

## Sea Louse Infestation in Wild Juvenile Salmon and Pacific Herring Associated with Fish Farms off the East-Central Coast of Vancouver Island, British Columbia

ALEXANDRA MORTON

Raincoast Research Society, Simoom Sound, British Columbia V0P 1S0, Canada

RICK ROUTLEDGE

Department of Statistics and Actuarial Science, Simon Fraser University,  
8888 University Drive, Burnaby, British Columbia V5A 1S6, Canada

MARTIN KRKOŠEK

Centre for Mathematical Biology, Department of Biological Sciences, 632 Central Academic Building,  
University of Alberta, Edmonton, Alberta T6G 2G1, Canada

**Abstract.**—Reports of infestations of sea lice *Lepeophtheirus salmonis* and *Caligus clemensi* in juvenile salmonids in Pacific Canada have been restricted to pink salmon *Oncorhynchus gorbuscha* and chum salmon *O. keta* from one salmon-farming region, the Broughton Archipelago of British Columbia. Here, we report on 2 years of sea louse field surveys of wild juvenile pink and chum salmon, as well as wild sockeye salmon *O. nerka* and larval Pacific herring *Clupea pallasii*, in another salmon farming region, the Discovery Islands region of British Columbia. For pink and chum salmon we tested for the dependency of sea louse abundance on temperature, salinity, sampling period, host species, and farm exposure category. For both louse species, farm exposure was the only consistently significant predictor of sea lice abundance. Fish exposed to salmon farms were infested with more sea lice than those in the peripheral category. Sea louse abundance on sockeye salmon and Pacific herring followed the same trends, but sample sizes were too low to support formal statistical analysis. The Pacific herring were translucent and lacked scales, and they were primarily parasitized by *C. clemensi*. These results suggest that the association of salmon farms with sea lice infestations of wild juvenile fish in Pacific Canada now extends beyond juvenile pink and chum salmon in the Broughton Archipelago. Canada's most abundant and economically valuable salmon populations, as well as British Columbia's most valuable Pacific herring stock, migrate through the Discovery Islands; hence, parasite transmission from farm to wild fish in this region may have important economic and ecological implications.

Salmon farming has been associated with infestations of sea lice *Lepeophtheirus salmonis* and *Caligus* spp. in wild juvenile salmonids in Norway (Bjorn and Finstad 2002), Scotland (MacKenzie et al. 1998), Ireland (Tully et al. 1999), and Canada (Morton et al. 2004). In Pacific Canada, farmed salmon have been identified as a primary determinant of sea louse infection patterns on wild juvenile pink salmon *Oncorhynchus gorbuscha* and chum salmon *O. keta* (Morton et al. 2004; Krkošek et al. 2005a), with farmed salmon initiating the spread of the parasites in wild juvenile salmon populations (Krkošek et al. 2005a). Physical factors such as temperature and salinity may also be important (Brooks 2005; Brooks and Stucchi 2006) but may not be significant predictors of sea louse abundance (Morton et al. 2004; Krkošek et al. 2005b).

Even low abundances of *L. salmonis* are lethal to juvenile pink and chum salmon (Morton and Routledge 2005). The transmission of sea lice from farmed salmon can cause high mortality in wild juvenile salmon (Krkošek et al. 2006a, 2006b), and pink salmon populations have collapsed following infestations (PFRCC 2002; Morton and Williams 2003; Krkošek et al. 2007a). Fallowing (removal of farm fish) a migration route in 1 year reduced sea louse abundances (Morton et al. 2005), and those salmon cohorts experienced high marine survival (Beamish et al. 2006). These types of associations have long been controversial (McVicar 1997; McVicar 2004; Hilborn 2006), and it remains unknown whether increased abundances of sea lice on wild juvenile salmon are associated with salmon farms in regions outside the Broughton Archipelago in Pacific Canada.

The migratory paths of many of the most abundant and economically important Canadian salmon populations pass through a region of intensive salmon

\* Corresponding author: wildorca@island.net

Received March 5, 2007; accepted August 13, 2007  
Published online March 31, 2008

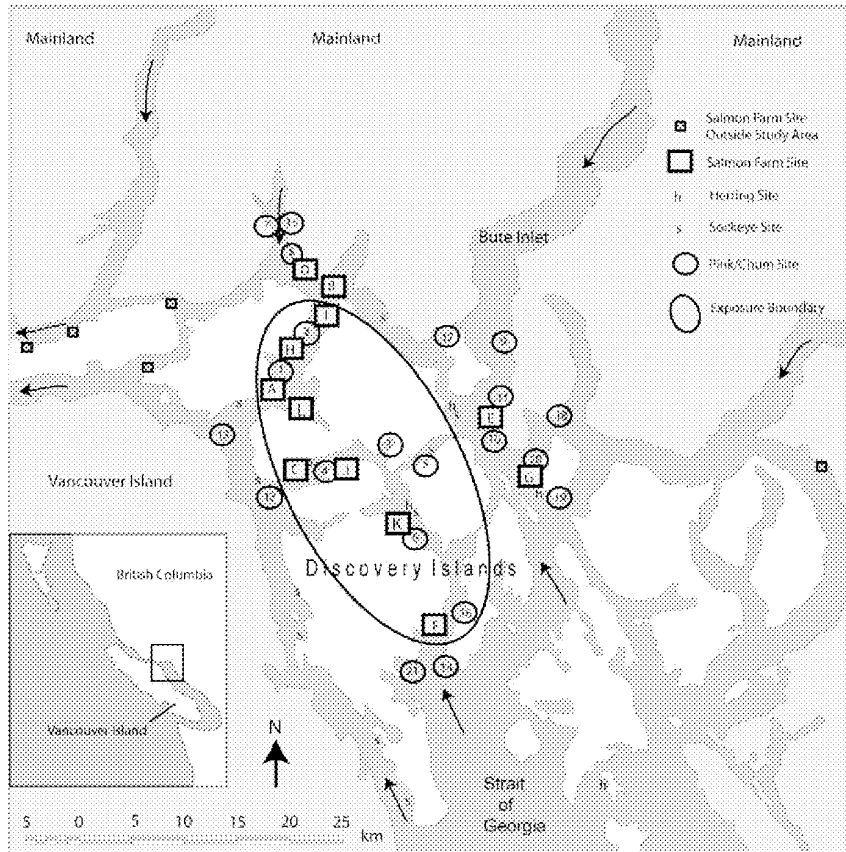


FIGURE 1.—Study area in the Discovery Islands where juvenile pink and chum salmon, juvenile sockeye salmon, and Pacific herring were targeted in beach-seine sampling to determine levels of sea louse infestation. Sample sites were considered peripheral (outside the large oval ring) or exposed (inside the oval ring), depending on their proximity to salmon farms and salmon migration routes (arrows). The letters within the salmon farm boxes correspond to those in Table 1; the numbers within the sample site ovals correspond to those in Tables 3 and 4.

aquaculture between the Strait of Georgia and Johnstone Strait (Groot and Margolis 1991) known as the Discovery Islands (Figure 1). Susceptible salmon populations include those from the Fraser River, east coast Vancouver Island, and mainland inlet stocks that migrate north between Vancouver Island and mainland British Columbia. These include not only pink and chum salmon but also sockeye salmon *O. nerka*, steelhead *O. mykiss*, coho salmon *O. kisutch*, and Chinook salmon *O. tshawytscha*. In addition, this region may be important early juvenile rearing habitat for Pacific herring *Clupea pallasii* in the Strait of Georgia, British Columbia's largest herring stock. Sea lice have not been found juvenile Pacific herring and are extremely in the Atlantic herring *C. harengus* (Tolonen and Karlsbakk 2003). We therefore examined

wild juvenile pink, chum, and sockeye salmon and juvenile Pacific herring in the Discovery Islands region for sea lice in relation to proximity to salmon farms.

#### Methods

The study area comprised the waters of the Discovery Islands, a region just north of the Strait of Georgia (Figure 1). We organized the sample sites into two categories, exposed and peripheral, based on the proximity of the collection site to salmon farms. Exposed sites were in channels with one or more salmon farms located in both directions from the sample site. The wild juvenile salmon must therefore have been directly exposed to at least some of the farms to reach these sites. The peripheral sites were outside these narrow channels in places where juvenile salmon

TABLE 1.—Production status of salmon farms in the Discovery Islands where salmon and Pacific herring were sampled for sea lice.

Site	Location	Year	Species of salmon	Life stage
A	Brougham Point	2005	Chinook	Growers
		2006	Unknown	Smolts
B	Owen Point	2005	None	Empty
		2006	Unknown	Unknown
C	Venture Point	2005	Atlantic	Growers
		2006	Unknown	Smolts
D	Philips	2005	Atlantic	Smolts
		2006	Atlantic	Half harvested
E	Church House	2005	Atlantic	Smolts
		2006	Atlantic	Growers
F	Conville Bay	2005	Unknown	Growers
		2006	Unknown	Smolts
G	Raza Island	2005	Atlantic	Growers
		2006	None	Empty
H	South Thurlow	2005	Atlantic	Growers
		2006	Atlantic	Half harvested
I	Sonora Point	2005	Chinook	Brood, growers
		2006	None	Empty
J	Brent Island	2005	Atlantic	Growers
		2006	Atlantic	Smolts
K	Cyrus	2005	Chinook	Growers
		2006	None	Empty
L	Young Pass	2005	Atlantic	Empty
		2006	None	Empty

and Pacific herring need not have been directly exposed to any salmon farms. Some peripheral sites were near salmon farms, but depending on direction of migration wild salmon sampled at these sites may or may not have passed the farm. We determined the production status of farms (Table 1) by collecting information directly from the salmon farm companies in 2005 and by observing the salmon farms from a boat in 2006.

We sampled fish at 15 sites (Figure 1) from April 19 to June 5 in 2005 and at 16 sites from April 3 to June 9 in 2006; samples were stratified by intervals of about 2 weeks. All sites were sampled within 2–3 d. We sampled 50 juvenile pink and (or) chum salmon at each site via a beach seine net (30 × 1.8 m with 1.6-cm knotless stretch mesh). There were approximately equal numbers of pink and chum salmon in each sample collected in 2005 but a higher abundance of chum salmon in 2006. All sampled fish were placed in individual bags and temporarily stored on ice and then quickly frozen within hours. The fish were subsequently weighed, measured (fork length), and identified to species. Sea lice were identified using a dissecting microscope, and categorized by species, age-class, and sex using Galbraith (2005). We occasionally collected juvenile Pacific herring and sockeye salmon as bycatch, which we also examined for lice. In June 2005 we also collected these two species in targeted sampling (the “h” and “s” sites in

Figure 1) with a beach seine (30 × 3 m with 1.6-cm knotless mesh). For these fish we used the nonlethal assay described in Krkošek et al. (2005b) to measure fish fork length and count and identify the sea lice. We did not repeat this targeted survey in 2006.

For pink and chum salmon, we analyzed the abundances of each louse species with respect to its dependence on exposure category (peripheral or exposed; Figure 1) and the following additional factors: sampling trip, salinity, temperature, and host species. Separate analyses were conducted for each of the 2 years. We treated site-to-site differences within the exposure categories as random, and included random effects associated with each sampling occasion at each site. To handle (1) the mixture of fixed and random effects, (2) unequal variances, and (3) possible nonlinear effects, we used the SAS procedure, GLIMMIX for handling generalized linear models with mixed effects. We specified a log-link (implying multiplicative as opposed to additive effects; Limpert et al. 2001) with a Poisson distribution for the counts on individual fish, given the random effects mentioned above (these random effects introduce extra Poisson variation with a correlation structure). In addition, when the GLIMMIX algorithm did not converge, and elsewhere as a check, we used the more traditional method (e.g., Steel and Torrie 1980:168, 235) of transforming the abundances ( $y$ ) to  $\log_e(y + 0.5)$  and then applying a linear model. To account for the mixture of fixed and random effects, we used the SAS procedure, MIXED, for this analysis. In both instances, we calculated denominator degrees of freedom with a Satterthwaite approximation. We fit the models in a backward stepwise fashion by first fitting the full model and then sequentially dropping the insignificant factor with the largest  $P$ -value and refitting the simplified model until only significant factors remained. The MIXED analysis on the transformed data were needed for convergence only in the initial stages of some of these analyses. We generated least-squares estimates for the exposure category means and associated standard errors using the SAS GLIMMIX procedure. Because both the generalized linear modeling and linear modeling on log-transformed data produced similar final results, we present results for the more modern GLIMMIX methodology only, for which the troublesome issue of back-transformations and associated biases does not arise.

## Results

Over the 2 years we examined 4,699 fish for sea lice infection (Table 2). In 2005, most of the salmon farms

TABLE 2.—Summary of capture data for pink, chum, and sockeye salmon and Pacific herring taken from the Discovery Islands area in 2005 and 2006 and subsequently examined for sea lice.

	Species	N	Mean length (mm) (range)	Mean weight (g) (range)
2005 (salinity = 28.3‰, temperature = 10.9°C)	Pink salmon	982	61.2 (27.8–115)	3.07 (0.10–77)
	Chum salmon	980	52.7 (27.8–1,070)	1.93 (0.16–15.1)
	Sockeye salmon	148	88.3 (54–124)	<sup>a</sup>
	Pacific herring	322	45.1 (34–57)	0.87 <sup>a</sup> (0.5–1.4)
2006 (salinity = 29‰, temperature = 10.6°C)	Pink salmon	726	54.8 (21–132)	2.72 (0.17–31.5)
	Chum salmon	1,534	57.0 (30–142)	3.21 (0.17–34.3)
	Sockeye salmon	7	69.9 (30–96)	5.93 (0.28–12.7)

<sup>a</sup> In 2005, no sockeye salmon were weighed; the herring weight was based on a lethal sample of 23 fish.

indicated in Figure 1 were stocked with older salmon (information provided in 2005 by the fish-farming companies Pan Fish, Stolt, and Heritage; Table 1). In 2006, only Church House farm was fully stocked with older salmon. All other farms were empty, partially empty, or stocked with smolts only (based on observation and previous year's data). In 2005, we found a total of 4,232 *L. salmonis* and 2,408 *C. clemensi* summed over all 2,432 fish that we lethally examined for sea lice. In 2006, we found 680 *L. salmonis* and 857 *C. clemensi* summed over all 2,267 fish examined. The number of samples for each species, mean fork length, weight, salinity, and temperature are given for each year in Table 2. There was little variation between exposure categories in salinity and temperature (Tables 3, 4). However, sea lice prevalence (the number of fish with a least one louse divided by the total number of fish examined), intensity (the number of lice per infected fish examined), and abundance (the number of lice per infected and uninfected fish examined) was substantially higher in exposed sites than in peripheral sites (Tables 5–8).

The results of the statistical model fitting are summarized in Table 9. Sea louse abundances on pink and chum salmon were significantly lower for peripheral sites than for exposed sites (Figure 2): for *L. salmonis*,  $P < 0.0001$  in 2005 and  $P = 0.0086$  in 2006; for *C. clemensi*,  $P = 0.0002$  in 2005 and  $P = 0.047$  in 2006. In addition, each of sampling trip and salmon species (pink versus chum) was significant in one instance only. Salmon species was significant for *C. clemensi* in 2006 ( $P = 0.011$ ); sampling trip was significant for *L. salmonis* in 2005 ( $P = 0.0045$ ). In 2006, *C. clemensi* was about 20% less abundant on pink salmon than chum salmon. Sea louse abundance was greater in 2005 than in 2006. For pink and chum salmon in 2005, sea louse abundance peaked on 23 May at a mean of 10.5 lice/fish (3.4 lice/g of host weight). There was not a clear peak in sea louse abundance in 2006.

The samples sizes for sockeye salmon and Pacific herring (Table 2) were too small to support formal statistical analyses, but the trends indicate that the abundances of sea lice on sockeye salmon followed the same pattern (Figure 3). In 2005, the abundance of lice

TABLE 3.—Mean fork length (*L*; mm) and body weight (*W*; g) of juvenile pink and chum salmon as well as sea surface salinity (*S*; ‰) and temperature (*T*; °C) for collection sites in the Discovery Islands in 2005.

Category	Site Number	19–20 Apr				5–7 May				23–24 May				4–5 Jun				
		<i>L</i>	<i>W</i>	<i>S</i>	<i>T</i>	<i>L</i>	<i>W</i>	<i>S</i>	<i>T</i>	<i>L</i>	<i>W</i>	<i>S</i>	<i>T</i>	<i>L</i>	<i>W</i>	<i>S</i>	<i>T</i>	
Exposed	1	43.6	0.83	29	9.5	53.9	1.71	30	10.1	54.9	1.80	33	10.2	73.5	4.49	29	11.5	
	2	64.1	2.72	30	10.2					53.0	1.67	30	10.5	61.2	2.61	31	10.8	
	3	50.0	1.39	29	10.1	38.3	0.57	33	10.3					82.6	6.53	29	10.2	
	4	40.5	0.66	30	10.1	56.4	2.06	30	10	72.4	4.52	31	10.5	73.1	4.65	29	10.5	
	5					65.4	3.30	34	10	56.7	1.97	30	10.8	72.3	4.55	29	10.8	
	6									65.0	3.24	30	11.2	86.0	7.44	29	11	
Peripheral	7	35.5	0.45	20	10	38.2	0.52	28	11.1	56.4	1.96	27	10.4	66.1	2.96	11	12.5	
	8	31.9	0.27	20	10.2	41.5	1.46	26	10	34.3	0.29	27	10					
	9	40.3	0.58	27	9.7													
	10	43.1	0.74	28	9.7	45.1	0.98	29	11.4	58.6	2.59	28	11.5					
	11	59.2	2.50	30	10.5	62.9	3.04	32	10	71.7	4.44	28	11.4					
	12	45.1	0.86	30	9.8	41.4	0.83	30	10.1	52.4	1.63	31	10.1					
	13					64.1	3.33	30	10	70.2	4.23	34	10					
	14					48.9	1.42	31	12	56.7	2.17	26	12					
	15									61.3	3.07	24	11.1	75.6	5.05	26	11.5	

TABLE 4.—Mean fork length (*L*; mm) and body weight (*W*; g) of juvenile pink and chum salmon as well as sea surface salinity (*S*; ‰) and temperature (*T*; °C) for collection sites in the Discovery Islands in 2006.

Site		3–4 Apr				14–15 Apr				10–11 May				8–9 Jun			
Category	Number	<i>L</i>	<i>W</i>	<i>S</i>	<i>T</i>	<i>L</i>	<i>W</i>	<i>S</i>	<i>T</i>	<i>L</i>	<i>W</i>	<i>S</i>	<i>T</i>	<i>L</i>	<i>W</i>	<i>T</i>	<i>S</i>
Exposed	1	35.2	0.48	28	9.2	39.6	0.68	31	9.5	52.8	1.76	30	10				
	2	39.2	0.63	30	9.5	39.8	0.65	30	9.6					73.4	4.56	30	10.5
	3									59.3	2.53	30	10.4				
	4	36.6	0.47	34	9.6	43.9	1.03	34	9.8	56.0	2.16	30	10	75.6	5.80	31	10.5
	5	37.9	0.50	31	9.5					56.7	2.02	31/30	11.2/10				
	6									60.9	2.75	31	10.4				
Peripheral	16									65.7	3.82	29	11.2	68.2	5.04	31	12.9
	7	35.7	0.42	27	9.2					50.3	1.61	27	10.8	74.2	6.75	25	11
	8	40.3	0.67	32	9.5					50.0	1.60	30	10	64.9	3.31	29	10.8
	9	37.0	0.50	30	9.5	44.6	1.03	28	9.5	56.5	2.20	27	11.5	109.1	16.18	26	15
	10	50.2	1.52	28	9.5	30.6	0.90	28	9.8	61.8	2.95	26	11	80.3	6.72	27	14
	17	40.1	0.65	31	9.6	46.9	1.55	30	9.8	69.5	4.16	27	10	77.6	5.98	32	10.2
	18	35.2	0.39	32	9.5	38.9	0.61	26	9.8	47.5	1.18	24	11				
	19	37.5	0.53	27	10									66.7	3.58	26	15.8
	20					59.5	2.85	25	9.5								
	21					51.9	1.58	28	7.5	63.3	3.46	29	11	124.8	23.12	27	15.8

on sockeye salmon was highest at the Church House site (8.8 lice/fish; host average weight, 2.4 g). On Pacific herring, *C. clemensi* were elevated at the exposed sites, whereas *L. salmonis* was essentially absent (Figure 3). None of the herring had scales.

### Discussion

Sea louse infestations of wild juvenile salmonids have been associated with salmon farms in several countries (MacKenzie et al. 1998; Tully et al. 1999; Bjorn and Finstad 2002; Morton et al. 2004). This study provides further evidence that this pattern is widespread, and it is the first observation of this association in Pacific Canada outside the Broughton

Archipelago, where all previous observations of high *L. salmonis* abundances on juvenile salmon have occurred (Morton and Williams 2003; Morton et al. 2004, 2005; Krkošek et al. 2005a, 2006a). Similar to these other findings, our analysis shows that farmed salmon were the most likely cause of the increased sea louse abundance that we observed on juvenile salmon in areas exposed to salmon farms as opposed to areas peripheral to salmon farms in the Discovery Islands. Exposure category was the only consistently significant factor explaining the data, whereas factors such as salinity and temperature were not significant. The difference in sea louse abundance between 2005 and 2006 can be explained by a decrease from 2005 to

TABLE 5.—Prevalence (*P*), intensity (*I*), and abundance (*A*) of a sea louse, *L. salmonis*, on juvenile pink and chum salmon collected in 2005 in the Discovery Islands. Prevalence is defined as the number of fish with at least one louse divided by the total number of fish examined, intensity as the number of lice per infected fish examined, and abundance as the number of lice per infected plus uninfected fish examined.

Site		19–20 Apr			5–7 May			23–24 May			4–5 Jun		
Category	Number	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>
Exposed	1	0.55	1.50	0.82	0.75	2.81	2.10	0.96	5.44	5.22	0.83	3.65	3.04
	2	0.75	4.47	3.35				0.74	3.59	2.64	0.76	3.21	2.45
	3	0.38	1.53	0.58	0.90	2.95	2.67				0.57	2.59	1.49
	4	0.10	2.00	0.20	0.47	2.39	1.12	0.69	3.45	2.38	0.63	6.76	4.26
	5				0.76	3.38	2.55	0.96	10.28	9.88	0.66	3.29	2.17
	6							0.98	5.96	5.85	0.71	3.42	2.41
Peripheral	7	0.02	1.00	0.02	0.02	1.00	0.02	0.15	1.38	0.21	0.02	6.00	0.12
	8	0.66	1.32	0.87	0.40	1.62	0.65	0.64	2.06	1.32			
	9	0.20	1.30	0.25									
	10	0.40	1.35	0.54	0.72	3.12	2.24	0.93	8.59	7.95	1.00	5.67	5.67
	11	0.85	3.73	3.19	0.57	2.83	1.60	0.62	6.84	4.24			
	12	0.04	1.00	0.04	0.57	1.56	0.89	0.74	2.54	1.89			
	13				0.22	1.18	0.26	0.40	3.21	1.27			
	14				0.53	1.78	0.94	0.23	2.67	0.62			
	15							0.48	4.55	2.17	0.35	1.58	0.56

TABLE 6.—Prevalence (*P*), intensity (*I*), and abundance (*A*) as defined in Table 5, of a sea louse, *C. clemensi*, on juvenile pink and chum salmon collected in 2005 in the Discovery Islands.

Site		19–20 Apr			5–7 May			23–24 May			4–5 Jun		
Category	Number	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>
Exposed	1	0.39	2.15	0.84	0.31	1.47	0.46	0.18	1.33	0.24	0.60	2.07	1.25
	2	0.50	3.88	1.94				0.55	3.45	1.89	0.49	2.44	1.20
	3	0.50	1.60	0.80	0.76	1.94	1.48				0.36	1.24	0.45
	4	0.00	0.00	0.00	0.22	1.64	0.37	0.79	5.61	4.40	0.57	2.42	1.37
	5				0.53	2.46	1.31	0.83	6.95	5.75	0.60	2.57	1.53
	6							0.58	3.03	1.75	0.29	1.20	0.35
Peripheral	7	0.00	0.00	0.00	0.02	1.00	0.02	0.02	1.00	0.02	0.06	1.00	0.06
	8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	9	0.02	1.00	0.02									
	10	0.02	1.00	0.02	0.30	1.21	0.37	0.78	4.32	3.35	0.33	1.00	0.33
	11	0.69	2.64	1.81	0.36	1.58	0.57	0.46	7.13	3.28			
	12	0.08	1.25	0.10	0.14	2.00	0.29	0.06	1.50	0.09			
	13				0.14	1.14	0.16	0.10	1.00	0.10			
	14				0.41	2.38	0.98	0.08	1.25	0.10			
	15							0.48	3.36	1.61	0.02	1.00	0.02

2006 in the abundance of adult farmed salmon; abundance of sea lice is known to be lower on wild salmon juveniles near salmon farms that are empty or stocked with smolts than near salmon farms stocked with older salmon (Morton et al. 2004, 2005). Furthermore, the prevalence of sea lice on juvenile salmon in regions of British Columbia without salmon farms is less than 0.05 (Morton et al. 2004; Krkošek et al. 2007b; Peet 2007). If 0.05 is taken to be the natural baseline prevalence of sea lice on juvenile pink and chum salmon, then our data suggest that the juvenile salmon in the peripheral area also experienced sea louse prevalences above the baseline level because of their proximity to salmon farms. However, the true natural baseline abundance of sea lice on juvenile pink and chum salmon in the Discovery Islands is unknown

because no sea lice surveys of juvenile pink and chum salmon were conducted in this area before salmon farming began.

We did not detect a significant effect of temperature or salinity on sea lice abundance on juvenile pink and chum salmon and only observed sporadic significance for two factors other than salmon farms. The significant effect of sampling trip for *L. salmonis* in 2005 could be due to temporal progression in sea louse development and (or) fish migration. The significant effect of host species for *C. clemensi* abundance in 2006 could be due to interspecific differences in migration or resistance to sea lice. Other studies of sea louse dynamics on salmon farms and experiments rearing larval lice in laboratory conditions have shown temperature and salinity can influence louse survival

TABLE 7.—Prevalence (*P*), intensity (*I*), and abundance (*A*), as defined in Table 5, of a sea louse, *L. salmonis*, on juvenile pink and chum salmon collected in 2006 in the Discovery Islands.

Site		3–4 Apr			14–15 Apr			10–11 May			8–9 Jun		
Category	Number	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>	<i>P</i>	<i>I</i>	<i>A</i>
Exposed	1	0.24	1.42	0.34	0.58	1.59	0.92	0.38	1.68	0.64			
	2	0.36	1.50	0.54	0.24	1.25	0.30				0.34	1.50	0.51
	3							0.26	1.46	0.38			
	4	0.10	1.00	0.10	0.22	1.09	0.24	0.14	1.00	0.14	0.22	1.55	0.34
	5	0.10	1.00	0.10				0.35	1.40	0.49			
	6							0.06	1.00	0.06			
Peripheral	16							0.46	1.57	0.72	0.19	1.35	0.26
	7	0.00		0.00				0.00	0.00	0.00	0.00	0.00	0.00
	8	0.40	1.60	0.64				0.12	1.00	0.12	0.12	1.00	0.12
	9	0.06	1.00	0.06	0.26	1.23	0.32	0.28	1.21	0.34	0.00	0.00	0.00
	10				0.42	1.85	0.77	0.37	1.26	0.46	0.10	1.00	0.10
	17	0.19	1.20	0.23	0.22	1.36	0.30	0.66	1.55	1.02	0.18	1.11	0.20
	18	0.00	0.00	0.00	0.00	0.00	0.00	0.15	1.00	0.15			
	19	0.06	1.00	0.06							0.12	1.17	0.14
	20				0.52	1.42	0.74						
	21				0.12	1.00	0.12	0.20	1.30	0.27	0.04	1.00	0.04

TABLE 8.—Prevalence (*P*), intensity (*I*), and abundance (*A*), as defined in Table 5, of a sea louse, *C. clemensi*, on juvenile pink and chum salmon collected in 2006 in the Discovery Islands.

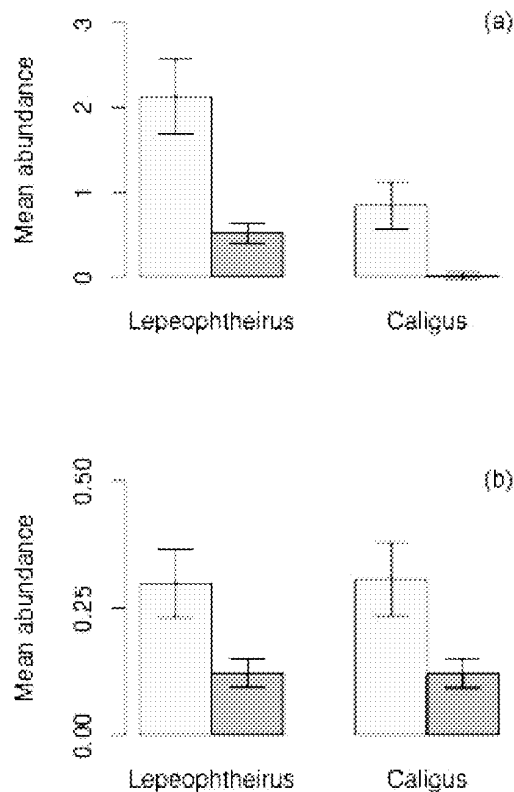
Site		3–4 Apr			14–15 Apr			10–11 May			8–9 Jun		
Category	Number	P	I	A	P	I	A	P	I	A	P	I	A
Exposed	1	0.04	1.00	0.04	0.20	1.30	0.26	0.50	1.60	0.80			
	2	0.08	1.00	0.08	0.44	1.68	0.74				0.20	1.45	0.29
	3							0.32	1.31	0.42			
	4	0.08	1.00	0.08	0.38	1.16	0.44	0.10	1.00	0.10	0.38	1.47	0.56
	5	0.15	1.00	0.15				0.36	1.36	0.49			
	6							0.22	1.36	0.30			
Peripheral	16							0.54	1.70	0.92	0.54	1.56	0.84
	7	0.00		0.00				0.15	1.14	0.17	0.00	0.00	0.00
	8	0.02	1.00	0.02				0.08	1.00	0.08	0.33	1.38	0.45
	9	0.63	1.58	1.00	0.78	2.62	2.04	0.20	1.10	0.22	0.00	0.00	0.00
	10				0.35	1.59	0.56	0.23	1.58	0.37	0.26	1.00	0.26
	17	0.02	1.00	0.02	0.20	1.50	0.30	0.46	1.39	0.64	0.04	1.00	0.04
	18	0.00	0.00	0.00	0.10	1.00	0.10	0.02	1.00	0.02			
	19	0.00	0.00	0.00							0.22	1.27	0.28
	20				0.30	2.27	0.68						
	21				0.26	1.38	0.36	0.33	1.31	0.43	0.40	2.05	0.82

(Johnson and Albright 1991) and epidemiology (Heuch et al. 2003; Revie et al. 2003). Based on these studies on salmon farms and under laboratory conditions, others have argued—without testing their predictions with field surveys—that temperature and salinity have a large effect on the spatial distribution of sea lice in the natural environment in the Broughton Archipelago (Brooks 2005; Brooks and Stucchi 2006). Meanwhile, field studies in British Columbia examining the geographic distribution of sea lice on juvenile salmon have not found salinity or temperature to be explanatory factors (Morton and Williams 2003; Morton et al. 2004). This discrepancy may be explained by behavior of sea lice larvae, where copepodids position themselves vertically in the water column to seek out and track suitable temperature and salinity regimes (Heuch 1995; Heuch et al. 1995). The discrepancy may also be explained by a strong effect of salmon farms that obfuscates the influence of these environmental factors on the geographic distributions of sea lice.

Although there are hosts other than farmed salmon that can contribute to sea louse abundances on wild juvenile salmon in the Discovery Islands, it is unlikely

TABLE 9.—Significant effects in models of infection rates of two sea louse species in pink and chum salmon in the Discovery Islands.

Louse species	Year	Effect	<i>P</i> -value
<i>L. salmonis</i>	2005	Exposure category	<0.0001
		Sampling trip	0.0045
<i>C. clemensi</i>	2006	Exposure category	0.009
	2005	Exposure category	0.0002
	2006	Exposure category	0.047
		Salmon species	0.011

FIGURE 2.—Mean abundance (error bars = SDs) of the sea lice *Lepeophtheirus salmonis* and *Caligus clemensi* on juvenile pink and chum salmon at exposed (light gray) and peripheral (dark gray) sites in the Discovery Islands in (a) 2005 and (b) 2006. Note the difference in the scale of the y-axis between years.

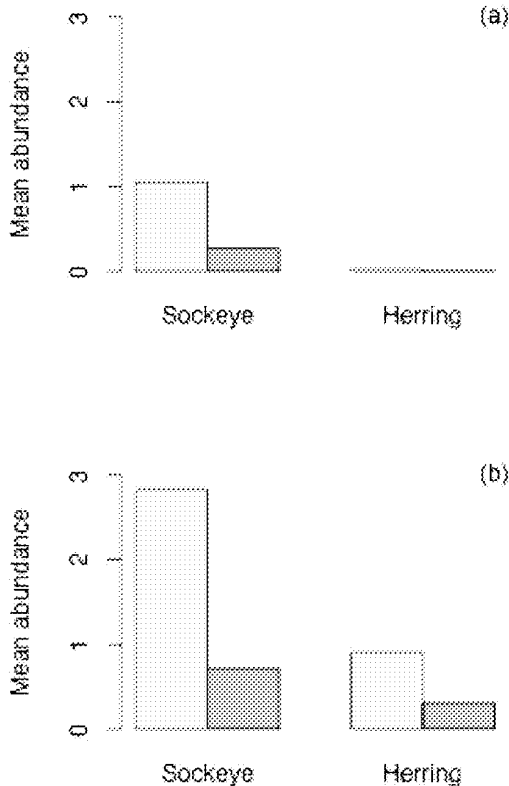


FIGURE 3.—Mean abundance of (a) *Lepeophtheirus salmonis* and (b) *Caligus clemensi* infecting juvenile sockeye salmon and Pacific herring in the Discovery Islands in 2005. Standard errors were not computed because of small sample sizes.

that these hosts caused the greater abundance of sea lice on wild juvenile salmon in the exposed area. Immature Chinook salmon in these waters may transmit sea lice to juvenile salmon in exposed and peripheral areas, but they are probably a negligible source compared with farmed salmon and wild adult pink, chum, and sockeye salmon, which are presumably much more abundant. Further, wild adult pink, chum, and sockeye salmon are situated offshore during our surveys (Groot and Margolis 1991). The threespine stickleback *Gasterosteus aculeatus* and other hosts for *C. clemensi* could also contribute to *C. clemensi* abundances observed on juvenile pink and chum salmon. We consider it doubtful that sticklebacks are a prominent source of *L. salmonis* because the occurrence of gravid *L. salmonis* on sticklebacks in other areas than the Discovery Islands has only been observed at very low abundances (Jones et al. 2006; Krkošek et al. 2007b). Aside from the difficulties

(a) described above in attributing increased sea lice abundance in the exposed versus peripheral areas, these other host species for sea lice must also occupy a spatial distribution that is similar to that of the salmon farms and is sustained for at least 2 months. We consider this last possibility unlikely.

These results suggest that sea lice infestations of wild juvenile salmon are not limited to juvenile pink and chum salmon, for which there are now several reports from the Broughton Archipelago (Morton and Williams 2003; Morton et al. 2004, 2005; Krkošek et al. 2005a, 2006a). The data on juvenile sockeye salmon and Pacific herring suggest that farmed salmon may transmit sea lice to these species as well. This latter evidence, though less definitive and preliminary, is important. Sea lice on juvenile herring are unreported for the Pacific and extremely rare in the Atlantic (Tolonen and Karlsbakk 2003). The herring were young of the year, translucent, and lacked scales, suggesting high vulnerability to mechanical damage of surface tissues caused by sea lice. Fraser River sockeye salmon are thought to migrate through the most infested areas of this study (Groot and Margolis 1991). Together, Fraser River sockeye salmon and Strait of Georgia herring are among British Columbia's most important commercial fish stocks, contributing a total of Can\$50 million (landed value) to the annual provincial economy. Ecologically, herring are a valuable forage fish for many other species and sockeye, pink, and chum salmon are the most abundant Pacific salmonids. Declines in these species and populations would probably have severe economic and ecological effects. We did not have the opportunity to examine steelhead or Chinook or coho salmon, so these salmonids could also be affected. Our results underscore an urgent need to develop and implement a conservation policy that protects wild salmon from sea lice.

#### Acknowledgments

This project would not have gone forward without the dedicated help of Steve Bergh, Matt Bergh, Jody Eriksson, Alice Woods, Emily Nilsen, Dane Stabel, and Marjorie Wonham. John Volpe contributed logistical support. Ashley Park assisted with data management. Redden Net Campbell River assisted with gear. This work was supported, in part, by Tides Canada, the David Suzuki Foundation, and members of the British Columbia Wilderness Tourism Association. R.R. was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant and M.K. by an NSERC Canada Graduate Scholarship D.



## References

- Beamish, R. J., S. Jones, C. E. Neville, R. Sweeting, G. Karreman, S. Saksida, and E. Gordon. 2006. Exceptional marine survival of pink salmon that entered the marine environment in 2003 suggests that farmed Atlantic salmon and Pacific salmon can coexist successfully in a marine ecosystem on the Pacific coast of Canada. *ICES Journal of Marine Science* 63:1326–1337.
- Bjom, P. A., and B. Finstad. 2002. Salmon lice, *Lepeophtheirus salmonis* (Kroyer), infestation in sympatric populations of Arctic char, *Salvelinus alpinus* (L.), and sea trout, *Salmo trutta* (L.), in areas near and distant from salmon farms. *ICES Journal of Marine Science* 59: 131–139.
- Brooks, K. 2005. The effects of water temperature, salinity, and currents on the survival and distribution of the infective copepodid stage of the salmon louse (*Lepeophtheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia, Canada. *Reviews in Fisheries Science* 13:177–204.
- Brooks, K., and D. Stucchi. 2006. The effects of water temperature, salinity, and currents on the survival and distribution of the infective copepodid stage of the salmon louse (*Lepeophtheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia, Canada (Brooks, 2005): a response to the rebuttal of Krkošek et al. (2005a). *Reviews in Fisheries Science* 14:13–23.
- Galbraith, M. 2005. Identification of larval stages of *Caligus clemensi* and *Lepeophtheirus salmonis* from the Broughton Archipelago. Canadian Technical Report of Fisheries and Aquatic Sciences 2548:414.
- Groot, C., and L. Margolis. 1991. Pacific salmon life histories. University of British Columbia Press, Vancouver.
- Heuch, P. A. 1995. Experimental evidence for aggregation of salmon louse copepodids (*Lepeophtheirus salmonis*) in step salinity gradients. *Journal of the Marine Biological Association of the United Kingdom* 75:927–939.
- Heuch, P. A., A. Parsons, and K. Boxaspen. 1995. Diel vertical migration: a possible host finding mechanism in salmon louse (*Lepeophtheirus salmonis*) copepodids. *Canadian Journal of Fisheries and Aquatic Sciences* 52:681–689.
- Heuch, P. A., C. W. Revie, and G. Gettinby. 2003. A comparison of epidemiological patterns of salmon lice, *Lepeophtheirus salmonis*, infections on farmed Atlantic salmon, *Salmo salar* L., in Norway and Scotland. *Journal of Fish Diseases* 26:539–551.
- Hilborn, R. 2006. Salmon farming impacts on wild salmon. *Proceedings of the National Academy of Sciences of the USA* 103:15277.
- Johnson, S. C., and L. J. Albright. 1991. The developmental stages of *Lepeophtheirus salmonis* (Kroyer, 1837) (Copepoda, Caligidae). *Canadian Journal of Zoology* 69:929–950.
- Jones, S., E. Kim, and S. Dawe. 2006. Experimental infections with *Lepeophtheirus salmonis* (Krøyer) on threespine sticklebacks, *Gasterosteus aculeatus* L., and juvenile Pacific salmon, *Oncorhynchus* spp. *Journal of Fish Diseases* 29:489–495.
- Krkošek, M., J. S. Ford, A. Morton, S. Lele, R. A. Myers, and M. A. Lewis. 2007a. Declining wild salmon populations in relation to parasites from farm salmon. *Science* 318:1772–1775.
- Krkošek, M., A. Gottesfeld, B. Proctor, D. Rolston, C. Carr-Harris, and M. Lewis. 2007b. Effects of host migration, diversity and aquaculture on sea lice threats to Pacific salmon populations. *Proceedings of the Royal Society of London B* 274:3141–3149.
- Krkošek, M., M. A. Lewis, A. Morton, L. N. Frazer, and J. P. Volpe. 2006a. Epizootics of wild fish induced by farm fish. *Proceedings of the National Academy of Sciences of the USA* 103:15506–15510.
- Krkošek, M., M. A. Lewis, and J. P. Volpe. 2005a. Transmission dynamics of parasitic sea lice from farm to wild salmon. *Proceedings of the Royal Society of London B* 272:689–696.
- Krkošek, M., M. A. Lewis, J. Volpe, and A. Morton. 2006b. Fish farms and sea lice infestations of wild juvenile salmon in the Broughton Archipelago: a rebuttal to Brooks (2005). *Reviews in Fisheries Science* 14:1–11.
- Krkošek, M., A. Morton, and J. P. Volpe. 2005b. Nonlethal assessment of juvenile pink and chum salmon for parasitic sea lice infections and fish health. *Transactions of the American Fisheries Society* 134:711–716.
- Limpert, E., W. A. Stahel, and M. Abbt. 2001. Log-normal distributions across the sciences: keys and clues. *BioScience* 51:341–352.
- MacKenzie, K., M. Longshaw, G. S. Begg, and A. H. McVicar. 1998. Sea lice (Copepoda: Caligidae) on wild sea trout (*Salmo trutta* L.) in Scotland. *ICES Journal of Marine Science* 55:151–162.
- McVicar, A. H. 1997. Disease and parasite implications of the coexistence of wild and cultured Atlantic salmon populations. *ICES Journal of Marine Science* 54:1093–1103.
- McVicar, A. H. 2004. Management actions in relation to the controversy about salmon lice infections in fish farms as a hazard to wild salmonid populations. *Aquatic Research* 35:751–758.
- Morton, A., and R. Routledge. 2005. Mortality rates for juvenile pink and chum salmon (*Oncorhynchus gorbuscha* and *keta*) infested with sea lice (*Lepeophtheirus salmonis*) in the Broughton Archipelago. *Alaskan Fisheries Research Bulletin* 11:146–152.
- Morton, A., R. Routledge, C. Peet, and A. Ladwig. 2004. Sea lice *Lepeophtheirus salmonis* infection rates on juvenile pink *Oncorhynchus gorbuscha* and chum salmon *Oncorhynchus keta* in the nearshore marine environment of British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 61:147–157.
- Morton, A., R. Routledge, and R. Williams. 2005. Temporal patterns of sea lice infestation on wild Pacific salmon in relation to the fallowing of Atlantic salmon farms. *North American Journal of Fisheries Management* 25:811–821.
- Morton, A., and R. Williams. 2003. First report of a sea louse, *Lepeophtheirus salmonis*, infestation on juvenile pink salmon, *Oncorhynchus gorbuscha*, in nearshore habitat. *Canadian Field Naturalist* 117:534–641.
- Peet, C. R. 2007. Interactions between sea lice (*Lepeophtheirus salmonis* and *Caligus clemensi*) and juvenile chum (*Oncorhynchus keta*) and pink salmon (*Oncorhynchus gorbuscha*) in British Columbia. Master's thesis. University of Victoria, Victoria, British Columbia.
- PFRCC (Pacific Fisheries Resource Conservation Council).

2002. Advisory: the protection of Broughton Archipelago pink salmon stocks. Report to the Minister of Fisheries and Oceans and B.C. Minister of Agriculture, Food, and Fisheries. PFRCC, Vancouver.
- Revie, C. W., G. Gettinby, J. W. Treasurer, and C. Wallace. 2003. Identifying epidemiological factors affecting sea lice (*Lepeophtheirus salmonis*) abundance on Scottish salmon farms using general linear models. *Diseases of Aquatic Organisms* 57:85–95.
- Steel, R. G. D., and J. H. Torrie. 1980. Principles and procedures of statistics: a biometrical approach, 2nd edition. McGraw-Hill, New York.
- Tolonen, A., and E. Karlsbakk. 2003. Parasites of herring (*Clupea harengus* L.) larvae from a local Norwegian fjord stock. *North Atlantic Marine Science* 88:154–157.
- Tully, O., P. Gargan, W. R. Poole, and K. F. Whelan. 1999. Spatial and temporal variation in the infestation of sea trout (*Salmo trutta* L.) by the caligid copepod *Lepeophtheirus salmonis* (Kroyer) in relation to sources of infection in Ireland. *Parasitology* 119:41–51.