on a given sampling date, vs variance between population means across sampling dates). We used where possible the variance between group means collected at different times or places within the same year by a single investigator because this level of variability probably represents that due to seasonal and spatial variability in environmental conditions. Estimates of the variability of muscle weight (% of body weight, as represented by fillet yield) were usually not presented in the literature compilations (24, 25) or the original sources. As a result we assumed that variability in fillet yield was proportionally similar to that observed (CV = 2%) in Atlantic salmon under a variety of feeding conditions (28).

**Results.** The concentrations of PCBs in fish vary between years and between species (Figure 2). This is most evident for herring muscle and cod liver, for which multiple time series are available. Concentrations in herring muscle were high in the late 1960s to early 1970s and have declined since that time (Figure 2A). Concentrations in cod liver were generally highest during the 1970s and declined by 4–5-fold during the 1980s and early 1990s (Figure 2b). During the early 1990s to mid-1990s, the concentration appears to have remained stable or risen slightly.

The landings of some of the fish species have fluctuated widely during the last 30 years (Figure S1, Supporting Information). Cod landings peaked in the late 1970s to early 1980s (300000–400000 tons yr\(^{-1}\)) and are presently at much lower levels (<100000 tons). Herring landings have decreased by ~25% since the 1970s, while sprat landings increased ~10-fold in the 1990s compared to the early 1980s. Salmon landings have fluctuated at low levels.

**Uncertainty Analysis.** Our calculations involve multiplication of several input variables, all of which are measured with variability. As a result when they are combined, the final level of uncertainty in the derived outputs could potentially be quite large. We conducted a first-order error sensitivity analysis of some of our removal estimates to quantify this uncertainty. The cases considered for analysis (see the Results) represent most of the different types of calculations we have conducted. They also correspond to the major fishery-related removal components close to or during the period represented by the PCB budget for the Baltic (10).

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The estimated removal of PCBs from the Baltic Sea by fisheries varied between years and sometimes exceeded 60 kg yr\(^{-1}\) (Figure 3). The sprat fishery alone removed 40–70 (kg of PCBs) yr\(^{-1}\) in several years between 1969 and 1977. The herring fishery was the second largest fishery component that removed PCBs; this fishery also removed 40–60 kg yr\(^{-1}\) for several years in the mid-1970s. The removal rate declined to ca. 20 kg yr\(^{-1}\) during the 1980s. The Danish cod liver landings removed 1–8 kg yr\(^{-1}\), and the salmon fishery removed the smallest amount (< 1.5 kg yr\(^{-1}\)).

The cod fishery could potentially remove a much larger amount of PCBs (Figure 4), if all cod livers were retained and not discarded at sea. This would have removed > 60 (kg of PCB) yr\(^{-1}\) during 1979–1984 on the basis of PCB concentrations measured by Bignert et al. (16) or > 100 kg yr\(^{-1}\) on the basis of PCB concentrations measured by Kannan et al. (29). This high level of potential removal is due to both high concentrations of PCBs in cod livers (Figure 2B) and high cod landings (Figure S1 in the Supporting Information).

Irrespective of uncertainty in concentrations and catches, the Baltic Sea fish community is a large sink for PCBs, and the fisheries annually remove substantial quantities of PCBs from the ecosystem. The average of the total burden of PCB in fish biomass for the late 1980s to early 1990s was 260 kg (Figure 6A). The annual PCB removal by fisheries was > 31 kg at the end of the 1980s and in the early 1990s (Figure 6B). This exceeds or is comparable to some other fluxes in a published PCB flow model (10), i.e., the degradation in the water column or the net hydrographic export to the North Sea (Figure 7). The total loss of PCBs from the Baltic Sea has been estimated (10) to be 881 kg yr\(^{-1}\) (sum of export to the North Sea, loss to sediments, degradation in the water column, and volatization to the atmosphere; Figure 7). If the fishery-related export is 31 kg yr\(^{-1}\), then this removal corresponds to 3.5% of the known total export due to all other causes.
FIGURE 6. (A) Estimated population-level burdens of PCBs in the three most abundant fish populations in the Baltic Sea during the late 1980s to early 1990s. The bar labeled as “total” is the sum of the individual components. The exact years represented by the bars differ slightly depending on data availability, and are the following: cod liver in ICES subdivisions 22–24, 1989, 1991; cod liver and herring in ICES subdivisions 25–32, and herring in subdivisions 22–24, 1987–1992; sprat in subdivisions 22–32, 1986, 1991, 1994–1995. Population burdens shown are means for the respective time periods. Herring and sprat estimates are based on PCB concentrations measured in muscle, except for sprat data in 1994–95, which are based on whole fish homogenates. (B) Estimated annual removal rates of PCB by different Baltic fishery components during the late 1980s to early 1990s. The “total” bar is the sum of the individual components. See the caption for panel A for exact time periods represented by the bars. Herring, sprat, and salmon estimates are based on PCB concentrations measured in muscle, except for sprat data in 1994–95, which are based on whole fish homogenates.

Discussion

We have estimated the removal of PCBs from the Baltic Sea by different fishery components, and we have estimated the total PCB burden of the main Baltic fish community. Our calculations indicate that fishing can and does annually remove several kilograms of PCBs from the Baltic Sea ecosystem and that this removal rate could be increased without increasing fishing mortality rates. Cod livers have a much higher concentration of lipid than herring, salmon, and sprat muscle, and PCBs and other chlorinated contaminants are highly lipophilic (7, 22, 30). One way to increase the PCB removal rate would be to land all cod livers and not allow them to be thrown overboard when the fish are cleaned at sea. We note that several new technologies for degrading chlorinated organic compounds (e.g., dioxins) are becoming available and that this field is an active area of research (31–33). In the future these and other new technologies could potentially be applied to retained cod livers to provide an active means of PCB reduction in the Baltic Sea.

Our calculations are the first estimates of pollutant removal by fishing for the Baltic Sea and to our knowledge also the first for any large marine or estuarine ecosystem. These rates will reflect the dynamics of fishing mortality rates and PCB concentrations in fish tissues. Variations in both factors will cause temporal variability in the removal rates we have calculated. This removal is not included in the present PCB budgets for the Baltic Sea.

Although it is not surprising that fishing removes PCBs, and likely many other contaminants from the Baltic, the relative size of this removal should not be overlooked. These removal rates are comparable to some other estimated fluxes of PCBs in the Baltic (10). For example, the fishery removal of PCBs exceeds or is similar to the degradation of PCBs in the water column and is approximately 75% of the net outflow of PCBs to the North Sea (Figure 7). Furthermore, our results underestimate the total removal of PCBs by fisheries, because only parts of the fish were included in the calculations, i.e., muscle tissue from herring, sprat, salmon, and cod, and liver tissue from cod. High concentrations of pollutants probably also occur in the fat-rich tissues of the skin and viscera in all four species. For example, the ratio of whole fish to fillet PCB concentration was 1.70 for coho salmon (Oncorhynchus kisutch) and 1.47 for rainbow trout (Oncorhynchus mykiss) in Lake Michigan (34). These data for other species suggest that the removal of PCBs by fishing may be substantially larger than we have estimated, especially given that many sprat and herring are landed ungutted for the fishmeal and fish oil industries (12).

We are aware that our estimates are uncertain, as are all similar flux and budget estimates. These uncertainties are due to the assumptions used in our calculations and the variability in the data themselves (e.g., PCB concentrations). In particular, our analyses and calculations assume that the fish measured for PCB concentration represent those in the entire populations of the given species. The variation in PCB concentrations in cod liver among studies (Figure 2B) could be partly due to spatial differences in the locations where samples were collected. The samples from the Swedish Contaminant Monitoring Programme (16) were collected along the Swedish coasts in subdivisions 25, 27, and 29, whereas other samples were collected in subdivisions 22–24 (western Baltic; 17) and in subdivision 26 (35).

However, even assuming that the comparatively low concentrations seen in Swedish data are representative for cod in the whole Baltic still suggests that the removal of PCBs by fishing activity could be large. Moreover, we have not included flatfish (e.g., flounder [Platichthys flesus] landings in 2001 in subdivisions 22–32 were 18000 tons; 12) or coastal species in our PCB budget because of lack of data. However, because PCB concentrations in coastal sediments, waters, and biota are often higher than in offshore areas (36), the contribution of these fish may be higher than expected from their biomass. Our conclusion that fish and fishing could be important factors in PCB and other pollutant dynamics in the Baltic Sea is therefore robust.

Remedial measures to reduce PCB and other contaminant concentrations in the Baltic have aimed to reduce inputs. These measures appear to be succeeding (8, 16). We note however that these measures do not target active removal from the ecosystem. All removals from the Baltic are presently under natural influence: sedimentation, vaporization, advective export to the Skagerrak and North Sea (10). Our calculations suggest that these natural removal processes could be supplemented and increased by an effective and sustainable management of existing fisheries. Moreover, fishing appears to be the only large-scale means for direct active removal of PCBs at the present time and for the
foreseeable future. A management approach which prevents the cod population from falling to critical levels not only would ensure its viability but could potentially contribute to an ongoing reduction in the PCB contamination of the Baltic Sea. This reduction will be slow given current fishery-related PCB removal rates and the estimated mass of PCBs in the Baltic (~19.5 tons; 4, 10).

Commercial fisheries influence the Baltic Sea ecosystem in many ways, most obviously through their capture of target and nontarget species. Direct effects of this exploitation include changes in food web structure, and removal of nutrients from the system. For example, the Baltic Sea fisheries annually remove 15000 tons of nitrogen and 3000 tons of phosphorus, which correspond to 1.4% and 7% of the total annual nutrient load, respectively (37). Our calculations suggest that fishing represents a similar removal of PCBs from the Baltic Sea (i.e., 3.5%, given the exports due to other processes estimated by Wania et al. (10)).

This reduction will be slow given current fishery-related PCB removal rates and the estimated mass of PCBs in the Baltic (~19.5 tons; 4, 10).

FIGURE 7. Overall mass balance of PCBs in the Baltic Sea for the late 1980s to early 1990s according to ref 10. Fluxes are given in kilograms per year. All data except for “fish landings” and the PCB content in the Baltic fish biomass are from ref 10. The values for PCB removal by fish landings and for PCB in Baltic Sea fish biomass are averages for results in the late 1980s and early 1990s (see Figure 6 for exact time periods).

Supporting Information Available

Two figures, an estimation of PCB removal associated with cod muscle, and references. This material is available free of charge via the Internet at http://pubs.acs.org.

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