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Global Assessment of Organic Contaminants in Farmed Salmon

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The annual global production of farmed salmon has increased by a factor of 40 during the past two decades. Salmon from farms in northern Europe, North America, and Chile are now available widely year-round at relatively low prices. Salmon farms have been criticized for their ecological effects, but the potential human health risks of farmed salmon consumption have not been examined rigorously. Having analyzed over 2 metric tons of farmed and wild salmon from around the world for organochlorine contaminants, we show that concentrations of these contaminants are significantly higher in farmed salmon than in wild. European-raised salmon have significantly greater contaminant loads than those raised in North and South America, indicating the need for further investigation into the sources of contamination. Risk analysis indicates that consumption of farmed Atlantic salmon may pose health risks that detract from the beneficial effects of fish consumption.

Between 1987 and 1999, salmon consumption increased annually at a rate of 14% in the European Union and 23% in the United States (*1*). Currently, over half the salmon sold globally is farm-raised in Northern Europe, Chile, Canada, and the United States, and the annual global production of farmed salmon (predominantly Atlantic salmon, *Salmo salar*) has risen from ~24,000 to over 1 million metric tons during the past two decades (*2*). The health benefits of eating fish such as salmon have been well documented (*3*, *4*). However, salmon are relatively fatty carnivorous fish that feed high in the food web, and as such, they bioaccumulate contaminants (*5*). The potential risks of eating contaminated farmed salmon have not been well evaluated. Three previous studies reporting contaminants in salmon are inconclusive because of their very small sample sizes and narrow geographic representation (*6*–*8*). As a result, the extent of this problem and the potential risks to human health remain unclear.

We measured organochlorine contaminants in approximately 700 farmed and wild salmon (totaling ~2 metric tons) collected from around the world. We do not report on other important contaminants, such as methylmercury, because our preliminary study (*9*) showed no significant difference in methylmercury levels between farmed and wild salmon. Using the data on organochlorine contaminants, we assessed the variation in contaminant loads between farmed and wild salmon and among geographic regions, and we calculated the human health risks of salmon consumption. Farmed Atlantic salmon from eight major producing regions in the Northern and Southern hemispheres were purchased from wholesalers that could obtain fish of the appropriate size within the sampling period; in addition, farmed Atlantic salmon fillets were purchased at supermarkets in 16 large cities in North America and Europe. For comparison, samples of five wild species of Pacific salmon [chum (*Oncorhyncus keta*), coho (*O. kisutch*), chinook (*O. tshawytscha*), pink (*O. gorbuscha*), and sockeye (*O. nerka*)] were obtained from three different geographic regions. Wild Atlantic salmon were not studied because few are available commercially; nor did we analyze farmed Pacific salmon because they are not raised in any substantial amounts (*2*, *10*).

A total of 594 individual whole salmon were purchased from wholesalers and filleted; an additional 144 fillets were purchased from retailers in Boston, Chicago, Denver, Edinburgh, Frankfurt, London, Los Angeles, New Orleans, New York, Oslo, Paris, San Francisco, Seattle, Toronto, Vancouver, and Washington, DC. Composites of fillets from whole salmon were made on the basis of the location where they were produced (farmed salmon) or purchased (wild salmon). Composites of fillets from retailers were made on the basis of the retail outlet where they were purchased. Each composite sample consisted of fillets from three salmon per location or three fillets per retail outlet, giving 246 measurable samples. All samples were homogenized and analyzed by gas chromatographic high-resolution mass spectrometry (*11*). Strict quality assurance and quality control procedures were followed (*11*). Thirteen samples of salmon feed were purchased from the European, North American, and South American outlets of the two major fish feed companies, which together have ~80% of the global market for fish feed (*12*), and were analyzed as above.

Contaminant concentrations in farmed and wild salmon were compared by analysis of variance. In comparing wild and farmed salmon, farmed salmon were considered as a single group. In addition, locations at which salmon were farmed were compared by analysis of variance with multiple comparisons of means to test for differences among locations in contaminant levels. In all analyses of vari-

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ance, the replicate composites from each source were not assumed to be independent observations. Differences between farmed and wild salmon and differences among farming locations were consistently substantial and highly significant.

Figure 1 shows the concentrations of 14 organochlorine contaminants in the samples of farmed and wild salmon. Thirteen of these contaminants were significantly more concentrated in the farmed salmon as a group than in the wild salmon [$F = 3.75$, $P = 0.0573$ for lindane; $F = 9.93$, $P = 0.0025$ for hexachlorobenzene (HCB); and $F \geq 11.71$, $P \leq 0.001$ for the other 12 contaminants, with df = (1, 64) for all]. Concentrations in farmed salmon from Europe and from North America were significantly higher than those in wild salmon for all 14 contaminants ($P < 0.05$ for all 28 comparisons). Concentrations in farmed salmon from South America were significantly higher than those in wild salmon for six contaminants [polychlorinated biphenyls (PCBs), dioxins, dieldrin, *cis*-nonachlor, total DDT, and mirex] but significantly lower for two contaminants (HCB and lindane) ($P < 0.05$ for each). In addition, concentrations of all contaminants in farmed salmon from Europe were significantly greater than concentrations in farmed salmon from both North and South America [$F = 8.31$ to 65.87, with df =(2, 48); $P < 0.001$ for all 14 contaminants].

We focused additional analysis on PCBs, dioxins, toxaphene, and dieldrin because the patterns of their occurrence in farmed and wild salmon are similar to the patterns of all contaminants evaluated in this study and because an abundance of human health risk information is available for these compounds (*13*–*19*).

The average measured concentrations for these four contaminants are shown in Fig. 2, A to D, as a function of location. As noted above, total PCBs, dioxins, toxaphene, and dieldrin were consistently and significantly more concentrated in the farmed salmon as a group than in the wild salmon [$F = 60.53$, 26.80, 15.03, and 32.22, with df =(1, 64) for all; $P \leq 0.0003$ for all]. Salmon fillets obtained from commercial outlets in the various cities generally clustered with the farmed samples, not with the wild samples.

PCB, dioxin, toxaphene, and dieldrin concentrations were highest in farmed salmon from Scotland and the Faroe Islands and lowest in farmed salmon from Chile and Washington state. Salmon produced in Europe had significantly higher contaminant levels than those produced in both North and South America [$F = 26.15$, 23.36, 64.42, and 59.26, with df =(2, 48) for all; $P < 0.0001$ for all]. Even the least contaminated farmed salmon, from Chile and Washington state, had significantly higher contaminant loads of PCBs, dioxins, and dieldrin than wild salmon [$F = 28.55$, 8.61, and 4.66, with df =(1, 26); $P < 0.0001$, $P = 0.0069$, and $P = 0.0402$, respectively]. Farmed salmon fillets purchased from supermarkets in Frankfurt, Edinburgh, Paris, London, and Oslo were generally the most contaminated, although those purchased in Boston and San Francisco approached these

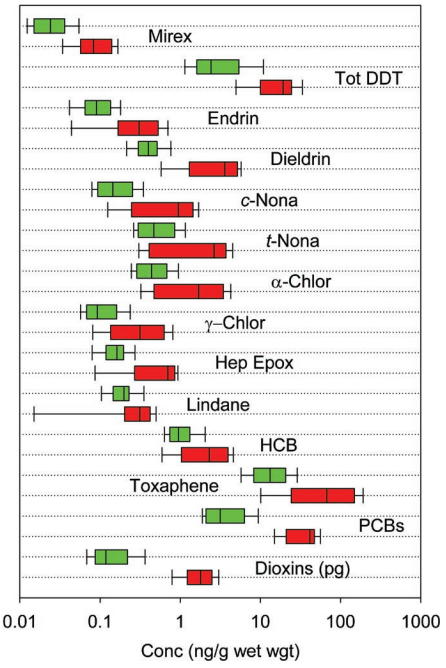

Fig. 1. Concentrations (in ng/g wet weight, except dioxins) of 14 contaminants found in farm-raised (red bars) and wild (green bars) salmon. The vertical lines represent the 10th, 50th, and 90th percentiles, and the boxes represent the 25th to 75th percentiles. Dioxins are in pg of World Health Organization toxic equivalents (WHO-TEQs) per g of wet weight and include polychlorinated dibenzo-*p*-dioxins and dibenzofurans and dioxin-like PCBs. Typically 75% of the total TEQ was due to the dioxin-like PCBs. Other abbreviations are as follows: Tot DDT, the *p*,*p*′ and *o*,*p*′ isomers of DDT, DDD, and DDE; Nona, nonachlor; Chlor, chlordane; Hep Epox, heptachlor epoxide.

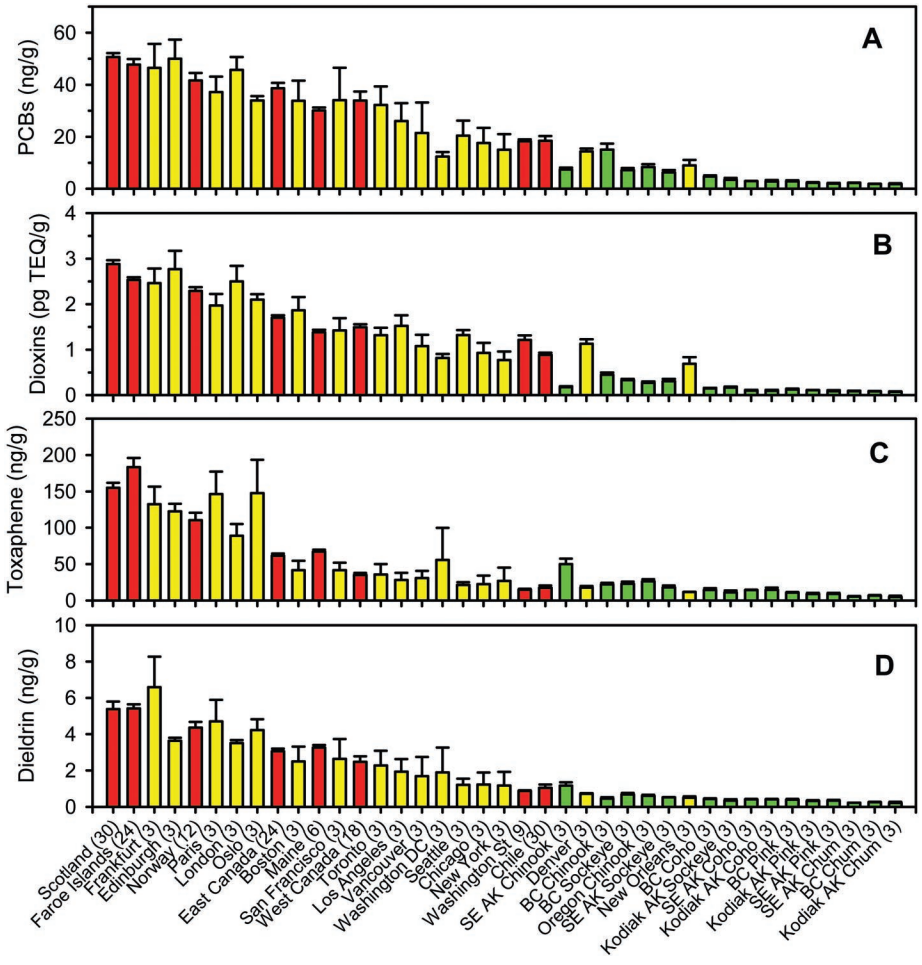

Fig. 2. Concentrations of (**A**) PCBs in ng/g wet weight, (**B**) dioxins (for detail, see Fig. 1) in pg of WHO-TEQ/g wet weight, (**C**) toxaphene in ng/g wet weight, and (**D**) dieldrin in ng/g wet weight in farmed, supermarket, and wild salmon. The concentrations are all given as functions of the locations where the salmon were grown or purchased. Red represents farmed salmon, green represents wild salmon, and yellow represents salmon purchased at supermarkets. The error bars represent standard errors. The number of samples is given in parentheses after the location identifier. The locations are sequenced by average contaminant rank.

concentrations. Those purchased in New Orleans and Denver were the least contaminated of the store-bought samples. The concentrations of PCBs, dioxins, toxaphene, and dieldrin in salmon fillets purchased in cities in Europe were significantly higher than in those purchased in cities in North America [F = 22.08, 31.46, 116.80, and 36.50, with df =(1, 14); $P < 0.0001$ for all]. Most of the salmon sold in European stores comes from European farms, which produce the more contaminated salmon, whereas much of the salmon sold in U.S. stores comes from Chile and Canada (*20*, *21*).

Some of the concentrations in the store-bought farmed samples were quite variable. For example, dieldrin concentrations in the three samples purchased in Washington, DC, were 4.63, 0.61, and 0.46 ng per gram of wet weight (ng/g wet weight). Based on information from the retailer, the two Washington, DC, samples with the lowest concentrations came from farms in Chile, and the one with the highest concentration came from a farm in Iceland. This is further evidence that farmed salmon from the North Atlantic had higher contaminant concentrations than those from Chile.

The large differences between the farmed and wild salmon contaminant concentrations are most likely a function of their diet. Farmed salmon are fed a concentrated feed high in fish oils and fish meal, which is obtained primarily from small pelagic fishes (*22*). We analyzed 13 samples of commercial salmon feed (Fig. 3). Although the concentrations in these feed samples were quite variable, they were generally similar to or greater than those in the farmed salmon. The concentrations in feed purchased from Europe were significantly higher than those in feed purchased from North and South America [F = 7.05, 11.16, 31.35, and 6.78, with df = (1, 11); P = 0.022, 0.007, 0.001, and 0.024, respectively]. This may reflect higher contaminant concentrations in forage fish from the industrialized waters of Europe's North Atlantic as compared to forage fish from the waters off North and South America—the primary sources of fish harvested for fish meal and fish oil (*23*). Uptake of organic contaminants from water to fish is a minor accumulation pathway (*24*), so we did not analyze contaminants in water where farmed and wild salmon live.

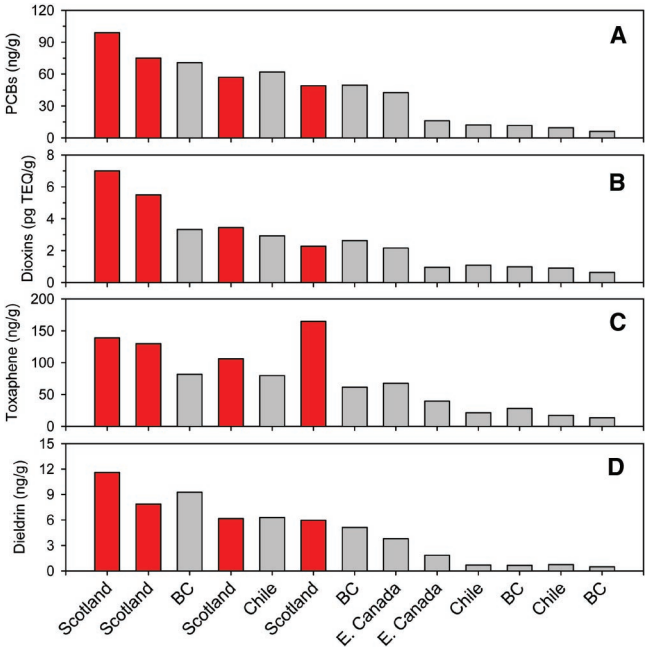

Fig. 3. Concentrations of (**A**) PCBs in ng/g wet weight, (**B**) dioxins (for detail, see Fig. 1) in pg of WHO-TEQ/g wet weight, (**C**) toxaphene in ng/g wet weight, and (**D**) dieldrin in ng/g wet weight in commercial fish feed purchased at facilities in various countries at various times of the year. Each bar represents the analysis of one sample of fish feed, and the country from which it was obtained is indicated. The concentrations are given as functions of the locations where the fish feed was purchased. Fish feed purchased in Europe is indicated by red, and fish feed purchased in North or South America is indicated by gray. The locations are sequenced by average contaminant rank.

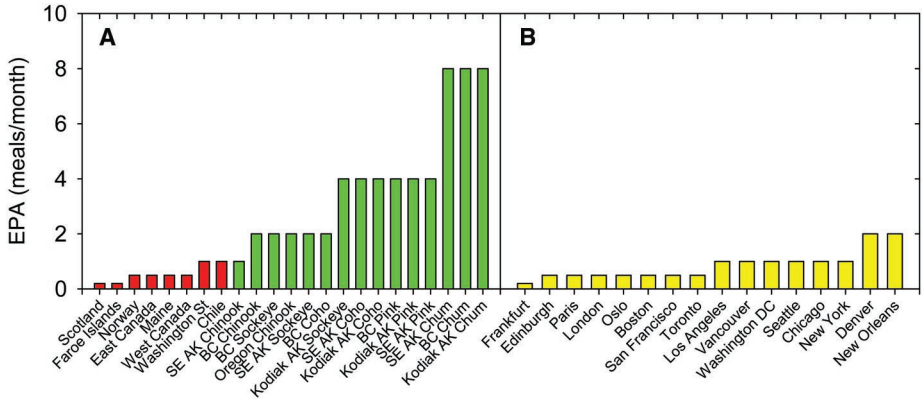

Fig. 4. Consumption advisories (in meals per month) based on U.S. EPA cumulative risk assessment methods for PCBs, toxaphene, and dieldrin for (**A**) farmed (red) and wild (green) salmon and for (**B**) supermarket salmon (yellow). The country in which the salmon was produced or the city from which it was purchased is indicated.

The human health effects of exposure to PCBs, toxaphene, and dieldrin in salmon tissues are a function of contaminant toxicity, concentration in fish tissues, and fish consumption rates. We used the approach of the U.S. Environmental Protection Agency (EPA) (*25*) to assess the comparative health risks of consuming farmed and wild salmon. Individual contaminant concentrations in farmed and wild salmon do not exceed U.S. Food and Drug Administration (FDA) action or tolerance levels for PCBs and dieldrin (*26*). However, FDA action and tolerance levels are not strictly health-based, do not address the health risks of concurrent exposure to more than one contaminant, and do not provide guidance for acceptable levels of toxaphene and dioxins in fish tissue (*27*–*29*). The U.S. EPA approach (*25*) is designed to manage health risks by providing risk-based consumption advice regarding contaminated fish (for example, one should limit consumption of a particular species to a specified number of meals per month or week).

The combined concentrations of PCBs, toxaphene, and dieldrin trigger stringent consumption advice for farmed salmon purchased from wholesalers and for store-bought farmed fillets. This advice is much more restrictive than consumption advice triggered by contaminants in the tissues of wild salmon (Fig. 4, A and B). The most restrictive advice (less than one-half meal of salmon per month), which reflects the highest health risks, was generated for farmed salmon fillets purchased from stores in Frankfurt, Germany, and for farmed salmon from Scotland and the Faroe Islands. The concentrations of PCBs, toxaphene, and dieldrin trigger EPA consumption advice of no more than 1 meal per month for all samples of farmed salmon and for all but two samples of store-bought salmon, for which the advice is no more than 2 meals per month.

The methods used to develop this consumption advice for PCBs, toxaphene, and dieldrin are based on estimates of potential cancer risks and on an assumption of risk additivity (*25*). A variety of noncancer health effects have also been associated with exposure to PCBs (*19*), toxaphene (*30*), dieldrin (*31*), and other contaminants found in salmon. Some of these noncancer endpoints, such as adverse neurobehavioral and immune ef-

fects and endocrine disruption, occur at lower concentrations than those implicated in cancer (*17*). However, these hazards were not considered in the present analysis because quantitative risk or threshold levels are not available regarding these effects.

Our data indicate that farmed salmon have significantly higher contaminant burdens than wild salmon and that farmed salmon from Europe are significantly more contaminated than farmed salmon from South and North America. Fish that is not contaminated is a healthy food, high in nutrients, such as omega-3 polyunsaturated fatty acids, that are known to have a variety of beneficial human health effects (*3*, *4*). However, this study suggests that consumption of farmed salmon may result in exposure to a variety of persistent bioaccumulative contaminants with the potential for an elevation in attendant health risks. Although the risk/benefit computation is complicated, consumption of farmed Atlantic salmon may pose risks that detract from the beneficial effects of fish consumption. This study also demonstrates the importance of labeling salmon as farmed and identifying the country of origin. Further studies of contaminant sources, particularly in feeds used for farmed carnivorous species such as salmon, are needed.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/303/5655/226/DC1
Materials and Methods
Table S1
Reference

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Regulation of Bone Mass in Mice by the Lipoxygenase Gene *Alox15*

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The development of osteoporosis involves the interaction of multiple environmental and genetic factors. Through combined genetic and genomic approaches, we identified the lipoxygenase gene *Alox15* as a negative regulator of peak bone mineral density in mice. Crossbreeding experiments with *Alox15* knockout mice confirmed that 12/15-lipoxygenase plays a role in skeletal development. Pharmacologic inhibitors of this enzyme improved bone density and strength in two rodent models of osteoporosis. These results suggest that drugs targeting the 12/15-lipoxygenase pathway merit investigation as a therapy for osteoporosis.

Osteoporosis is one of the most common bone and mineral disorders in all aging communities. It is characterized by low bone mass (and thus, low bone strength), which results in fractures from relatively minor trauma. Although life-style and environmental factors play key roles in the development of osteoporosis, there is now clear evidence that genetic factors are also of great importance (*1*). Bone mineral density (BMD) achieved in early adulthood (peak bone mass) is a major predictor of osteoporotic fracture risk. Genetic segregation analyses in inbred mouse strains (*2*) have identified linkage between peak BMD and several chromosomal regions (or quantitative trait loci, QTLs), but the identities of the underlying genes remain unknown. Recent studies suggest that regulatory variation is important in a variety of complex traits (*3*). Quantitative gene expression studies can identify genetic variation affecting transcription within genes contributing to differences in complex traits. This is particularly useful for analysis of traits for which a priori gene candidates do not exist.

To identify genes that might regulate BMD, we investigated a region on mouse chromosome 11 that strongly influences peak BMD (*4*). We generated a DGA/2 (D2) background congenic mouse with an 82-megabase (Mb) region of chromosome 11 replaced by the corresponding region of the C57BL/6 (B6) ge-

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