Sea lice infestation of wild juvenile salmon and herring associated with fish farms off the east central coast of Vancouver Island, BC

Alexandra Morton[1], Rick Routledge[2] and Martin Krkošek[3]

[1]Raincoast Research Society, Simoom Sound, BC, Canada, V0P 1S0

[2]Department of Statistics and Actuarial Science, Simon Fraser University

[3]Centre for Mathematical Biology, Department of Biological Sciences, University of Alberta

Abstract

Reports of sSea lice (*Lepeophtheirus salmonis* and *Caligus clemensi*) infestations of juvenile salmonids in Pacific Canada have been restricted to pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon from one salmon farming region only – the Broughton Archipelago, British Columbia. Here, we report on two years of sea lice field surveys of wild juvenile pink, chum, and sockeye (*O. nerka*) salmon and wild larval herring (*Clupea harengus pallasi*) in another salmon farming region, the Discovery Islands region of British Columbia. For pink and chum salmon we tested for dependency of sea lice abundance on temperature, salinity, sampling period, host species, and farm exposure category. For both species of lice, farm exposure was the only consistently significant predictor of sea lice abundance. Fish exposed to salmon farms were infected with more sea lice than those in the peripheral category. Sea lice abundance on sockeye and herring followed the same trends, but sample sizes were too low (148 for sockeye and 322 for herring) to support formal statistical analysis. Herring were translucent and lacked scales and were primarily parasitized by *C. clemensi*. These results suggest the association of salmon farms with sea lice infestations of wild juvenile fish in Pacific Canada extends beyond juvenile pink and chum salmon in the Broughton Archipelago to juvenile pink, chum, and sockeye salmon, as well as, larval herring in the Discovery Islands. Canada's most abundant and economically valuable salmon populations, as well as, BC's most valuable herring stock migrate through the Discovery Islands, and henceso parasite transmission from farm to wild fish in this region may have important economic and ecological implications.

Introduction

Salmon farming is associated with sea lice (*Lepeophtheirus salmonis* and *Caligus* spp.) infestations of 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, farm salmon have been identified as a primary determinant of sea lice infection patterns on wild juvenile pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon (Morton et al 2004; Krkošek et al. 2005a), with farm salmon initiating population growth and 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 lice abundance (Morton et al. 2004; Krkosek et al. 2005b). Low abundances of *L. salmonis* are lethal to juvenile pink and chum salmon (Morton and Routledge 2005), sea lice transmission from farm salmon can cause high mortality in wild juvenile salmon (Krkošek et al. 2006), and pink salmon populations have collapsed following infestations (Morton and Williams 2003; PFRCC 2002). Fallowing a migration route in one year reduced sea lice abundances (Morton et al. 2005) and those 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 are constricted through a region of intensive salmon 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 BC. These include pink, chum, sockeye (*O. nerka*), steelhead (*O. mykiss*), coho (*O. kisutch*) and chinook (*O. tshawytscha*) salmon. In addition, this region may be important early juvenile rearing habitat for Strait of Georgia herring (*Clupea harengus pallasi*), BC's largest herring stock. Sea lice on juvenile herring are unreported for the Pacific and extremely rare in the Atlantic (Tolonen and Karlsbakk 2003). We report on sea lice infestations of wild juvenile pink and chum salmon, with observations of sea lice on juvenile sockeye salmon, and juvenile herring, all associated with salmon farms in the Discovery Islands.

Field 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 inamong the channels with one or more salmoncontaining several active 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. Peripheral sites were outside these narrow channels in places where juvenile salmon and herring need not have been directly exposed to anythe 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. There were four 2-3 day bi-weekly surveys in each year, over the time period April 19-June 5 in 2005 and April 3-June 9 in 2006, when we sampled 50 juvenile pink and/or chum salmon from each of 15 sites (in

2005) and 16 sites (in 2006) during each survey using a 30m x 1.8m beach seine net with1.6 cm knotless mesh. There were approximately 25 individuals of pink and chum in each sample collection in 2005 and higher abundance of chum than pink in 2006. We occasionally collected some juvenile herring and sockeye salmon as by-catch and also examined these fish for lice. 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). Additionally, we collected some juvenile sockeye and herring with a 30m x 3m beach seine with 1.6 cm knotless mesh during one survey in June 2005 of sites labeled h and s in Figure 1. For these fish we used the non-lethal assay described in Krkošek et al. (2005b) to measure fish fork length and count and identify the sea lice. We did not survey sockeye and herring in 2006 except those collected as by-catch in the pink/chum surveys.

Statistics

We analyzed abundances of each louse species on pink and chum salmon for dependence on exposure category (peripheral or exposed; Figure 1) and on the following factors: sampling trip, salinity, temperature, and host species. Separate analyses were conducted for each of the two years. We treated site-to-site differences within the exposure categories as random, and also included random effects associated with each sampling occasion at each site. To handle (i) the mixture of fixed and random effects, (ii) unequal variances and (iii) 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 el al. 2001) with a Poisson distribution for the counts on individual fish given the random effects mentioned above. (Note that these random effects will 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 expedient (e.g., Steel and Torrie 1980, pp. 168 & 235) of transforming the abundances (y) to $\log_e(y+.5)$, 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 was needed for convergence only in the initial stages of these some of these analyses.) We generated least squares estimates for the exposure category means and associated standard errors using the SAS GLIMMIX procedure. Since 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 two years we examined 4,699 fish for sea lice infections. . In 2005, most of the salmon farms indicated in Figure 1 were stocked with farm salmon more mature than smolts (information provided in 2005 by Pan Fish, Stolt and Heritage) Table 1. In 2006, only Church House was fully stocked with older salmon. All other sites were empty, partially empty or stocked with smolts only (based on observation and pervious year’s data). In 2005, we found a total of 4,232 *Lepeophtheirus salmonis* and 2,408 *Caligus clemensi* summed over all 2,432 fish that we lethally examined for sea lice. In 2006, we found 680 *Lepeophtheirus salmonis* and 857 *Caligus 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 Tables 2. There was little variation between exposure categories in salinity and temperature (Tables 3-4), but substantial increases in sea lice prevalence, intensity, and abundance in exposed sites relative to peripheral sites (Tables 5-8).

Results of the statistical model fitting are summarized in Table 9. For both years and both sea lice species, abundances on pink and chum salmon declined significantly from the exposed to the peripheral sites (Figure 2). For both *L. salmonis* and *C. clemensi*, the decline was significant in 2005 ($p < 0.0001$ and $p = 0.0002$, respectively) and in 2006 ($p = 0.0086$ and 0.047, respectively). In addition, each of sampling trip and salmon species (pink vs. chum) was significant in one instance only. Salmon species was significant for *C. clemensi* in 2006 ($p = 0.011$); sampling trip, for *L. salmonis* in 2005 ($p = 0.0045$). *C. clemensi* in 2006 was about 20% less abundant on pink vs. chum salmon. Sea lice abundance was greater in 2005 than in 2006. For pink and chum salmon in 2005, sea lice abundance peaked on 23 May at a mean of 10.5 lice per fish (3.4 lice$\cdot$g^{-1} host weight). There was not a clear peak in sea lice abundance in 2006.

Samples sizes for sockeye salmon and herring were too small to support formal statistical analyses, but trends indicate abundances of sea lice on sockeye salmon followed the same pattern (Figure 3). Louse abundance on sockeye salmon in 2005 was highest at the Church House site at 8.8 lice per fish that averaged 2.4 g host weight. On 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 lice infestations of wild juvenile salmonids have been associated with salmon farms in several countries (Bjorn and Finstad 2002; MacKenzie et al. 1998; Tully et al. 1999; 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; Morton et al. 2005; Krkošek et al. 2005; Krkošek et al. 2006). Similar to these other findings, our analysis shows that farm salmon were the most likely cause of the increased sea lice abundance observed on juvenile salmon in areas exposed to salmon farms relative to areas peripheral to salmon farms in the Discovery Islands. Exposure category was the only consistently significant factor explaining the data and other factors such as salinity and temperature were not significant. The difference in sea lice abundance between 2005 and 2006 can be explained by a decrease from 2005 to 2006 in the abundance of adult farm 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, Morton et al. 2005). It is useful to note that 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; Peet 2007; Allen Gottesfeld, Skeena Fisheries Commission, pers. com.). If 0.05 is taken to be the natural baseline prevalence of sea lice on juvenile pink and chum salmon then the data in this study suggest that salmon farms may also have increased sea lice abundance on juvenile salmon in the peripheral area relative to baseline levels. 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 lice 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 lice dynamics on salmon farms and/or experiments rearing larval lice in laboratory conditions have shown temperature and salinity can influence lice survival (Johnson and Albright 1991) and epidemiology (Heuch et al. 2003; Revie et al. 2003). Based on these studies on salmon farms and in lab 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 other studies in British Columbia based on field surveys on the spatial distribution of sea lice on juvenile salmon have considered, but not detected salinity and temperature as alternate explanatory factors to salmon farm proximity in explaining sea lice abundance data on juvenile salmon (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 and may therefore 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 spatial distributions of sea lice.

Although there are hosts other than farm salmon that can contribute to sea lice abundances on wild juvenile salmon in the Discovery Islands, it is unlikely that these hosts caused the increased abundance of sea lice on wild juvenile salmon in the exposed area relative to the peripheral 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 relative to farm salmon and wild adult pink, chum, and sockeye salmon, which are likely orders of magnitude more abundant. Further, wild adult pink, chum, and sockeye salmon are situated off-shore during our surveys (Groot and Margolis 1991). Stickleback 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 stickleback are a prominent source of *L. salmonis*, because the occurrence of gravid *L. salmonis* on stickleback, in other areas than the Discovery Islands, has only been observed at very low abundances (Jones et al. 2006; Allen Gottesfeld, Skeena Fisheries Commission, pers. com.). Aside from the difficulties described above in attributing increased sea lice abundance in the exposed area relative to the peripheral area, 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 two months. We consider this last possibility unlikely.

These results suggest 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; Morton et al. 2005; Krkošek et al. 2005; Krkošek et al. 2006). The data on juvenile sockeye and herring suggest that farm 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 sockeye and Strait of Georgia herring are British Columbia's most important commercial fish stocks – contributing a total of $50 million dollars (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 likely have severe economic and ecological effects. We did not have opportunity to examine steelhead, chinook or coho and this does not imply these salmonid species remain unaffected. These results underscore an urgent need to develop and implement conservation policy that protects wild salmon from sea lice.

Acknowledgement

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 BC Wilderness Tourism Association. RR was supported by an NSERC Discovery Grant and MK by an NSERC Canada Graduate Scholarship D. Collection was done under scientific collection permits #2005-06(s).

References

Beamish R.J., Jones S., Neville C.E., Sweeting R., Karreman G., Saksida S. and Gorden E. 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.

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 Stucchi D. 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 Krkosek et al. (2005a). Reviews in Fisheries Science 14: 13-23.

Bjorn, P. A., and Finstad, B. 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.

Galbraith, M. 2005. Identification of larval stages of *Caligus clemensi* and *Lepeophtheirus salmonis* from the Broughton Archipelago. Technical report of Fisheries and Aquatic Sciences 2548. 414.

Groot, C., and Margolis, L. 1991. Pacific salmon life histories. University of British Columbia Press, Vancouver.

Hilborn R. 2006. Salmon-farming impacts on wild salmon. Proceedings of the National Academy of Sciences of the United States of America, 103, 15277-15277.

Heuch, P.A., Revie, C.W. and Gettinby, G. 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.

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, A. and Boxaspen, K. 1995. Diel vertical migration – a possible host finding mechanisms in salmon louse (*Lepeophtheirus salmonis*) copepodids. Canadian Journal of Fisheries and Aquatic Sciences 52, 681-689.

Johnson, S. C. and Albright, L. J. 1991. The developmental stages of *Lepeophtheirus salmonis* (Kroyer, 1837) (Copepoda, Caligidae). Canadian Journal of Zoology. 69, 929-950.

Krkošek, M., Lewis, M. A. and Volpe, J.P. 2005a. Transmission dynamics of parasitic sea lice from farm to wild salmon Proceedings of the Royal Society Series B. 272, 689-696.

Krkosek, M., Lewis, M. A., Volpe, J. and Morton, A. 2006a. Fish Farms and sea lice infestations of wild juvenile salmon in the Broughton Archipelago - A rebuttal to Brooks (2006). Reviews in Fisheries Science. 14: 1-11.

Krkošek, M., Lewis, M. A., Morton, A., Frazer, L.N., and Volpe, J.P. 2006b. Epizootics of wild fish induced by farm fish. Proceedings of the National Academy of Sciences of the United States of America 103, 15506-15510.

Krkošek, M., Morton, A. and Volpe, J.P. 2005b. Nonlethal assessment of juvenile pink and chum salmon for parasitic sea lice infections and fish health**.** Transactions of the American Fisheries Society: Vol. 134, No. 3, pp. 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., Longshaw, M., Begg, G. S. and Mcvicar, A. H. 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 Williams, R. 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.

Morton, A., Routledge, R., Peet, C. and Ladwig, A. 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 Science 61:147-157.

Morton, A. and Routledge, R. 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., Routledge, R., and Williams, R. 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.

Peet, C. 2007. MSc. Thesis. University of Victoria, Victoria, BC, Canada.

PFRCC (Pacific Fisheries Resource Conservation Council) 2002 Advisory: the protection of Broughton Archipelago pink salmon stocks. In: Report to the Minister of Fisheries and Oceans and B.C. Minister of Agriculture, Food, and Fisheries. PFRCC, Vancouver.

Revie, C. W., Gettinby, G., Treasurer, J. W., and Wallace, C. 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 Torrie, J.H. 1980. Principles and procedures of statistics: A biometrical approach, 2nd ed. McGraw-Hill, New York, NY. 633 pp.

Tolonen, A. and Karlsbakk, E. 2003. Parasites of herring (*Clupea harengus* L.) larvae from a local Norwegian fjord stock. North Atlantic marine Science 88: 154-157

Tully, O., Gargan, P., Poole, W. R., and Whelan, K. F. 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

Table 1. Status of salmon farms within study area.

	Site	Year	Species	Age
A	Brougham Pt.	2005	Chinook	Growers
		2006	?	Smolts
B	Owen Pt.	2005		Empty
		2006	?	?
C	Venture Pt.	2005	Atlantic	Growers
		2006	?	Smolts
D	Philips	2005	Atlantic	Smolts
		2006	Atlantic	½ Harvested
E	Church House	2005	Atlantic	Smolts
		2006	Atlantic	Growers
F	Conville B.	2005	?	Growers
		2006	?	Smolts
G	Raza I.	2005	Atlantic	Growers
		2006		Empty
H	S. Thurlow	2005	Atlantic	Growers
		2006	Atlantic	½ Harvested
I	Sonora Pt.	2005	Chinook	Brood/Growers
		2006		Empty
J	Brent I.	2005	Atlantic	Growers
		2006	Atlantic	Smolts
K	Cyrus	2005	Chinook	Growers
		2006		Empty
L	Young Pass	2005	Atlantic	Empty
		2006		Empty

Table 2. A summary of salinity and temperature, the number of each species caught (*n*) with fork length and weight by year.

Year	Salinity ‰	Temperature °C	Species	*N*	Length mm (range)	Weight g (range)
2005	28.3	10.9	Pink	982	61.2 (27.8-115)	3.07 (0.10-77)
			Chum	980	52.7 (27.8-1070)	1.93 (0.16-15.1)
			Sockeye	148	88.3 (54-124)	n/a
			Herring	322	45.1 (34-57)	0.87* (0.5-1.4)
2006	29	10.6	Pink	726	54.8 (21-132)	2.72 (0.17-31.5)
			Chum	1534	57.0 (30-142)	3.21 (0.17-34.3)
			Sockeye	7	69.9 (30-96)	5.93 (0.28-12.7)

*based on a lethal sample of 23 fish.

Table 3. Mean fork length (L) and mean body weight (W) of juvenile pink and chum salmon, as well as, sea surface salinity (S) and temperature (T) measured at each collection in 2005. Fork length is measured in mm, body weight is measured in grams, salinity is measured in parts per thousand, and temperature is measured in degrees centigrade.

Category	Site	19-20 Apr				5-7 May				23-24 May				4-5 Jun			
		L	W	S	T	L	W	S	T	L	W	S	T	L	W	S	T
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) and mean body weight (W) of juvenile pink and chum salmon as well as sea surface salinity (S) and temperature (T) measured at each collection in 2006. Fork length is measured in mm, body weight is measured in grams, salinity is measured in parts per thousand, and temperature is measured in degrees centigrade.

Category	Site	3-4 Apr				14-15 Apr				10-11 May				8-9 Jun			
		L	W	S	T	L	W	S	T	L	W	S	T	L	W	T	S
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	-	-	-	-
	16			-	-	-	-	-	-	65.7	3.82	29	11.2	68.2	5.04	31	12.9
Peripheral	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

Table 5. *L. salmonis* prevalence (P), intensity (I), and abundance (A) on juvenile pink and chum salmon for each collection in 2005.

Category	Site	19-20 Apr			5-7 May			23-24 May			4-5 Jun		
		P	I	A	P	I	A	P	I	A	P	I	A
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. *C. clemensi* prevalence (P), intensity (I), and abundance (A) on juvenile pink and chum salmon for each collection in 2005.

Category	Site	19-20 Apr			5-7 May			23-24 May			4-5 Jun		
		P	I	A	P	I	A	P	I	A	P	I	A
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

Table 7. *L. salmonis* prevalence (P), intensity (I), and abundance (A) on juvenile pink and chum salmon for each collection in 2006.

Category	Site	3-4 Apr			14-15 Apr			10-11 May			8-9 Jun		
		P	I	M	P	I	M	P	I	M	P	I	M
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	-	-	-
	16	-	-	-	-	-	-	0.46	1.57	0.72	0.19	1.35	0.26
Peripheral	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. *C. clemensi* prevalence (P), intensity (I), and abundance (A) on juvenile pink and chum salmon for each collection in 2006.

Category	Site	3-4 Apr			14-15 Apr			10-11 May			8-9 Jun		
		P	I	M	P	I	M	P	I	M	P	I	M
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	-	-	-
	16	-	-	-	-	-	-	0.54	1.70	0.92	0.54	1.56	0.84
Peripheral	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

Table 9. Summary of significance for effects remaining in each model.

Louse Species	Year	Effect	*p*-value
L. salmonis	2005	Exposure Category	< 0.0001
		Sampling Trip	0.0045
	2006	Exposure Category	0.009
C. clemensi	2005	Exposure Category	0.0002
	2006	Exposure Category	0.047
		Salmon Species	0.011

Figure Headings

Figure 1. The study area, with arrows showing migration directions for young salmon, sample sites for all species (numbered for pink and chum), salmon farms (identified by letters) and the contour that groups sample sites as peripheral (outside the oval ring) and exposed (inside the oval ring). Site categorization (salmon and herring) was based on proximity to salmon farms and probable migration routes (salmon). The salmon farms, indicated by capital letters in square boxes, correspond to descriptions in Table 1. The sample sites, indicated by numbers in ovals, correspond to sample site numbers in Tables 3 and 4.

Figure 2. Mean abundance of sea lice on juvenile pink and chum salmon at exposed (light grey) and peripheral (dark grey) sites in 2005 (a) and 2006 (b). Error bars are standard errors. Note difference in y-axis scale.

Figure 3. Mean abundance of *Lepeophtheirus salmonis* (a) and *Caligus clemensi* (b) infecting juvenile sockeye and herring in 2005. Error bars were not computed for sockeye and herring due to small sample sizes. See *Statistics* section for methods on mean and standard error calculations.

Figure 1.

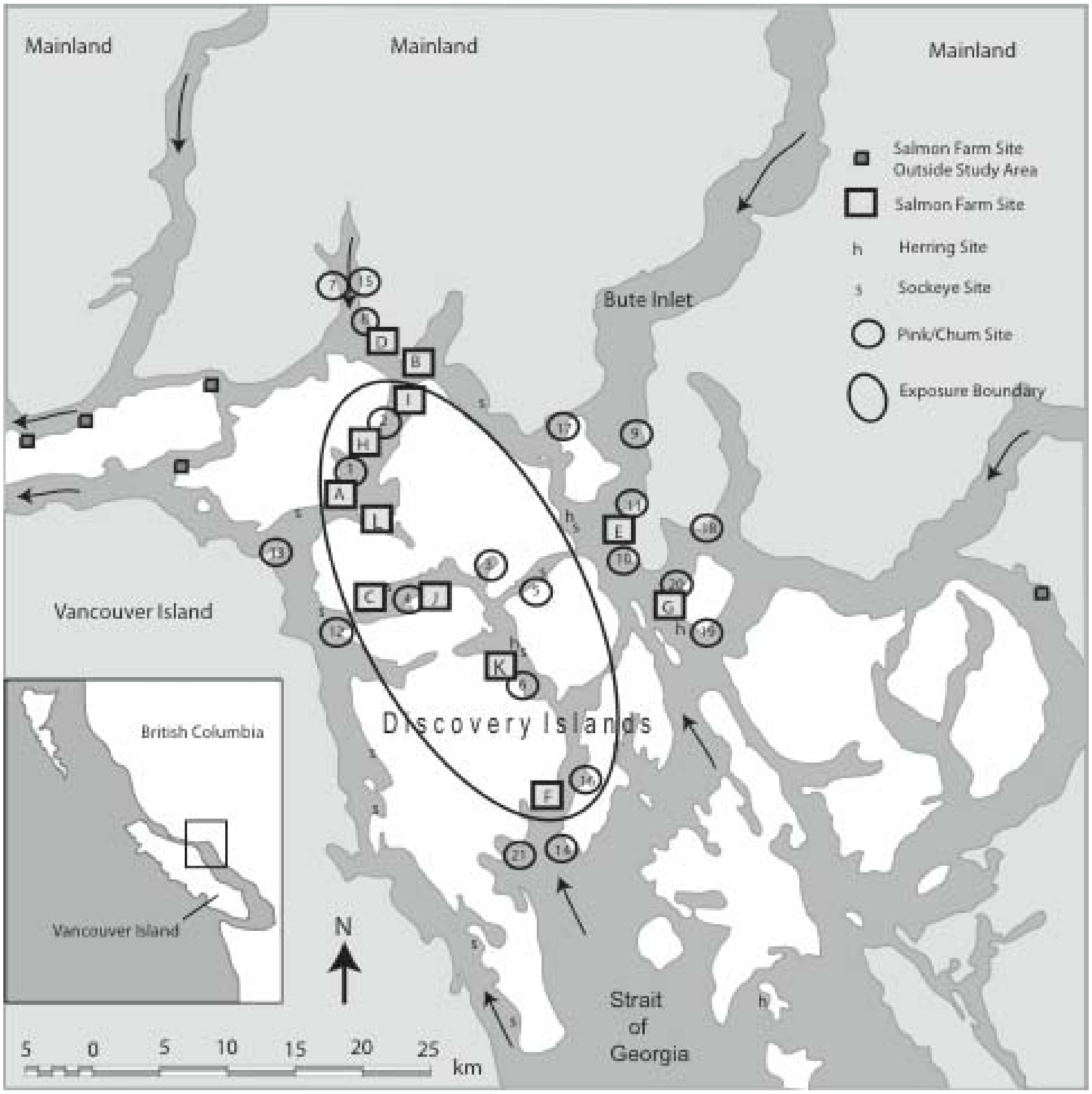

Mainland
Mainland
Mainland
Salmon Farm Site Outside Study Area
Salmon Farm Site
h Herring Site
s Sockeye Site
Pink/Chum Site
Exposure Boundary
Bute Inlet
Vancouver Island
Discovery Islands
Strait of Georgia
British Columbia
Vancouver Island
N
5 0 5 10 15 20 25 km
A
B
C
D
E
F
G
H
I
J
K
L
7
15
8
2
1
17
9
11
18
13
10
20
5
4
12
19
16
14
21
h
s

Figure 2.

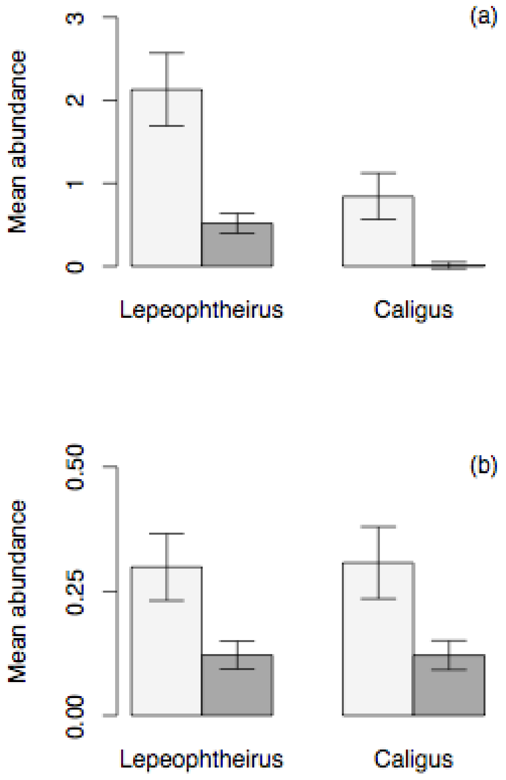
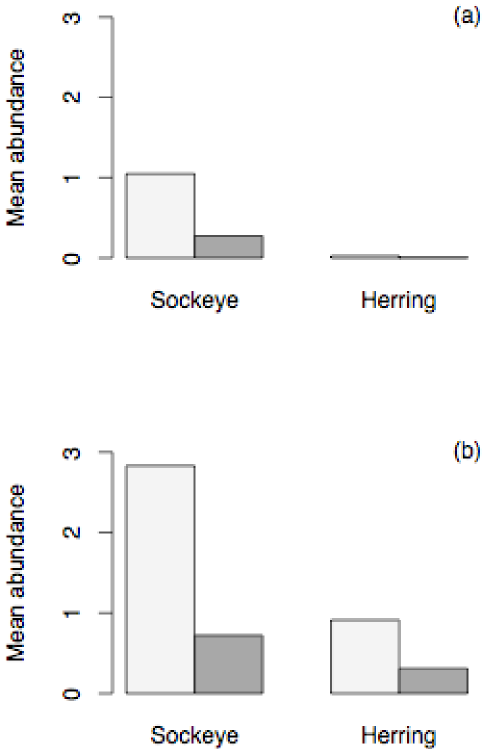
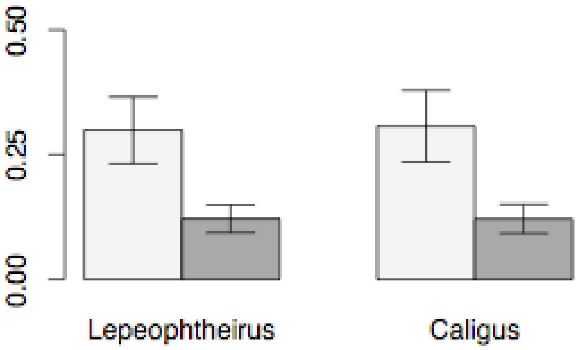

(a)
Mean abundance
0
1
2
3
Lepeophtheirus
Caligus
(b)
Mean abundance
0.00
0.25
0.50
Lepeophtheirus
Caligus

Figure 3.


(a)
Mean abundance
0
1
2
3
Sockeye
Herring
(b)
Mean abundance
0
1
2
3
Sockeye
Herring


0.50
0.25
0.00
Lepeophtheirus
Caligus