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Ecosystemic Effects of Salmon Farming Increase Mercury Contamination in Wild Fish

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Net-pen salmon aquaculture has well-known effects on coastal ecosystems: farm waste increases sediment organic content and the incidence of sediment anoxia, supports increased production of deposit-feeding invertebrates, and attracts higher densities of demersal fish and other mobile carnivores. These impacts are widely considered to be localized and transitory, and are commonly managed by imposing a period of fallowing between cycles of production. The implications of these ecosystemic effects for contaminant cycling, however, have not previously been considered. We found elevated levels of mercury in demersal rockfishes near salmon farms in coastal British Columbia, Canada, attributable to a combination of higher rockfish trophic position and higher mercury levels in prey near farms. Mercury concentrations in long-lived species such as rockfishes change over a longer time scale than cycles of production and fallowing, and thus at least some important effects of fish farms may not be considered transitory.

Introduction

Consumption of marine fish is the major source of mercury exposure in humans (*1*). Mercury is present throughout the world's oceans, it is readily transformed by anaerobic bacteria into highly bioaccumulative organometallic forms (*2*), and it is biomagnified to high levels at the top of marine food webs (*1*, *3*). Mercury is a natural part of the lithosphere, but a host of human activities alter mercury biogeochemistry and cycling in aquatic ecosystems, most notably by physically redistributing the element, by producing conditions that enhance methylation, and by altering food web structure. These ecosystemic effects of human activities can lead to increases in mercury levels in harvested species, increasing health risks to human consumers and decreasing the marketability of affected stocks (*4*, *5*).

Salmon aquaculture has the potential to alter mercury cycling through some or all of the effects listed above. Some sources of fish feed have been found to contain high levels of mercury (*6*) and fish farms routinely produce zones of anoxic sediment (*7*−*9*), a condition that promotes conversion of inorganic mercury into the bioaccumulative organometallic form methylmercury (*2*, *10*). Organically enriched sediments also support very high production of deposit-feeding invertebrates (*9*, *11*) and attract high densities of demersal fish (*12*, *13*) and other mobile carnivores (*14*), enhancing benthic-pelagic coupling and the transfer of sediment-associated contaminants into higher trophic levels (*15*, *16*). The ecosystemic effects of fish farming are generally considered to be localized and transitory (*7*−*9*), but changes to mercury cycling may be persistent in long-lived species, and relatively far-reaching where biota disperse mobilized mercury throughout the local environment.

Aboriginal peoples face a particularly high health risk from mercury due to their reliance on traditional, wild-caught diets (*17*). In addition, many of Canada's coastal First Nations have expressed concern about the rapid expansion of the aquaculture industry within their traditional harvesting territories (*18*, *19*). This study was initiated to address concerns within Canada's coastal First Nations communities about the safety of their traditional marine foods, and to assess the potential for salmon aquaculture to influence food safety.

In this paper, we present mercury levels in fillets of copper rockfish (*Sebastes caurinus*) and quillback rockfish (*S. maliger*) from the traditional harvesting territories of three First Nations communities on the coast of British Columbia, Canada. These rockfish species are demersal, long-lived carnivores that associate with high-relief substrates such as rocky reefs (*20*). Because of their site fidelity, high trophic level, slow growth, and long lifespan, these species tend to accumulate relatively high levels of persistent pollutants such as mercury (*21*). These are also culturally important species for British Columbia's coastal First Nations (*22*). We compare mercury levels in rockfish near active salmon farms to those from reference sites, and we explore possible mechanisms for observed differences in mercury levels among sites.

Materials and Methods

We sampled in the traditional harvesting territories of the Ahousaht First Nation (near Ahousaht, BC: 49°17′N; 126°4′W), the Kitasoo/Xaixais First Nations (near Klemtu, BC: 52°35′N; 128°32′W), and the member nations of the Musgumagw Tsawataineuk Tribal Council (MTTC, near Alert Bay, BC: 50°35′N; 126°55′W). Within each territory, we collected fish from three sites 250−750 m down-current of active fish farms and from two to three reference sites that were not directly down-current of any currently or recently active salmon farm, i.e., the water passing through the site would not have passed through any salmon farm on the same tidal cycle. Reference sites within each territory were 3−20 km away from the nearest active salmon farm, and spread over a geographic area encompassing the near-farm sites to avoid conflating spatial variation in mercury levels with an effect of farms (see Supporting Information for maps). Within each site, we sampled near rock walls and underwater reefs at various depths to obtain as wide a range of body sizes as possible.

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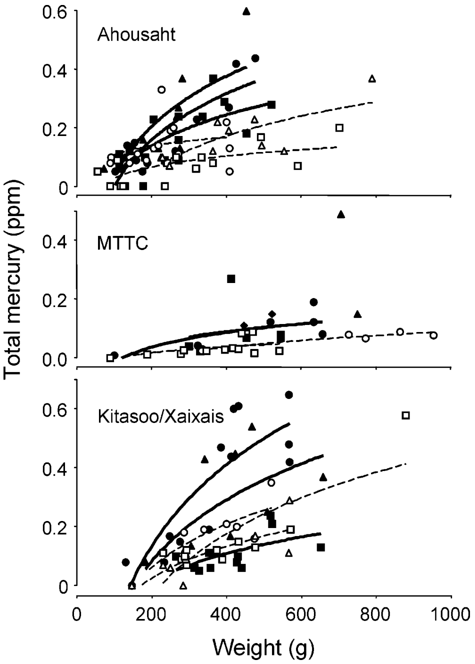

FIGURE 1. Mercury levels as a function of body size in demersal rockfish (*Sebastes* spp.) in the traditional harvesting territories of three coastal First Nations groups in British Columbia, Canada. Open symbols and dashed lines are reference sites; filled symbols and bold lines are sites near active salmon farms. Symbols are matched to sites in Table 1. Mercury levels were significantly higher at near-farm sites in all three territories.

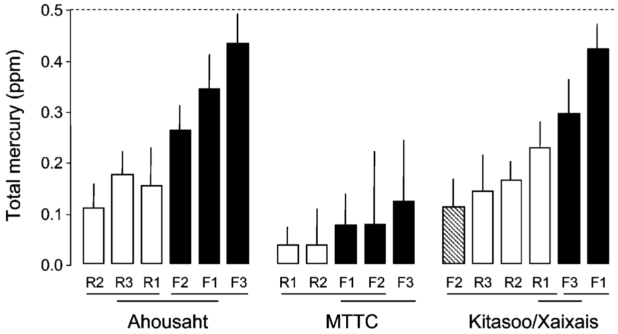

FIGURE 2. Mercury levels in 450 g demersal rockfish (*Sebastes* spp.) in the traditional harvesting territories of three coastal First Nations groups in British Columbia, Canada (a 450 g rockfish is considered edible by First Nations consumers and is within the sampled size range at all sites). Values were estimated from site-specific regressions of total mercury on body size. Vertical lines are standard errors of the estimated values. Dashed horizontal line is Health Canada's consumption guideline for mercury (*29*). White bars are reference sites, dark bars are sites near active salmon farms. F2 in Kitasoo/Xaixais territory is a farm that had been in operation less than one year. Breaks in solid horizontal lines indicate significant differences in total mercury among sites, identified by Tukey post-hoc multiple comparisons following analysis of covariance with body size as a continuous covariate.

Sampling was conducted on two to three visits to each territory in July−December, 2004 and October, 2005.

We measured total mercury concentrations in fillets of 96 copper (*Sebastes caurinus*) and 75 quillback rockfish (*S. maliger*). Rockfish were captured by hook and line with unbaited lures. Captured fish were handled as little as possible, sacrificed by a blow to the top of the head, then immediately wrapped in hexane-rinsed aluminum foil, double-bagged in new zip-loc bags with unique sample identifier labels, and stored on ice until the end of the sampling day (no more than a few hours), when they were transferred to a −20 °C freezer. Fish-handling gloves (to prevent injuries from rockfish spines) and the club were scrubbed with detergent and rinsed thoroughly in seawater between sites. On each visit to each site, we also collected clams (Manila clams [*Venerupis* philippinarum], littleneck clams [*Protothaca staminea*], and butter clams [*Saxidomus gigantea*]) from nearby beaches to serve as an isotopic baseline for the estimation of rockfish trophic position (the mean level in the food web at which rockfish are feeding) (*23*).

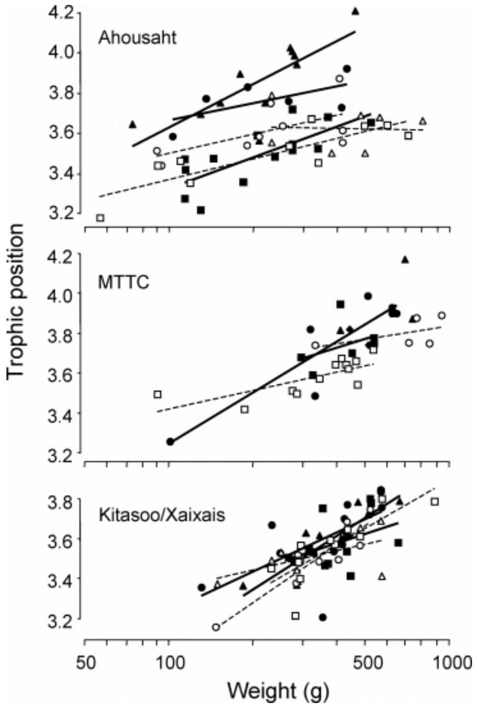

FIGURE 3. Ontogenetic shift in trophic position of demersal rockfish (*Sebastes* spp.) in the traditional harvesting territories of three coastal First Nations groups in British Columbia, Canada. Open symbols and dashed lines are reference sites; filled symbols and bold lines are sites near active salmon farms. Symbols are matched to sites in Table 1. Trophic position of rockfish was significantly higher at two near-farm sites in Ahousaht territory and at one near-farm site in MTTC territory.

For mercury analysis, we removed a square patch of skin (∼4 × 4 cm) from behind the pectoral fin and subsampled ∼5 g of muscle tissue with a stainless steel scalpel. Muscle tissue adhering to skin was scraped off and added to the sample. Subsamples were transported frozen to Aquatic Research Inc. (Seattle, WA; a Washington State Department of Ecology Accredited Laboratory), where they were digested and analyzed for total mercury by cold vapor atomic absorption spectrometry according to the U.S. Environmental Protection Agency Method 245.1, using a Leeman PS200 automated mercury analyzer.

To determine trophic position, we measured stable nitrogen isotopes (δ^{15}N) in fish and clams with a Thermo Finnigan Delta Advantage Isotope Ratio Mass Spectrometer fitted with a Costech Elemental Combustion System (Valencia, CA; precision ± 0.3‰ δ^{15}N). Fish muscle δ^{15}N was converted to trophic position after correction for the local baseline δ^{15}N estimated from clams (*23*). Mean clam δ^{15}N varied less than 1‰ within each territory and did not differ significantly between near-farm and reference sites in any territory.

Mercury concentration and trophic position were compared between the two rockfish species by analysis of covariance with site as a categorical factor and body size as a continuous covariate, using data from all sites at which

TABLE 1. Effect of Fish Farms on Mercury Levels in Demersal Rockfish (*Sebastes* Spp)

			450 g rockfish[b]					
site[a]	symbol	n	Hg (ppm) ± s.e.	TP ± s.e.	Meals/wk[c]	TP effect	prey Hg effect	overall farm effect[d]
A–R1	○	14	0.15 ± 0.07	3.63 ± 0.04	2.0			
A–R2	□	14	0.11 ± 0.05	3.60 ± 0.03	2.9			
A–R3	△	10	0.17 ± 0.05	3.71 ± 0.04	1.8			
A–F1	●	11	0.34 ± 0.07	3.67 ± 0.03	0.9	1.0x	2.4x	2.4x
A–F2	■	17	0.26 ± 0.05	3.85 ± 0.04	1.2	1.4x	1.3x	1.9x
A–F3	▲	11	0.43 ± 0.06	4.11 ± 0.04	0.7	2.1x	1.5x	3.1x
M–R1	○	5	0.04 ± 0.03	3.76 ± 0.03	8.6			
M–R2	□	12	0.04 ± 0.07	3.62 ± 0.02	8.4			
M–F1	●	7	0.07 ± 0.06	3.80 ± 0.05	4.2	1.2x	1.7x	2.0x
M–F2	■	6	0.08 ± 0.14	3.75 ± 0.05	4.1	1.1x	1.9x	2.1x
M–F3	▲	3	0.12 ± 0.12	3.86 ± 0.13	2.6	1.3x	2.5x	3.3x
K–R1	○	8	0.22 ± 0.05	3.62 ± 0.03	1.4			
K–R2	□	12	0.16 ± 0.04	3.62 ± 0.03	1.9			
K–R3	△	7	0.14 ± 0.07	3.56 ± 0.04	2.2			
K–F1	●	12	0.42 ± 0.05	3.67 ± 0.05	0.7	1.1x	2.1x	2.4x
K–F2	■	12	0.11 ± 0.05	3.60 ± 0.04	2.8	-	-	-
K–F3	▲	10	0.29 ± 0.07	3.67 ± 0.03	1.1	1.1x	1.5x	1.7x

[a] Sites are in the traditional harvesting territories of the Ahousaht (A), the Musgumagw Tsawataineuk Tribal Council (M), and the Kitasoo/Xaixais (K), and are designated as reference (R) or near-farm (F). [b] Total mercury concentration (Hg) and trophic position (TP) of a 450 g fish, estimated from site-specific regressions of Hg or TP on body size (based on *n* fish), shown with the standard error of the estimated value. [c] Number of rockfish meals per week recommended for children and women of child-bearing age, based on Health Canada guidelines (*29*) for consumption of methylmercury (0.2 μg per kg body weight per day). [d] The overall observed effect of fish farms on Hg levels is decomposed into an effect on rockfish trophic position and an effect on Hg levels in rockfish prey.

more than one individual of each species was captured. Mercury levels in fish increase with body size as rates of growth and elimination decline (*24*, *25*) and trophic level increases (*5*, *26*). Analysis of covariance controls for these effects while comparing the two species. Mercury concentration and body size (fresh weight) were log-transformed to stabilize variance and linearize the mercury-body size and trophic position-body size relationships for analysis of covariance.

Mercury concentration and trophic position were then compared among all sites within each region by analysis of covariance with body size as a continuous covariate. Mercury levels in carnivorous fish vary spatially and temporally with mercury concentrations and rates of methylation at the base of the local food web. Tukey post-hoc multiple comparisons were used to examine the categorical effect of site on mercury levels and trophic position. All tests were two-tailed at an alpha level of 0.05.

To examine the persistence of mercury levels through the production-fallow cycle, we constructed a model to simulate the bioaccumulation of mercury in rockfish over time. We estimated the concentration of Hg in the prey consumed by rockfish at near-farm and reference sites by combining a rockfish bioenergetics model (*27*) with a mercury mass balance model (*25*). For each age-class, we adjusted prey contamination until the concentration of mercury in rockfish at the end of the age-class matched the observed mercury vs body size relationship (*28*). This was done simultaenously for each age-class by modeling prey contamination as a function of fish size. For simplicity, the fish were all assumed to be immature. Observed and simulated Hg concentration differed by no more than 0.002 ppm for any age-class. Next, we modeled the accumulation of Hg in rockfish using the prey contamination derived from the reference sites for 6 months, then the prey contamination derived from the near-farm sites for 18 months, repeatedly alternating between these two conditions. Detailed methods and modeled relationships are presented in the Supporting Information.

Results and Discussion

Analysis of covariance could detect no difference in the mercury-body size relationship or the trophic position-body size relationship between the two rockfish species, and the species were, therefore, pooled for all subsequent analyses. In all three territories, mercury concentrations in rockfish increased with body size [Ahousaht: $F_{1,59} = 64.6$, $p < 0.00001$; Kitasoo: $F_{1,51} = 90.0$, $p < 0.00001$; MTTC: $F_{1,25} = 31.8$, $p < 0.00001$] and differed significantly among sites [Ahousaht: $F_{5,59} = 2.87$, $p = 0.022$; Kitasoo: $F_{5,51} = 16.8$, $p < 0.00001$; MTTC: $F_{4,25} = 5.14$, $p = 0.0037$] (Figure 1). There was a significant interaction between body size and site in Ahousaht territory only [$F_{5,59} = 3.51$, $p = 0.0076$]. Complete analysis of covariance tables are presented in the Supporting Information. Post-hoc Tukey multiple comparisons of the categorical site effect revealed that significant differences were between near-farm and reference sites in all three territories (Figure 2).

At three of the near-farm sites, higher mercury levels could be attributed partially to an increase in trophic position relative to reference sites. Rockfish undergo an ontogenetic shift in trophic position from 3.3 ($\sim$secondary consumers) at 100 g to about 3.6 at 500 g [pooled reference sites: $\text{TP} = 0.382 \cdot \log W + 2.61$, $F_{1,68} = 52.1$, $p < 0.00001$] (Figure 3). This trend reflects a shift from invertebrates to fish as the dominant prey as the rockfish grows, although even >1000 g rockfish continue to consume a mixture of these prey types (*20*). Rockfish at six of the near-farm sites followed a similar trend. At two of the near-farm sites in Ahousaht territory and one of the near-farm sites in MTTC territory, however, trophic position was significantly elevated [Ahousaht: $F_{5,50} = 19.7$, $p < 0.00001$; MTTC: $F_{4,27} = 3.14$, $p = 0.030$], ranging from 3.7 at 100 g to >4.0 at 500 g (Figure 3). This change reflects a greater reliance on fish prey at all sizes, and a largely or completely piscivorous diet in larger individuals. As has been found in some lakes (*5*), anthropogenic changes to the local food web at these sites elevates the trophic position of predatory fish, and this in turn, increases mercury levels in these fish.

Mercury concentration typically increases by a factor of 5 between prey and predator (*5*, *26*), so the increase in trophic position observed at three near-farm sites (0.2−0.5 trophic levels) is sufficient to produce 1.4- to 2.2-fold increases in mercury levels in a 450 g rockfish (Table 1). Observed increases in mercury levels were greater than this in all three cases, indicating an additional effect of fish farms on mercury levels in prey at these sites. As well, there was no shift to higher trophic position at the remaining near-farm sites, so observed increases in mercury levels at these other sites must reflect higher mercury concentrations in rockfish prey (Table 1). The single near-farm site that showed no increase in mercury levels had been in operation for less than one year, so it is possible that mercury is elevated in prey at this site also, but that levels in slow-growing rockfish have not yet responded. Continued monitoring of this site is warranted.

Elevated mercury concentrations in rockfish prey near net-pen salmon farms likely result from a combination of mercury loading (in waste feed and fish feces (*6*)) and mobilization of native and added mercury in sediment due to farm-induced anoxia (*2*, *10*). Sediment anoxia occurs under many fish farms throughout the production cycle, and persists for months (*8*) to years (*7*) after farm production ceases. When the sediment redox profile returns to normal, methylation rates decline and there may be a net demethylation of mercury back into inorganic forms (*2*). Concentrations in the food web will then slowly decline as the pool of methylmercury in the sediment is depleted, but this decline will be very slow in large and long-lived species such as demersal rockfish. Even if prey concentrations could revert to pre-farm (reference) levels instantaneously, we estimate that a six month period of fallowing could produce, at most, a 10−15% decline in mercury levels in rockfish (see Supporting Information for simulation model results). In reality, methylmercury in sediment and in prey species will decline much more slowly than this, and so the decline in predatory species, such as rockfish, will be much less than 10−15%. Mercury levels in rockfish will remain elevated through fallowing and will rise again when farm production is resumed.

Under the guidelines set by Health Canada (*29*), the mercury levels we observed permit unrestricted consumption of rockfish by adult males at any site, and require only slightly restricted consumption near farms by children and women of child-bearing age (Table 1). It is unknown, however, how these mercury levels will respond to future increases in the number of farms and in the size of individual farms in coastal British Columbia and globally. Aquaculture management plans in all areas should begin to address potential effects on contaminant levels in wild biota.

Our analysis indicates that while some ecosystemic effects of fish farming may be transitory, the effects on mercury cycling are not. Altered sediment biogeochemistry mobilizes mercury and effects on food web structure act to enhance biomagnification in higher trophic levels. The combined effect in this study was to produce persistently higher mercury levels in long-lived, carnivorous rockfishes. Ongoing monitoring will be required to ensure that British Columbia's First Nations communities, and coastal communities everywhere, can safely continue to consume marine foods.

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Supporting Information Available

Details of bioaccumulation modeling; analysis of covariance tables for comparison of total mercury concentration and trophic position between rockfish species and among sampling sites; map of sampling locations; simulated trajectories of total mercury concentration with size in rockfish. This material is available free of charge via the Internet at http://pubs.acs.org.

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