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Cadmium Contamination in American Lobster, *Homarus americanus*, Near a Coastal Lead Smelter: Use of Multiple Linear Regression for Management

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In 1980 cadmium (Cd) concentrations in digestive gland from American lobster (Homarus americanus), captured at Belledune Harbour, New Brunswick, Canada were found to range 47.6-372 mg/kg wet wt. (Uthe et al. 1980). Since the digestive gland is commonly eaten the harbour fishery was closed. The adjacent area was decreed a controlled fishery zone. All lobsters from this zone received special processing to yield only frozen lobster meat while the carcasses containing the digestive gland were disposed of in a safe manner (Uthe et al. 1982).

The cadmium source was a lead smelter on the harbour shore. The company installed an aqueous effluent treatment plant and improved handling procedures within the plant area. Aqueous Cd discharges were subsequently reduced by more than 95% (Uthe et al. 1983). Cadmium levels in lobsters have been monitored annually since 1980 by sampling in early spring, immediately after the lobsters emerged from their overwintering locations. The results from the 1981-1985 monitoring program were used to model the system, analyze the data and predict the years in which certain changes to the management plan might be implemented.

MATERIALS AND METHODS

Lobsters were collected using lobster traps, at the sites shown in Fig. 1. The lobsters were held in our aquarium in running seawater overnight. Both claws (at body joint) and tail were removed from the animal and cooked over boiling glass-distilled water for 10 min. The intact digestive gland was removed and weighed. Cooked meat was removed from the tail and claws, the digestive tract and blood clots washed off with glass-distilled water and the meat homogenized with an equal weight of glass-distilled water (Polytron, Brinkman Scientific). Analytical samples were taken immediately and the remaining material stored at -40 C. Digestive gland samples were digested by refluxing with nitric acid (1-2 g tissue with 4 mL nitric acid) for approximately two hours while cooked meat samples (2.5-3.0 g) were digested for the same time with 4 mL nitric-sulfuric acid mixture (5:3, v/v). Cadmium measurements were carried out by using atomic absorption

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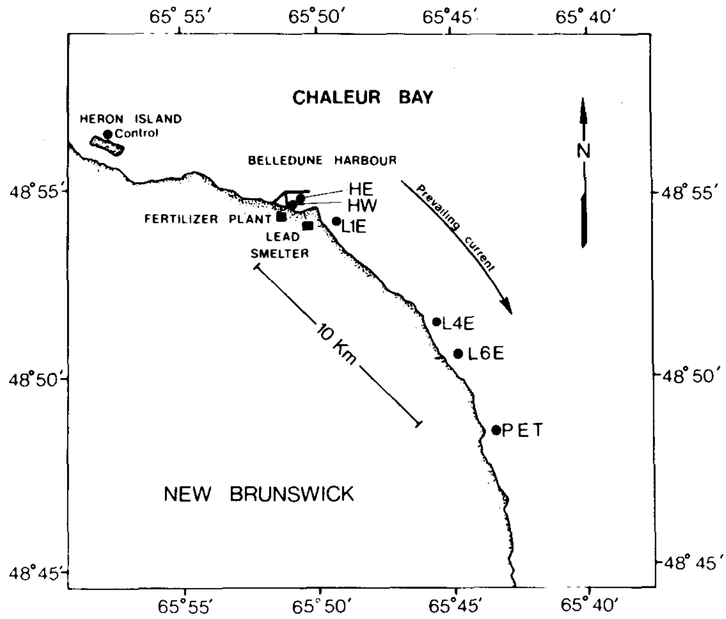

Figure 1. Location of Belledune Harbour in Chaleur Bay in the Gulf of St. Lawrence, Canada showing lobsters sampling sites. The location of the effluent pipeline from the lead smelter of the harbour is shown by a solid line.

spectrophotometry using a graphite tube furnance and the method of standard additions where needed. Our methodology has been shown to be satisfactory in intercomparative studies (Holden and Topping 1981).

RESULTS AND DISCUSSION

Canadian lobster fishermen are allowed to fish for only a limited period each year. In the Belledune area the season is open between May 1 and June 30. Fishermen are not allowed to keep either berried females (with ripening eggs) or lobsters of less than 64 mm standard carapace length. Lobsters greater than 100 mm carapace length are uncommon (5.8% in the present study) probably as a result of fishing pressure and the size of the trap entrance (D.G. Robinson personal communication). Lobsters in the Belledune area are estimated to reach sexual maturity between 65-70 mm carapace length. The commercial fishery is dependant upon both mature and immature animals and an appreciable recruitment of new lobsters into the fishery each year.

Lobster mean dimensions and Cd concentrations are given in Table 1. The statistical analysis was based upon stepwise, backward, multiple linear regression using the equation:

$$X_j (j=8 \text{ to } 10) = (\beta_o + \sum_{i=1}^{7} \beta_i X_i)^2 - (\beta_3 X_3)^2 + \varepsilon$$

where the basic variables were:

X_1 = year of capture, appropriately coded.

X_2 = $\log_{10}$ distance in km from point source.

X_3 = sex (males = -1, females = +1).

X_4 = $\log_{10}$ carapace length in mm.

X_5 = $\log_{10}$ net weight in g (total weight-cooked meat weight-digestive gland weight).

X_6 = $\log_{10}$ cooked meat weight in g.

X_7 = $\log_{10}$ digestive gland weight in g.

X_8 = $\log_{10}$ digestive gland Cd burden in mg.

X_9 = $\log_{10}$ cooked meat Cd burden in mg.

X_{10}= $\log_{10}$ total body Cd burden.

The following should be noted: 1. Since only two values of X_3 exist no squared term is possible. 2. Carapace length is measured from the posterior of eye orbit to the posterior end of the mid-line of the carapace. 3. The digestive gland and cooked meat Cd burdens were calculated by multiplying the Cd concentration by the weight of the tissue. The total body Cd burden is the sum of the digestive gland and cooked meat Cd burdens. 4. The point source of Cd was designated as the site of the untreated effluent from the lead smelter within Belledune Harbour (Fig. 1). A clock-wise gyre is present in the harbour (Loring et al. 1980), i.e. Hw is closer effectiviely to the Cd source than Ht.

Selection of the above variables is based on three hypotheses. First, length was chosen as the dominant biological or size variable. It was assumed that length was a rough estimate of age. Net weight, as related to length, was considered as the basic condition factor, while cooked meat weight and digestive gland weight were estimates of the relative sizes of compartments containing Cd burdens. The individual relationships between these four log variables are rectilinear in form, hence the transformation. Second, decreases in Cd tissues burdens over time were considered to be related by a simple first-order type relationship proportional to the local concentration of bioavailable Cd and that such local concentration could be approximated by an inverse power function of concentration (C') and distance from the putative point source of contamination (D), similar to the inverse square law of light intensities. Thus, the appropriate transformations of burden and distance are to logarithms while time remains untransformed.

Table 1. Geometric mean dimensions of all legal-sized lobsters from sample areas, 1981-1985.

Area	Length (mm)	Cooked Meat Weight (g)	Digestive gland Weight (g)	Total Weight (g)
HW	83	112	22.0	461
HE	85	123	24.1	506
L1E	76	86	17.1	354
L4E	78	94	18.6	388
L6E	77	90	17.8	370
PET	74	79	15.8	326

In order to minimize rounding errors all sample values were converted to standard measure (Draper and Smith 1981). In additon, all cross-product (interaction and squared) terms were also standardized. Such standardizations are necessary when the number of predictor variables is large and are most important when the computer used has limited digital capacity; the Hewlett-Packard 9830 available for this study is only capable of 12-digit capacity in floating point format, far too few digits to avoid rounding errors in ill-conditioned data.

The fundamental fishery management questions in the Belledune lobster fishery are: (1) What is the effect of the smelter clean-up and treatment steps initiated in 1980 on Cd levels in lobsters in the area? (2) How long will Belledune harbour remain closed to lobster fishing, or subject to restrictions? (3) Can the controlled fishing zone surrounding the Harbour be reduced in size in which years might this occur, and when might the controlled fishing zone be re-opened to normal fishing and processing?

Lobster size and wandering complicate the study of these questions. Cadmium concentrations (and, obviously, burdens) are positively related to lobster size (Uthe et al. 1980; Uthe and Freeman 1980; Ray et al. 1981). Lobsters caught in Belledune Harbour were, on average, larger than those caught outside the harbour (Table 1, Uthe and Chou 1985). In order to compare Cd concentrations with time and distance, the results for mean legal-sized lobster (>64 mm carapace length) for each sample site are presented (Table 2). No confidence limits for these values are presented; such limits are not only extremely difficult to compute for multiple regressions, but are relatively meaningless when there is significant multicollinearity, i.e. significant bi- and multi-correlations among the predictor variables.

Table 2. Geometric mean digestive gland (DG) and cooked meat (CM) Cd concentrations mg/kg wet wt.) of legal-sized lobsters by year and area 1986 numbers are predicted values from 1981-85 sample.

Area	Km*	N	Tissue	1981	1982	1983	1984	1985	(% of 1981)	1986
HW	0.75	94	DG	160.1	123.5	95.3	73.5	56.7	(35.4)	43.8
			CM	0.76	0.61	0.49	0.39	0.32	(42.1)	0.25
HE	1.50	63	DG	115.4	89.7	69.8	54.3	42.3	(36.7)	32.8
			CM	0.45	0.37	0.30	0.25	0.20	(44.4)	0.16
L1E	2.85	55	DG	61.9	46.6	35.2	26.5	20.0	(32.3)	15.1
			CM	0.28	0.21	0.17	0.13	0.10	(35.7)	0.08
L4E	7.65	60	DG	38.6	29.3	22.3	16.9	12.9	(33.4)	9.8
			CM	0.14	0.11	0.09	0.07	0.05	(35.7)	0.04
L6E	10.85	56	DG	31.3	23.7	17.9	13.6	10.3	(32.9)	7.8
			CM	0.11	0.09	0.07	0.05	0.04	(36.4)	0.03
PET	17.25	52	DG	23.3	17.4	13.1	9.8	7.3	(31.3)	5.5
			CM	0.08	0.06	0.05	0.04	0.03	(37.5)	0.02

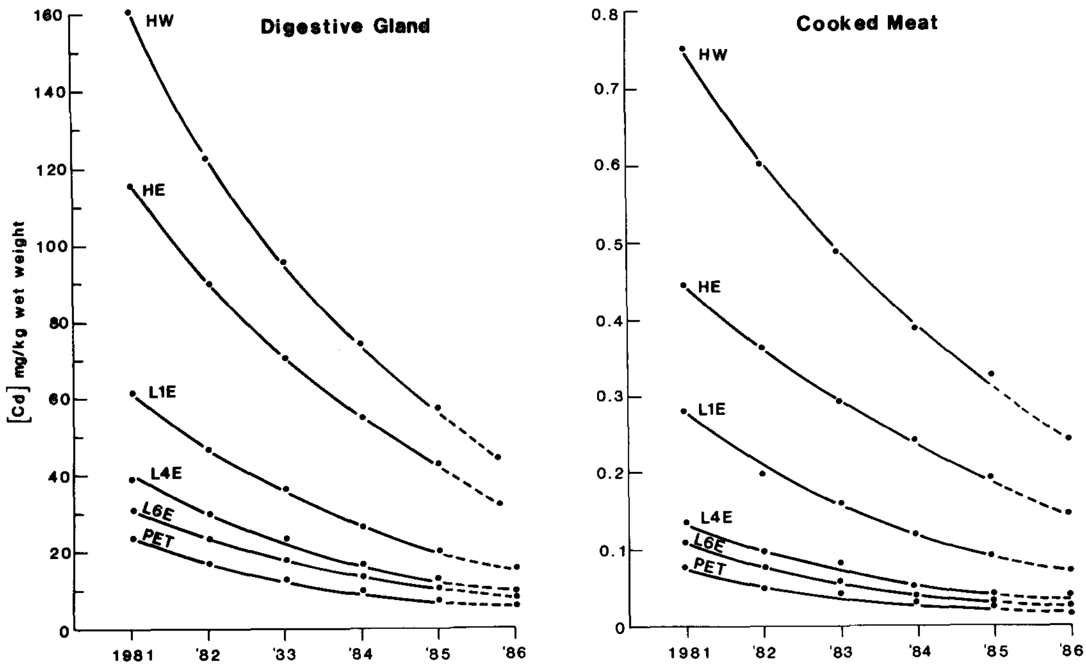

Figure 2: Changes in geometric mean cadmium concentrations in lobster digestive gland and cook meat. 1981-1985 and predicted concentrations for 1986

The presence of very high Cd contamination of Belledune Harbour lobsters is readily apparent from Table 2 with digestive gland Cd mean at the HW site of 160 mg/kg wet wt. Substantially lower Cd concentrations were found in lobsters outside the harbour and levels continued to decrease to 23.3 mg/kg at the PET site. One factor responsible for the lower Cd concentrations in lobsters captured outside the harbour is that highly contaminated lobsters (greater than 200 mg Cd/kg wet wt in digestive gland) rarely wander out of the harbour. However, later in the spring and the summer other lobsters wander in and out of the harbour (Uthe et al. 1982).

Between 1981 and 1985 concentrations in digestive gland have decreased 63.3-68.7% and in cooked meat 55.6-64.3% (Table 2 and Figure 2). The consistency of the decline curves among sample sites is evidence that the major source of cadmium was the smelter, the overall decline reflecting the return of the ecosystem towards cleaner conditions with no evidence of other Cd inputs. The time decay curves also suggest that the observed rate of change (on a logarthmic basis) has been constant since the installation of clean-up and treatment procedures in 1980. We have predicted mean Cd levels in digestive gland and cooked meat in 1986 (Table 2, Fig. 2).

Table 3. Expected year when mean digestive gland and cooked meat cadmium concentrations of legal-sized lobsters drop below 20 mg/kg wet wt. in digestive gland and 0.20 mg/kg wet wt. in cooked meat, by area.

Area	Digestive gland	Cooked Muscle
HW	1989	1987
HE	1988	1985
L1E	1985	1982
L4E	1983	1979*

* no 1980 data on cooked meat

Maximum permissible Cd concentrations in lobsters from the Belledune area are 20 mg/kg wet in the digestive gland and 0.20 mg/kg in cooked meat product. Using these benchmarks and current concentration decay rates it is possible to determine dates at which changes could be made in the control zone boundary (Table) 3. The data predict that the controlled fishery zone may safely be eliminated by 1987 and that the harbour itself should be re-opened to a normal fishery in 1989.

A rational sampling plan coupled with intensive statistical investigation enabled us to monitor the system with a high degree of confidence using a relatively small number of samples from each site. Simple statistical analyses would not have been satisfactory due to the large variance characterizing the results for each sample site and the relatively high coefficient of determination characterizing the relationship between Cd concentrations and lobster size, compared with the coefficients of determination related to time trends. In other words, the majority of variation in Cd concentrations in these data are attributable to size variation and distance but a highly significant fraction is attributible to time after clean-up.

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