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Human Dietary Intake of Organochlorines from Baltic Herring: Implications of Individual Fish Variability and Fisheries Management

This study examines the extent to which Finnish human dietary intake of organochlorines (PCDD/Fs and PCBs) originating from Northern Baltic herring can be influenced by fisheries management. This was investigated by estimation of human intake using versatile modeling tools (e.g., a herring population model and a bioenergetics model). We used a probabilistic approach to account for the variation in human intake of organochlorines originating from the variation among herring individuals. Our estimates were compared with present precautionary limits and recommendation for use. The results show that present consumption levels and frequencies of herring give a high probability of exceeding recommended intake limits of PCDD/Fs and PCBs. Furthermore, our results clearly demonstrate that in the risk management of dioxinlike organochlorines, regulating fishing (in this case increasing fishing pressure) is a far less effective way to decrease the risk than regulating the consumption of herring. Increased fishing would only slightly decrease organochlorine concentrations of herring in the Finnish fish market.

INTRODUCTION

The Baltic Sea is among the sea areas in Europe most heavily loaded by organochlorines. High levels of organochlorines, such as polychlorinated dibenzo-*p*-dioxins and furans (PCDD/F) and polychlorinated biphenyls (PCB), have been measured from the Baltic's biota since the 1970s. Concentrations of these compounds in the biota, along with human dietary exposure, have been declining, but very high levels are still measured from commercially important fish species. These include Baltic herring (*Clupea harengus* L.), which is the origin of about one-third of the total dietary intake of PCDD/Fs and PCBs in Finland (1). If a significant amount of toxins is concentrated in one particular foodstuff, it may cause increased health risk for high-level consumers of this single foodstuff (i.e., herring in Finland). However, such risk could be managed by regulating intake or by reducing contaminants in this particular foodstuff.

Substantial global differences exist in human health risk assessment of the PCDD/Fs and PCBs, which mainly arise from uncertainty about the toxicity of these contaminants (2, 3). The Scientific Committee of Food of the European Union (EU SCF) has identified a maximum total weekly intake (TWI) of PCDD/Fs and "dioxinlike" PCBs of 14 pg of World Health Organization toxic equivalents (WHO-TEq) kg^{-1} (4), which is 840 pg WHO-TEq wk^{-1} for a 60-kg person. This intake limit is in line with recommendations by the WHO and the Joint FAO/WHO Expert Committee on Food Additives (JECFA) (2). However, the U.S. Environmental Protection Agency (USEPA) recommends a much more conservative total daily intake (TDI) of 0.001 to 0.01 pg WHO-TEq kg^{-1}, which is some 2000–200 times stricter than EU guidelines.

The EU has also adopted maximum permissible levels for PCDD/Fs in feed and food, which have recently been reevaluated to include dioxinlike PCBs (6). A new maximum level for the sum of dioxins, furans, and PCBs in fish and fisheries products was set to 8 pg $WHO_{PCDD/F\text{-}PCB}$-TEq g^{-1} (henceforth referred to as WHO_{total}-TEq). Even though the PCDD/F concentration of large Baltic herring may exceed this limit manyfold (7, 8), Finland and Sweden are still authorized to place herring on their domestic markets for a transitional period until 2011. These countries have considered that risks of contaminants in Baltic fish are outweighed by their health benefits; therefore a total ban on consumption has not been recommended (9). At the national level, Finnish and Swedish health and food authorities have recommended that pregnant women, children, and people of fertile age should consume only moderate amounts of fatty Baltic fish and only small herring (<17 cm), which do not exceed the 8 pg WHO_{total}-TEq g^{-1} limit (10, 11).

Consumption limits might be an effective way to reduce the human health risks from contaminants. However, if limits are exceeded, as in the case of Baltic herring, a total ban or heavy restriction on consumption may cause serious socioeconomic and cultural problems such as extinction of herring fisheries. This could be avoided by reducing contaminants in the foodstuff itself. It has been demonstrated that PCDD/F and PCB levels can be manipulated to some extent by fish introductions (12). It has also been suggested that increased fishing of Baltic herring would make the herring stock younger and thus substantially reduce the organochlorine concentration of the catch (6). Increased fishing may lead to higher growth rates of individuals because of density dependency. Fast growing individuals allocate relatively more energy to growth than to maintenance and hence they feed less to reach a particular weight. Consequently fish will get fewer persistent organic pollutants from food, and have lower toxicant concentrations in their tissues.

In this study we assess the extent to which Finnish human dietary PCDD/F and PCB intake originating from Northern Baltic herring can be influenced by fisheries management. Human intake of organochlorines comprises a very complex system of fluxes, organochlorine concentrations, human consumption habits, consumption guidelines, industrial practices, as well as management and policy tools (9). This complexity was investigated here by estimation of human intake using versatile modeling tools that comprised three closely connected submodels (Fig 1): *i)* a population dynamics model of herring, *ii)* a bioenergetics accumulation model of herring, and *iii)* a probabilistic model of human intake. Modeling of fluxes concentrated on herring, which is the most important single organochlorine source in the human diet in Finland.

Most approaches to calculating human dietary intake are based on *average* concentrations and consumption rates of a

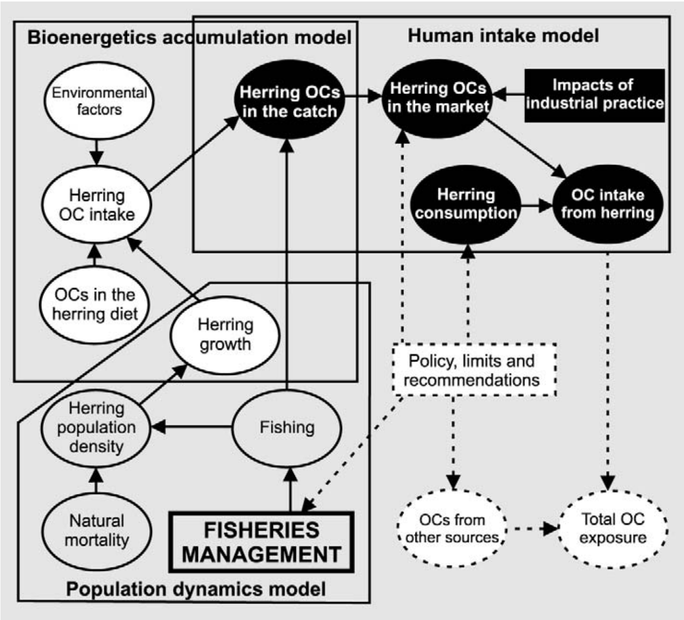

Figure 1. Simplified structure of the modeling scheme used to estimate Finnish human dietary intake of organochlorines (OCs) in Bothnian Sea herring under different fisheries management scenarios. The procedure comprises three independent but closely connected models. Ellipses denote variables and arrows their dependencies; squares are decision variables. Dashed variables and arrows represent variables and dependencies not included in the model.

foodstuff and hence cannot provide information on the variability of organochlorine concentrations in that foodstuff. Because considerable variation exists among herring individuals in their PCDD/F and PCB concentrations (8), we use a probabilistic modeling approach to account for this variation. Our estimates from model simulations are then compared with the present precautionary limits and recommendations for use to evaluate their compatibility at the level of individual humans within time scales from a week to several years.

MATERIALS AND METHODS

Population and bioenergetics models are used to evaluate the effect of fisheries on organochlorine concentrations in the herring catch through density dependent growth and herring physiology. The data are further used for probabilistic estimation of human organochlorine intake (Fig. 1).

Population Dynamics and Bioenergetics Model

A population dynamics model was applied to predict the stock dynamics and weight-at-age (14 age groups) of the Bothnian Sea herring assuming alternative fishing effort scenarios (see next paragraph). Weights-at-age were modeled with the von Bertalanffy growth equation, which was modified to allow density dependence. Spawning stock biomass and recruitment estimates in ICES (13) were applied to generate a Beverton-Holt–type stock-recruitment model, which has been found suitable for Bothnian Sea herring stocks (13). Detailed description of the model is given by Peltonen et al. (14). Four scenarios for fish stock dynamics and weights-at-age, over two decades from 2005 to 2025, were generated by changing fishing mortality rates (F): *i)* present F ($F = 0.15$) maintained; *ii)* 50% increase in F; *iii)* 100% increase in F; and *iv)* 50% decrease in F. Natural mortality rates ($M = 0.20$) were expected to remain at the present level. Mean weight-at-age and number of herring in catch from year 2020 were taken and used in subsequent estimations of future human intake.

Mean weight-at-age values from the population model were used in a "Wisconsin type" (15) bioenergetics accumulation model to predict the accumulation of 17 PCDD/F and 12 PCB congeners into tissues of herring from their diet. The physiological parameters for the model were set according to Rudstam (16) with minor adjustments (14). Dietary information, diet organochlorine concentrations and their assimilation efficiencies, as well as environmental factors, were collected from the literature and from databases available to our research group. Food consumption estimates were calculated with time steps of one day. Congener-specific assimilation of organochlorine consumed by herring was calculated by multiplying the amount of organochlorine consumed by the assimilation efficiencies for organochlorines taken from the literature. The complete model is presented in Peltonen et al. (14).

From the congener-specific accumulation estimates, we calculated age-group-specific mean WHO_{total}-TEqs in catch for all four scenarios. These mean WHO_{total}-TEqs and the age-specific relative proportions of herring individuals in catch (calculated by the population dynamics model) were further used in the human intake model. The baseline estimates (referred to later as status quo 2002) for age-group-specific WHO_{total}-TEqs were estimated from empirical data of 90 Bothnian Sea herring individuals analyzed for organochlorines in 2002 (8). The relative frequencies of age groups in catch in 2002 were calculated from herring population estimates provided by the Finnish Game and Fisheries Research Institute.

Probabilistic Model for Human Intake

To quantify the uncertainty about the human intake of WHO_{total}-TEq, the Bayesian approach to scientific reasoning was adopted. In the Bayesian approach, one presents the current knowledge about the quantities of interest in the form of probability (prior distributions) and then updates this knowledge in the light of interpretation of new observations (e.g., 17–19). In this work, substantial prior information about the parameter values was not available, thus the posterior distributions reported will reflect the interpretation of the analyzed data. This section describes the conditional priors assigned to the data set and prior distributions assigned to model parameters.

In the human intake model age-group-specific mean WHO_{total}-TEqs in the herring catch were further combined with age-group-specific interindividual variation in WHO_{total}-TEqs. Information about this variation was obtained from empirical data for 90 Bothnian Sea herring individuals mentioned earlier. The relationship between the expected amount of WHO_{total}-TEq contained by a herring and the age of a herring was assumed to be nonlinear:

$$\log\mu_i = \alpha + \beta\log a_i, \qquad \text{Eq. 1}$$

where μ_i denotes the expected WHO_{total}-TEq (pg or pg g^{-1}), a_i denotes the age in years, and α and β are regression coefficients. Furthermore, the variation among individuals of the same age was thought to be best characterized by a log-normal distribution with expected value μ_i and coefficient of variation γ. In other words, the log of the WHO_{total}-TEq content was assumed to be normally distributed conditional on knowing the expected value and coefficient of variation on the original scale:

$$\log(x_i)|\mu_i, \quad C \sim N\left[\log(\mu_i) - 0.5\log(\gamma^2+1),\ \log(\gamma^2+1)\right], \qquad \text{Eq. 2}$$

where C denotes coefficient of variation of γ. Very little prior knowledge about the model parameters α, β, and γ was accounted for in this analysis, and therefore they were assigned the following prior distributions

$$\alpha \sim N(0, 1000) \quad \text{Eq. 3}$$

$$\beta \sim N(0, 1000) \quad \text{Eq. 4}$$

$$\gamma \sim \mathrm{Unif}(0.001, 2) \quad \text{Eq. 5}$$

Herring smaller than 23 g (>6 in EU size categories, total length <15–16 cm) were assumed not to be consumed by humans (20) and were excluded from the WHO_{total}-TEq distributions of herring in the Finnish fish market produced by our probabilistic model.

The average amount of whole herring in a meal was assumed to be 250 g (21). However, human individuals were assumed to consume only fillets, which are 52% of total fish body mass (22). Since the relative concentrations PCDD/Fs and PCBs of fillet versus whole fish are not equal, concentrations of PCDD/F and PCBs in the fillets were further corrected according to Amrhein, Stow, and Wible (23).

Human herring consumption frequencies were obtained from the survey of the Finnish National Health Institute (24). Sampling covered about 80% of the Finnish population, excluding the population in the most northern part of Finland. The total number of observations was 968 from which 178 had information missing on herring consumption. Intake of picograms of WHO_{total}-TEq wk^{-1} was estimated for five consumption groups obtained from the survey: C_1 = once a month (42.8%), C_2 = twice a month (27.8%), C_3 = once a week (4.9%), C_4 = twice a week (0.6%), C_5 = five times a week (0.4%). Of the studied consumers, 23.4% had not eaten herring.

The number of herring of different ages consumed was estimated using the assumed human consumption frequency of herring, the estimated age and weight distribution, as well as the estimated portion size. Conditional on knowing the number of herring (N_a) at age to be consumed, the distribution of the WHO_{total}-TEq intake can be derived in the following way.

The amount of WHO_{total}-TEq taken from N_a herring is simply the sum of WHO_{total}-TEq contained by each of those fish.

$$T_a = \sum_{i=1}^{N_a} x_i. \quad \text{Eq. 6}$$

Assuming that those fish can be seen as a random sample from the herring population within the age group, then the conditional expected value of T_a, given that α, β, and a were known, is given by

$$E(T_a) = E\left(\sum_{i=1}^{N_a} x_i\right) = \sum_{i=1}^{N_a} E(x_i) = \sum_{i=1}^{N_a} \mu_i = N_a \exp(\alpha + \beta \log a). \quad \text{Eq. 7}$$

For a fish at age a, the variance of the WHO_{total}-TEq is simply given by

$$V(x_i) = (\mu_i \gamma)^2 = [\gamma \exp(\alpha + \beta \log a)]^2. \quad \text{Eq. 8}$$

Then, based on the assumption of a random sample, the variance of the WHO_{total}-TEq of N_a individuals is the sum of the individual variances, i.e.,

$$V(T_a) = N_a [\gamma \exp(\alpha + \beta \log a)]^2. \quad \text{Eq. 9}$$

The coefficient of variation of T_a is then

$$CV(T_a) = \frac{\sqrt{V(T_a)}}{E(T_a)} = \frac{\sqrt{N_a}\gamma}{N_a} = \frac{\gamma}{\sqrt{N_a}}, \quad \text{Eq. 10}$$

which shows that the relative uncertainty about the human intake of the WHO_{total}-TEq will be lower when the consumption of herring is higher and vice versa. This can be intuitively understood by acknowledging that pure chance plays a bigger role when only few fish are consumed: one big herring can contain a high or low concentration of dioxin, which leads to higher uncertainty about the intake. When larger amounts are consumed, it is more likely that the consumed biomass originates from individuals with high, low, and medium concentration, thus making the total intake more predictable.

According to standard theory of statistics, the distribution of a sum approaches the normal distribution when N approaches infinity. However, in this case the number of herring consumed can be fairly small, rendering the normal approximation useless. Instead of a normal distribution, we approximated the sum of log-normals by another log-normal distribution, which has mean $E(T_a)$ and variance $V(T_a)$.

The WHO_{total}-TEq intake (D) from herring consumption was calculated by adding up the age-specific intakes

$$D = \sum_{a=1}^{A} T_a, \quad \text{Eq. 11}$$

where A denotes the maximum age of herring. The distribution of D could again have been approximated by a log-normal distribution in the same way as the distribution of T_a by adding the expected values and variances. However, our computational approach enabled us to calculate the distribution exactly by drawing a high number of random draws from age-specific distributions and adding them up directly.

All posterior distributions of model parameters were calculated using a Markov chain Monte Carlo (MCMC) simulation (25). The simulation was implemented using the OpenBUGS 2.2.0 software package, which is an open-source continuation of the well-known WinBUGS software (26).

Intake Period and Precautionary Limits

Organochlorines accumulate in the human body during the whole life span, and any health effects may arise only after decades. Weekly intake values are frequently used as precautionary limits for toxins, and they are often calculated as mean values during a longer period such as a year. To illustrate the variation in human intake of PCDD/F and PCB originating from herring from week to week, we calculated probability distributions of WHO_{total}-TEqs intake for 1 week, 1 year, and 10 years. The intake was described in all cases as average weekly intake values.

To compare our results to present precautionary limits (see introduction) and earlier intake approximations (1, 7, 27), we derived a maximum limit of WHO_{total}-TEqs originating from herring. This limit indicates how much WHO_{total}-TEqs Finnish consumers may receive from herring without exceeding the EU SFC limit for all foodstuff (840 pg WHO_{total}-TEq wk^{-1} for a 60-kg person). A recently estimated mean weekly intake of Finnish consumers from all foodstuff and herring is 796 WHO_{total}-TEq wk^{-1} and 220 pg WHO_{total}-TEq wk^{-1} for a 60-kg person, respectively (1). On average, herring comprise about 11% of total fish consumption by an individual consumer in Finland (27). The maximum limit for herring was iterated by increasing the herring consumption level to reach the total maximum limit of 840 pg WHO_{total}-TEq wk^{-1}. We assumed that the proportions of all foodstuff remained unchanged except that the consumption rate of herring increased and herring substituted for imported fish. The maximum limit of WHO_{total}-TEqs originating from herring was then 275 pg WHO_{total}-TEq wk^{-1}.

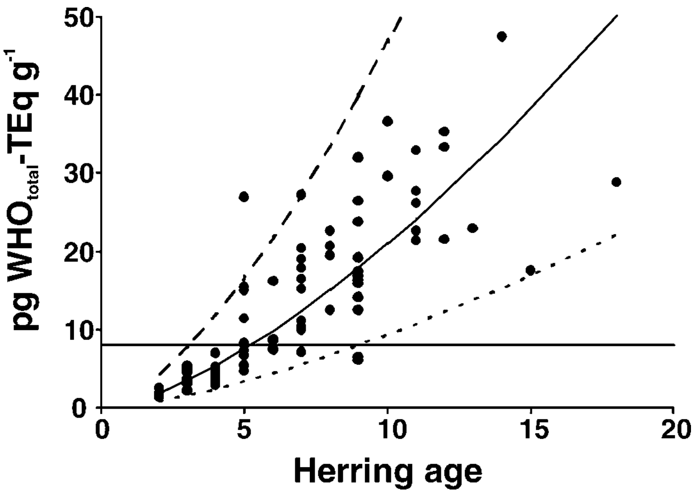

Figure 2. Current (measured in 2002) WHO$_{total}$-TEq concentrations (pg g^{-1}) of individual Bothnian Sea herring in relation to age. The solid line represents the median and dashed and dotted lines 95% confidence limits of fitted nonlinear relationship (see text). The horizontal solid line represents present EU limit for WHO$_{total}$-TEq in foodstuffs (8 pg WHO$_{total}$-TEq g^{-1}).

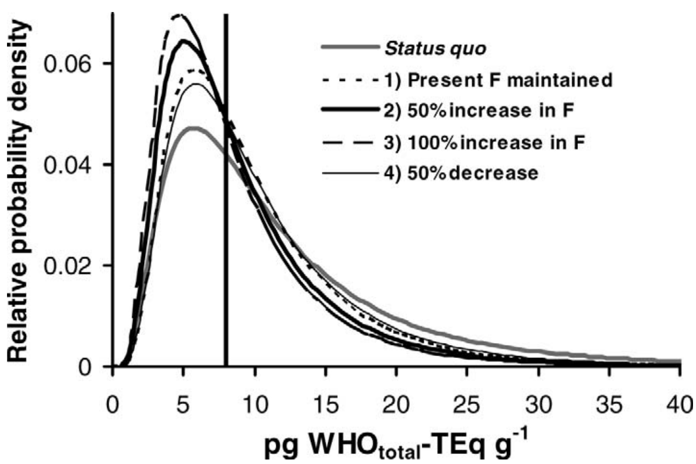

Figure 3. Relative probability distribution of whole market herring WHO$_{total}$-TEq concentrations (pg g^{-1}) estimated for present day (status quo 2002) and future fisheries scenarios. Herring individuals <23g were assumed not to be consumed by humans and were excluded from the distributions. The vertical solid line represents present EU limit for WHO$_{total}$-TEq in foodstuffs (8 pg WHO$_{total}$-TEq g^{-1}).

Analytical Procedures

Altogether 90 herring individuals were collected from the Bothnian Sea, northern Baltic, in June 2002. A detailed description of individual weight and length measurements as well as sex and age determination procedures used is given by Parmanne et al. (8). In the laboratory freeze-dried and homogenized individuals were Soxhlet-extracted for 20 h with toluene, and fat content was measured gravimetrically from the extract. Purification of the samples and fractionation of the studied compounds were identical to those in recently published papers (28, 29). High resolution gas chromatography–mass spectrometry was used to determine organochlorine concentrations. The analytical procedure and quality control has been described in more detail by Isosaari et al. (30). Concentrations of 17 PCDD/F and 12 PCB congeners were calculated as lower bound values (concentrations of nondetected congeners are set to zero) per fresh weight (fw) of herring muscle tissue. The toxic equivalent concentrations (WHO-TEq) for both PCDD/Fs and PCBs were calculated according to Van den Berg et al. (31). Results are presented as WHO$_{total}$-TEq, which is the sum of WHO$_{PCDD/F}$-TEq and WHO$_{PCB}$-TEq concentrations.

RESULTS

Organochlorine concentrations in Baltic Sea herring increased with fish age (Fig. 2). Age explained a high proportion of the variation in herring WHO$_{total}$-TEq (pg g^{-1}) and this relationship was described by Eq. 1. Posterior means (and standard deviations) of regression coefficients α and β were −0.289 (0.141) and 1.483 (0.078).

Our model simulations suggest substantial differences in WHO$_{total}$-TEqs (pg g^{-1}) of herring in the Finnish fish market (>23 g herring) under different fishing scenarios (Fig. 3). Sustaining present fishing mortality rates would decrease WHO$_{total}$-TEqs (pg g^{-1}) compared with status quo 2002. In 2002, there was a 57% probability (mean ± sd WHO$_{total}$-TEq concentration 12.16 ± 9.974 pg g^{-1}) that randomly picked herring in the fish market exceeded the EU limits of 8 pg g^{-1}. In the future fishing scenarios, correspondingly randomly picked herring in the fish market would have a 50% (mean ± sd, 9.71 ± 6.57 pg g^{-1}) probability of exceeding this limit if present fishing mortality is maintained (Scenario 1). In the other future fishing scenarios, 2, 3, and 4, the probabilities were 43% (8.79 ± 6.151 pg g^{-1}), 38% (8.106 ± 5.712 pg g^{-1}), and 52% (10.08 ± 7.042 pg g^{-1}), respectively. Thus, further increases in exploitation rate and subsequent changes in growth rates of herring influenced WHO$_{total}$-TEqs in herring only slightly. On the other hand, complete closure of the herring fishery would clearly increase WHO$_{total}$-TEqs (pg g^{-1}) in the Bothnian Sea herring.

Similarly, the mean human dietary intake of WHO$_{total}$-TEqs would decrease according to all fishing scenarios compared with present day intake (status quo 2002) (Table 1). The relative decrease in mean intake would be 17%, 24%, 30%, and 14% for fishing scenarios 1, 2, 3, and 4 respectively. However, the probability of exceeding the recommended maximum limit of human intake from herring (275 pg wk^{-1}) is high under all fishing scenarios if the consumption rate is higher than one portion per month (Fig. 4a). High-level herring consumers (6–8 portions per month) would have over a 50% probability of exceeding the total maximum limit of WHO$_{total}$-TEqs (840 pg wk^{-1}) only by consuming herring (Fig. 4b).

The shape of probability distributions of weekly human intake changes in relation to intake period. This is due to the high interindividual, week-to-week variation in WHO$_{total}$-TEqs among individual herring. The high consumption frequency (classes C_3–C_4) particularly increases the probability of very high weekly intake values (Table 1, Fig. 5). Uncertainty about average weekly intake decreases substantially when longer intake periods are considered. Organochlorines accumulate during the whole life span of a human individual and intake of one single week is likely not high enough to cause any medical problems. Therefore, the 1- and 10-y intake periods used here are more appropriate for risk evaluation of these contaminants in herring.

DISCUSSION

Our results clearly demonstrate that in the risk management of organochlorines, regulating fishing (in this case increasing fishing pressure) is a far less effective way to decrease the risk than regulating the consumption of herring (Table 1). If fishing was used as a management tool, the managers would need to compare the risk of overfishing the herring stock to the health risks, which is a very difficult trade-off. There is effectively no manager for such an issue because fisheries authorities are different from food safety and health authorities. However, an individual fish consumer could easily decrease this risk by consuming other fish instead of herring. Our results also

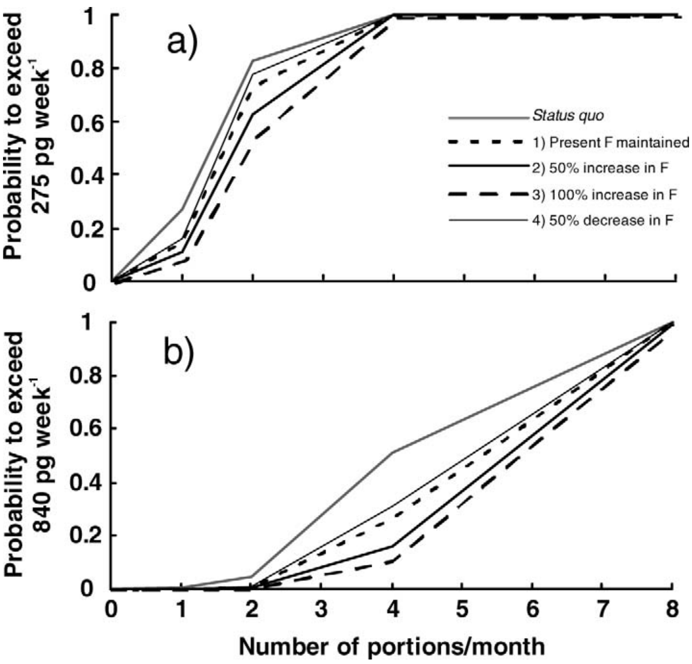

Figure 4. The probability of human WHO$_{total}$-TEq intake from herring exceeding the (a) 275 and (b) 840 pg wk^{-1} limits. The limit for human intake from herring that cannot be exceeded without exceeding the EU SCF limit for all foodstuff of WHO$_{total}$-TEq 840 pg wk^{-1} is 275 pg WHO$_{total}$-TEq wk^{-1}.

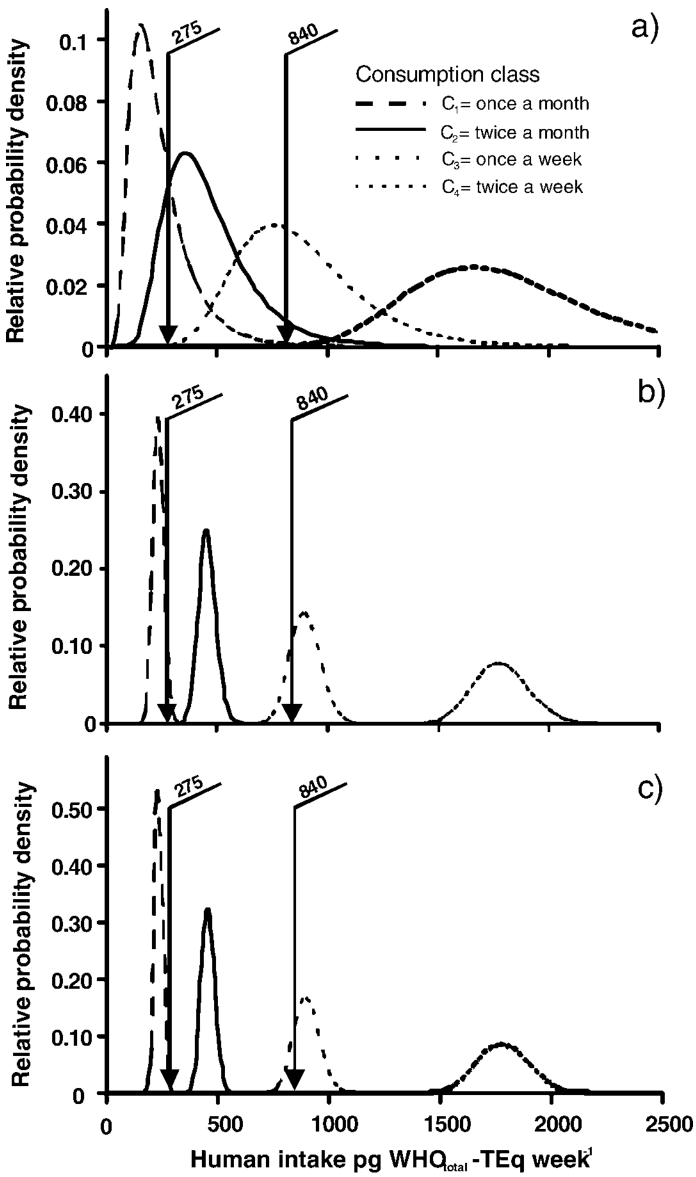

Figure 5. The relative probability distribution of WHO$_{total}$-TEq intake (pg g^{-1}) in four main herring consumption classes: (a) intake within 1 wk, (b) weekly intake within 1 y, (c) weekly intake within one decade. The limit for weekly intake from herring that cannot be exceeded without exceeding the EU SCF limit for all foodstuff of 840 pg WHO$_{total}$-TEq week^{-1} is 275 pg WHO$_{total}$-TEq wk^{-1} (see text).

demonstrate that the randomness arising from the big differences in toxin concentrations among herring individuals is an underestimated issue. It is likely that the randomness in other sources of uncertainty of organochlorines may also be high, and therefore all these uncertainties should be taken into account when considering risk management in future.

Peltonen et al. (14) observed in their simulation studies that the observed density-dependence in herring growth enabled development of a deterministic model to evaluate the impact of changes in the herring exploitation rate on population dynamics and growth, and of changes in growth on bioaccumulation of PCDD/Fs and PCBs in herring. They concluded that if the exploitation rate increases, growth rates would be higher and herring in the weight categories of commercial fisheries would be younger and contain less PCDD/F and PCB. Hence, the average toxicant concentrations in catches and subsequent human intake would also decline. The potential for reduction of PCDD/F and PCB intake by intensive fishing is in any case constrained by the relatively high present fishing mortality in the Bothnian Sea. A considerable increase (e.g., 100%) in fishing mortality would increase the risk of a collapse of the herring stock.

In this probabilistic simulation study, we expanded approach of Peltonen et al. (14) by modeling accurately one of the main variation components, interindividual variation in PCDD/F and PCB concentration of herring, in the complex process of organochlorine accumulation. Only one component of the complex system was modeled so the uncertainties of the whole accumulation process from biological system to human system were underestimated. Although a fully probabilistic model (i.e., one accounting for all known sources of uncertainty) would be the ideal solution, our simpler model clearly indicates that this approach still produces important new information for the risk assessment of dioxinlike organochlorine compounds. In future, more attention should be paid to regional differences in food consumption within the Finnish population and to obtaining more prior knowledge about model parameters α, β, and γ.

In the Bothnian Sea, age of herring has been shown to explain about 76%–80% of total interindividual variation in their WHO$_{PCDD/F}$-TEq and WHO$_{PCB}$-TEq values (8). The source of the remaining variation is still unknown but might be explained by differences in diet or in herring physiology. Species-specific variation in organochlorine concentrations of fish is generally well documented (8, 32, 33). From the human consumption point of view, the variation in the PCDD/F and PCB concentrations would transmit all the way to consumers, although there might be some shifts due to herring processing and classification. Generally, most of the Baltic herring used for human consumption are between 23 and 85 g (20); large herring are preferred in the human food industry; and smaller herring are sold as whole fish to customers. However, herring size in the catch and on the market varies by season, and this may be an important uncertainty that is not included in our present model.

The probability distributions of organochlorine concentrations in herring in the whole market showed that today nearly 60% of marketed herring exceeds EU limits for WHO$_{total}$-TEq in foodstuff (8 pg g^{-1}). Our simulation scenarios of fishing

Table 1. Mean, standard deviation, 95% probability interval (PI), and mode of the human weekly intake (pg WHO-TEq wk^{-1}) at present (status quo 2002) and at four modeled fisheries management scenarios. Intake was calculated for five herring consumption classes over three different periods: week, year, and decade. The 95% probability interval is calculated here by using the 2.5 and 97.5 percentiles of the posterior distribution as end points. C_1 = once per month, C_2 = twice per month, C_3 = once per week, C_4 = twice per week, C_5 = five times per week.

	Status quo 2002			1) Present F maintained			2) 50% increase in F		
Class	Mean ± sd	95% PI	Mode	Mean ± sd	95% PI	Mode	Mean ± sd	95% PI	Mode
Intake within 1 week									
C_1	225 ± 139	89–536	141	185 ± 97	77–414	128	168 ± 90	67–380	115
C_2	449 ± 198	220–910	343	370 ± 140	190–700	301	336 ± 130	170–642	270
C_3	898 ± 284	521–1566	772	740 ± 200	452–1207	661	672 ± 187	405–1108	596
C_4	1795 ± 412	1189–2756	1648	1480 ± 284	1032–2128	1395	1334 ± 268	927–1953	1261
C_5	4487 ± 693	3367–6050	4306	3702 ± 451	2927–4698	3612	3362 ± 425	2641–4291	3272
Intake/week within 1 year									
C_1	222 ± 24	181–275	217	183 ± 14	158–213	181	166 ± 13	143–194	164
C_2	444 ± 40	374–530	437	366 ± 18	330–407	364	332 ± 19	298–371	331
C_3	888 ± 70	764–1038	878	732 ± 28	680–790	731	665 ± 26	616–719	663
C_4	1775 ± 128	1548–2049	1759	1465 ± 39	1390–1545	1464	1330 ± 37	1259–1406	1329
C_5	4438 ± 302	3898–5081	4401	3663 ± 62	3543–3788	3662	3326 ± 59	3213–3444	3324
Intake/week within 1 decade									
C_1	222 ± 16	194–255	220	183 ± 4	175–192	183	166 ± 4	158–1175	166
C_2	444 ± 30	390–508	440	366 ± 6	354–379	366	333 ± 6	321–344	332
C_3	888 ± 59	782–1013	880	733 ± 9	716–750	732	665 ± 8	649–682	665
C_4	1775 ± 117	1565–2025	1761	1465 ± 12	1441–1490	1465	1330 ± 12	1308–1354	1330
C_5	4438 ± 290	3917–5058	4403	3663 ± 20	3625–3702	3663	3326 ± 19	3290–3363	3326

management indicated that this probability would decline when fishing increases, but that there is still a 38%–50% probability of exceeding 8 pg g^{-1}. Peltonen et al. (14) observed that the arithmetic means (9.1–11.2 pg g^{-1}) produced by their deterministic model would exceed EU limits for WHO$_{total}$-TEq in foodstuff. Our new probabilistic evaluation led to somewhat lower mean WHO$_{total}$-TEqs, but again all mean values are higher than the maximum limit. Organochlorine concentrations in Bothnian Sea herring are higher than in the other Baltic Sea areas (34). This may lead to an overestimation of total organochlorine intake by Finnish consumers in our study. The total Bothnian Sea catch comprises, however, 60%–70% of the total Finnish herring catches (35) and thus, it comprises a significant part of the total PCDD/F and PCB loads originating from the Finnish herring catch.

Kiviranta et al. (7, 27) and Hallikainen et al. (1) have recently estimated the average dietary intake of PCDD/Fs and PCBs of Finnish consumers by the market basket method (36). At the weekly level, the average total dietary intake varied from 700 to 805 WHO$_{total}$-TEqs (pg wk^{-1}). From the data available in Hallikainen et al. (1), we also calculated the dietary intake originating from herring; this weekly intake rate was 220 WHO$_{total}$-TEqs (pg wk^{-1}). Our intake rates for herring in this study were calculated differently: they were based on the consumption frequency data for Finnish consumers (how many portions per month), mean portion size (250 g total fresh body mass, 130 g fresh mass of fillet), and WHO$_{total}$-TEqs. In the consumption class C_1 (once per month), where the consumer frequency (42.8%) was highest, the mean intake rate obtained in this study (225 pg WHO$_{total}$-TEqs wk^{-1}) equaled the earlier estimates. These mean intake rates were clearly under the recommended maximum daily intake of PCDD/Fs and PCBs (275 pg WHO$_{total}$-TEqs wk^{-1}). Our results, however, showed clearly that even those consumers who use herring only once a month would have remarkably high weekly loads of PCDD/Fs and PCBs due to the high variation in the organochlorine concentration among herring individuals. Within longer intake periods (a year or a decade), which are more appropriate time scales for risk assessment of PCDD/Fs and PCBs, the variation decreased and the distribution was narrower (meaning smaller uncertainty) because the high and low concentration portions balanced each other. Nevertheless, those Finnish consumers who use herring twice per month would still have PCDD/Fs and PCBs loads clearly higher than the recommended maximum weekly intake limits for herring. Consumers who use herring once per week or more could have a remarkably high probability of getting loads higher than the total recommended intake limits (840 pg WHO$_{total}$-TEq week^{-1}) just by consuming herring.

The recent recommendation of the Finnish Food Safety Authorities (e.g., 1) is that Finnish consumers may use herring smaller than 17 cm once or twice per month. This recommendation has two significant drawbacks: first, a consumer cannot choose herring individuals by size because a major part of herring is consumed in forms that obscure the original size. Secondly, a major part of herring for human consumption is greater than 15–16 cm (23 g mean fresh body weight) and a large proportion is greater than 17 cm (30 g mean fresh body weight). In practice, a consumer can only follow the instruction regarding consumption frequency (1–2 times per month), which could lead to considerable risk of exceeding recommended intake limits for PCDD/Fs and PCBs. More information about the size composition of fresh herring and herring in processed products on the market is clearly needed. One way to reach the recommendations would be to size-sort herring individuals before processing and consumption, and to process the large herring individuals for feed of fur animals.

Nowadays there are two concrete practices for regulating human dietary intake of PCDD/Fs and PCBs in Europe: maximum intake limits with recommendations of consumption frequencies and maximum concentrations in the foodstuff. The major difference between these two is that maximum concentration in the foodstuff does not take into account consumer choice. If foodstuff exceeds certain limits, it cannot be sold and must be removed from the market. The principle underlying this practice is to ensure that maximum intake limits are not exceeded. However, in the case of herring, Finland and Sweden have given freedom of choice to consumers, although maximum concentration in this foodstuff is likely to be exceeded. For some consumers, information that herring contains dioxins is enough for them to make a decision, but for others it makes no difference. The policy of the Finnish and Swedish food safety authorities is that, although herring contains contaminants that may cause health problems, it also has welcome health benefits,

Table 1. Extended.

3) 100% increase in F			4) 50% decrease in F		
Mean ± sd	95% PI	Mode	Mean ± sd	95%PI	Mode
Intake within 1 week					
155 ± 84	63–353	106	192 ± 98	82–428	136
310 ± 121	156–596	249	385 ± 141	202–726	316
620 ± 174	372–1023	549	771 ± 202	477–741	693
1240 ± 249	853–1806	1161	1543 ± 286	1085–2202	1459
3102 ± 397	2432–3975	3017	3858 ± 453	3073–4859	3771
Intake/week within 1 year					
153 ± 12	131–179	152	191 ± 14	166–220	189
307 ± 17	275–343	305	382 ± 20	345–423	380
614 ± 25	567–664	612	763 ± 28	711–821	762
1227 ± 35	1161–1298	1226	1527 ± 40	1451–1607	1525
3069 ± 55	2963–3179	3067	3817 ± 63	3697–3943	3816
Intake/week within 1 decade					
153 ± 4	146–161	153	191 ± 4	182–200	191
307 ± 6	296–318	307	382 ± 6	370–394	382
614 ± 8	599–629	614	764 ± 9	746–781	763
1227 ± 11	1206–1249	1227	1527 ± 13	1503–1552	1527
3069 ± 17	3035–3103	3069	3817 ± 20	3779–3856	3817

which have been estimated to outweigh the costs. In cost–benefit analysis (see, e.g., 3), risks, costs, and benefits must be quantified and valued. The determination and quantification of risks, costs, and benefits is the responsibility of scientists, whereas the valuation must be done by the policy makers.

In this study we estimated what would be the risk of exceeding present precautionary limits of PCDD/Fs and PCBs set by food safety and health authorities. Our results clearly indicate that new information is still needed to evaluate whether these limits are set appropriately. Several causal dependencies behind the "dioxin problem" are highly uncertain, and the probabilistic approach used here is an excellent tool for modeling this type of uncertainty. Uncertainty plays an important role in the human decision-making system, and a very concrete example of this is the big difference in the precautionary limits for human intake between Europe and the United States. The precautionary limits in the United States are much more conservative (up to 2000-fold lower), and this difference arises mainly from the uncertainty in health effects at low doses of organochlorines and from different perceptions about health costs and benefits.

References and Notes

1. Hallikainen, A., Parmanne, R., Kiviranta, H. and Vartiainen, T. 2006. Are herring still eatable? Human intake of dioxin re-evaluated. *Duodecim 122*, 801–804. (In Finnish).
2. Kiviranta, H. 2005. *Exposure and Human PCDD/F and PCB Body Burden in Finland*. National Public Health Institute. A14. Edita Prima Oy, Helsinki, 191 pp.
3. Tuomisto, J.T. and Pekkanen, J. 2005. Assessing environmental health risks or net health benefits? *Scand. J. Public Health 33*, 162–163.
4. EC 2001. Opinion of the Scientific Committee of Food, risk assessment of dioxins and dioxin-like PCBs in food. *Off. J. Eur.* Communities CS/CNTM/DIOXIN/20 final, adopted 30 May 2001, 29 pp.
5. USEPA. 2000. *Exposure and human health reassessment of 2,3,7,8-tetrachlorodibenzo-p-dioxin and related compounds*. *Draft Final*. National Center for Environmental Assessment, US Environmental Protection Agency, Washington, DC.
6. EC 2006. Commission regulations (EC) No 199/2006, amending Regulation (EC) No. 466/2001 setting maximum levels for certain contaminants in foodstuffs as regards dioxins and dioxin-like PCBs. *Off. J. Eur Union L 32,* 34–38.
7. Kiviranta, H., Hallikainen, A., Ovaskainen, M.L., Kumpulainen, J. and Vartiainen, T. 2001. Dietary intakes of polychlorinated dibenzo-p-dioxins, dibenzofurans and polychlorinated biphenyls in Finland. *Food Addit. Contam. 18*, 955–953.
8. Parmanne, R., Hallikainen, A., Isosaari, P., Kiviranta, H., Koistinen, J., Laine, O., Rantakokko, P., Vuorinen, P.J., et al. 2006. The dependence of organohalogen compound concentrations on herring age and size in the Bothnian Sea, northern Baltic. *Mar. Pollut. Bull. 52*, 149–161.
9. Assmuth, T. and Jalonen, P. 2005. *Risk and Management of Dioxin-Like Compounds in Baltic Sea Fish: An Integrated Assessment*. TemaNord, Copenhagen, 376 pp.
10. Swedish National Food Agency. 2002. *Fish and our health*. Swedish National Food Agency. Uppsala (www.slv.se/). (In Swedish).
11. National Food Agency Finland. 2004. New recommendations for fish use (Uudistetut kalan syönti suositukset EU-kalat tutkimusahankkeen seurauksena), (www.evira.fi) (in Finnish).
12. Jackson, L.J. 1996. How will decreased alewife growth rates and salmonid stocking affect sport fish PCB concentrations in Lake Ontario? *Environ. Sci. Technol. 30*, 701–705.
13. ICES. 2005. Report of the Baltic fisheries assessment working group. ICES advisory commission on fishery management. ICES CM 2005/ACFM 19, 607 pp.
14. Peltonen, H., Kiljunen, M., Kiviranta, H., Vuorinen, P.J., Verta, M. and Karjalainen, J. 2006. Predicting effects of exploitation rate on weight-at-age, population dynamics and bioaccumulation of PCDD/Fs and PCBs in herring (*Clupea harengus* L.) in the northern Baltic Sea. *Environ. Sci Technol.* (DOI 10.1021/es0618346).
15. Hewett, S.W. and Johnson, B.L. 1992. *A Generalized Bioenergetics Model of Fish Growth for Microcomputers*. University of Wisconsin Sea Grant Institute, Madison, Wisconsin. UW Sea Grant Tech. Rept.
16. Rudstam, L.G. 1988. Exploring the dynamics of herring consumption in the Baltic: applications of an energetic model of fish growth. *Kieler Meeresforsch. Sonderh. 6*, 312–322.
17. DeFinetti, B. 1979. *Theory of Probability*. John Wiley & Sons, Ltd., Bristol.
18. Gelman, A., Carlin, J.B., Stern, H.S. and Rubin, D.B. 1995. *Bayesian Data Analysis*. Chapman & Hall, London, 696 pp.
19. Howson, C. and Urbach., P. 1991. Bayesian reasoning in science. *Nature 350*, 371–374.
20. Anon. 2002. *Producer Prices for Fish 2002*. *Finnish Game and Fisheries Institute*. Official Statistics of Finland 2003.
21. Sääksjärvi, K. and Reinivuo, H. 2004. *Portion Size of Foodstuff* (*Ruokamittoja*). Kansanterveyslaitoksen julkaisuja B15, 46 pp. (in Finnish).
22. Reay, G.A., Cutting, C.L. and Shewan, J.M. 1943. The nation's food VI. Fish as food II. The chemical composition of fish. *J. Soc. Chem. Ind. 62*, 77–85.
23. Amrhein, J.F., Stow, C.A. and Wible, C. 1999. Whole-fish versus filet polychlorinated-biphenyl concentrations: an analysis using classification and regression tree models. *Environ. Toxicol. Chem. 18*, 1817–1823.
24. Tuomisto, J.T., Pekkanen, J., Kiviranta, H., Tukiainen, E. and Vartiainen, T. 2004. Soft-tissue sarcoma and dioxin: a case-control study. *Int. J. Cancer 108*, 893–900.
25. Gilks, W., Richardson, S. and Spiegelhalter, D. 1995. Introducing Markov chain Monte Carlo. In: *Markov Chain Monte Carlo in Practice*. Gilks, W., Richardson, S. and Spiegelhalter, D. (eds.), Chapman & Hall, London, 1–20.
26. Spiegelhalter, D.J., Thomas, A., Best., N.G. and Lunn, D.W. 2003. *WinBUGS Version 1.4 User Manual*. MRC Biostatistics Unit, Cambridge.
27. Kiviranta, H., Ovaskainen, M.A.L. and Vartiainen, T. 2004. Market basket study on dietary intake of PCDD/Fs, PCBs, and PBDEs in Finland. *Environ. Int. 30*, 923–932.
28. Isosaari, P., Vartiainen, T., Hallikainen, A. and Ruohonen, K. 2002. Feeding trial on rainbow trout: comparison of dry fish feed and Baltic herring as a source of PCDD/Fs and PCBs. *Chemosphere 48*, 795–804.
29. Kiviranta, H., Vartiainen, T., Parmanne, R., Hallikainen, A. and Koistinen, J. 2003. PCDD/Fs and PCBs in Baltic herring during the 1990s. *Chemosphere 50*, 1201–1216.
30. Isosaari, P., Hallikainen, A., Kiviranta, H., Vuorinen, P. J., Parmanne, R., Koistinen, J. and Vartiainen, T. 2006. Polychlorinated dibenzo-p-dioxins, dibenzofurans, biphenyls, naphthalenes and polybrominated diphenyl ethers in the edible fish caught from the Baltic Sea and lakes in Finland. *Environ. Pollut. 141*, 213–225.
31. Van den Berg, M., Birnbaum, L., Bosveld, A.T.C., Brunstrom, B., Cook, P., Feeley, M., Giesy, J.P., Hanberg, A., et al. 1998. Toxic equivalency factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. *Environ. Health Perspect. 106*, 775–792.
32. Ion, J., de Lafontaine, Y., Dumont, P. and Lapierre, L. 1997. Contaminant levels in St. Lawrence River yellow perch (*Perca flavescens*): spatial variation and implications for monitoring. *Can. J. Fish. Aquat. Sci. 54*, 2930–2946.
33. Green, N.W. and Knutzen, J. 2003 Organohalogens and metals in marine fish and mussels and some relationships to biological variables at reference localities in Norway. *Mar. Pollut. Bull. 46*, 362–374.
34. Vuorinen, P.J., Parmanne, R., Kiviranta, H., Isosaari, P., Hallikainen, A. and Vartiainen, T. 2004. Differences in PCDD/F concentrations and patterns in herring (*Clupea harengus*) from the southern and northern Baltic Sea. *Organohal. Compd. 66*, 1858–1863.
35. Anon. 2004. *Finnish Fisheries Statistics*. Finnish Game and Fisheries Research Institute, Helsinki.
36. Rantakokko, P., Kuningas, T., Saastamoinen, K. and Vartiainen, T. 2006. Dietary intake of organotin compounds in Finland: a market-basket study. *Food Addit. Contam. 23*, 749–756.

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