

Evaluation of sea lice abundance levels on farmed Atlantic salmon (*Salmo salar* L.) located in the Broughton Archipelago of British Columbia from 2003 to 2005

Sonja Saksida¹, Joanne Constantine², Grace A. Karreman³ & Alan Donald⁴

¹British Columbia Centre for Aquatic Health Sciences, Campbell River, BC, Canada

²British Columbia Ministry of Agriculture and Lands, Courtenay, BC, Canada

³Pacific Marine Veterinary Services, Nanaimo, BC, Canada

⁴Donald Associates Statistical Consulting, Vancouver, BC, Canada

Correspondence: S Saksida, British Columbia Centre for Aquatic Health Sciences, Box 277, Campbell River, BC, Canada V9W 5B1.
E-mail: sonja.saksida@cahs-bc.ca

Abstract

Salmon farming began in British Columbia (BC) in the 1970s and in 2006, aquaculture represented BC's largest agricultural export. Along with this growth in production has been a growth in controversy, including the concern that sea lice originating from Atlantic salmon farms negatively impact wild juvenile pink salmon in the Broughton Archipelago. To understand the dynamic interaction between wild and farmed fish, data for on-farm abundance of sea lice are required. In this study, 33 000 Atlantic salmon from 20 active farms were examined over 3 years. Two species of lice were found: *Lepeophtheirus salmonis* and *Caligus clemensi*. Inter-annual and seasonal variations in abundance levels occurred with lower levels of *L. salmonis* in 2003 compared with 2004 and 2005, while *C. clemensi* levels were highest in 2003. The abundance of *L. salmonis* was greater on older farmed fish. The findings are compared with European and eastern Canadian sea lice reports, and possible sources of sea lice on farmed salmon are discussed.

Keywords: sea lice, epidemiology, farmed Atlantic salmon

Introduction

Salmon farming in British Columbia (BC) began in the early 1970s on Pacific salmon species; e.g. chi-

nook salmon *Oncorhynchus tshawytscha* (Walbaum), coho salmon *O. kisutch* (Walbaum) and rainbow trout *O. mykiss* (Walbaum). The Atlantic salmon *Salmo salar* (L.) was introduced as a farmed species to BC in the mid-1980s. By 2002, the industry had grown to 83 000 metric tonnes of annual production with 82% of its volume derived from Atlantic salmon (BCSEA 2005). Along with this growth in production has been a growth in controversy about the environmental impacts of salmon farming. One of the most recent issues is the perception that sea lice originating from Atlantic salmon farms are negatively impacting juvenile Pacific salmon, specifically pink salmon *O. gorbuscha* (Walbaum), in a region locally referred to as the 'Broughton Archipelago' (Morton, Routledge, Peet & Ladwig 2004). The Broughton Archipelago is considered an important early rearing area for wild juvenile salmonids, including pink salmon, the most abundant of the six major anadromous salmon species indigenous to the coastal waters of BC (Groot 1996). The Broughton Archipelago is also one of seven major salmon farming regions in BC and represents approximately 25% of the total farmed salmon production in BC.

In spring 2003, in response to claims of elevated numbers of sea lice on juvenile pink salmon in the Broughton Archipelago, Fisheries and Oceans Canada (DFO) initiated several surveys to examine lice levels on wild salmonid juveniles and other fin-fish species in the region. At the same time, the Provincial government of BC initiated the Broughton

Archipelago Sea Lice Action plan for monitoring sea lice on farmed Atlantic salmon. The BC Ministry of Agriculture and Lands (BCMAL) – formerly the Ministry of Agriculture, Food and Fisheries – initiated a regulatory programme similar to those already in place in Norway, Scotland and Ireland (Treasurer & Pope 2000; Heuch & Mo 2001; O'Donohoe, Kennedy, Kane, Naughton, Tierney & Jackson 2005). Under the plan, all farms in the Broughton Archipelago initiated routine inspection of individual farmed salmon for sea lice – *Lepeophtheirus salmonis* (Kroyer) (*L. salmonis*) and *Caligus clemensi* (*C. clemensi*) – during the spring outmigration of wild juvenile salmonids. In October 2003, BCMAL fish health staff commenced an auditing programme of on-farm monitoring. The programme was extended to include year-round monitoring, reporting and auditing of all farmed salmon in BC. The initial auditing programme was designed to sample 25% of the Atlantic salmon farming industry quarterly. This was modified in 2005, and auditing was increased to include 50% of the industry sites in the second quarter (March–June). Audit levels were maintained at 25% for the remaining quarters. In cooperation with the Provincial government, the threshold for action ('trigger level') was set in late 2003 at three mobile *L. salmonis* during the outmigration period (March–June) and six for the remainder of the year. An action could include a veterinarian-prescribed therapeutic treatment or increased harvesting. In October 2004, the trigger level was reduced to three mobile lice year round. At the same time, increased monitoring was included as an acceptable action outside the outmigration period.

The following report summarizes the results of the industry sea lice monitoring and BCMAL regulatory audit programmes from March 2003 to December 2005 for the farms situated in the Broughton Archipelago. This study is part of a larger collaborative study addressing sea lice on wild and farmed salmon in the area. The effects of factors such as fish age, time of year, farm location, water temperature and salinity and treatment of farm sea lice levels are examined. The findings are compared with European and eastern Canadian sea lice reports. Probable sources of sea lice on BC-farmed salmon are discussed.

Materials and methods

The data set evaluated in this study comes from Atlantic salmon farms situated within the Broughton Archipelago region of BC. This region measures

3000 km² and is situated between the BC mainland and Vancouver Island; it includes the area of eastern Queen Charlotte Strait and associated inlets (Fig. 1). The farms in the region are operated by two independent companies.

Environmental data collected by the individual farms from January 2003 to the end of 2005 was submitted for examination. The environmental data included salinity measured at the surface (0–1 m) using a salinity refractometer (VISTA model A366ATC, Dynamic Aqua-Supply Ltd, Surrey, Canada), and temperature measured at 5 m using a hand held dissolved oxygen meter (Oxyguard gamma, Birkerød, Denmark).

Sea lice data collected from March 2003 to the end of 2005 were submitted for evaluation. Sea lice monitoring was conducted in accordance with BCMAL requirements (BCMAL 2005). Fish were sampled a minimum of two times per month during the juvenile salmon migration periods (March–July) and once per month for the balance of the year. The migration periods of juvenile salmonids were established by DFO. Lice monitoring on each farm commenced 1 month following smolt introduction onto the farm site and continued until harvest. Monitoring stopped when there were fewer than three pens remaining on the farm. Monitoring could be exempted only if there were fish health concerns, which were reported monthly to the BC Salmon Farmers Association (BCSFA) database if they occurred. In the rare case where sites were not monitored for other reasons, these were reported directly to the BCMAL veterinarian.

For each farm, a minimum of three pens of fish were sampled at each time. This included one reference population ('standard' pen) and two randomly selected ones. At sampling, a portion of the population in the pen was crowded using a seine and 20 fish were randomly selected. Fish were removed by dip net and transferred to an anaesthetic bath containing tricaine methanesulphonate (TMS, Syndel International, Vancouver, BC, Canada). Anaesthetized salmon were visually inspected for sea lice. Sea lice were counted and categorized as follows:

- Chalimus (attached stages of any louse species).
- Adult female *L. salmonis* (with and without egg strings).
- All mobile *L. salmonis* (including pre-adult and adult males and females).
- All mobile *C. clemensi*.

Before October 2003, farms managed by one company in the Broughton area classified only adult

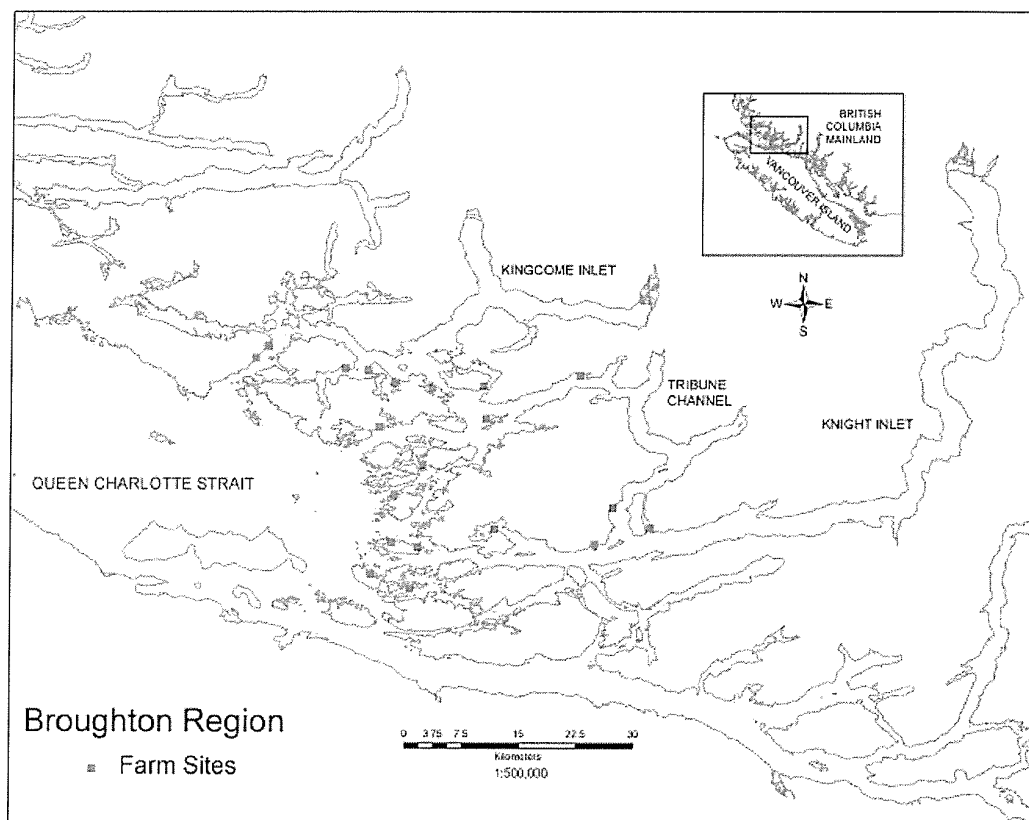


Figure 1 The Broughton Archipelago study area showing location of salmon farms.

female *L. salmonis* with egg strands as adult female *L. salmonis*. However, this protocol was amended in October 2003 whereafter farms in both companies identified all adult females (with and without egg strings) into the single category. Following sampling, the anaesthetic tote was visually inspected for detached lice. These lice were identified, counted and included in the calculations of sea lice abundances for the farm. Farm-level sea lice abundances were calculated on a monthly basis by averaging the pen-level values. In addition to sea lice numbers, farms also reported the age of the salmon sampled and whether an action was taken as a result of the observed sea lice levels (e.g. increased monitoring, harvest or treatment). The individual site data were managed by an independent third party using a web-based SQL Server database, whose technical structure is owned by the BCSEA.

Fish health personnel from the BCMAL (BCMAL 2005) audited 25% of all the 'active farms' in the province in each of the three quarters between July and March [July–September (Q3), October–December

(Q4) and January–March (Q1)] and 50% of all active farms between April and June (Q2). For the purpose of the audit programme, active farms were defined as farms that contained populations of salmon > 1 month in seawater and did not include brood stock farms. Farms to be audited were selected using a computer-generated random numbers table. The audits were conducted in conjunction with routine farm lice monitoring to ensure accuracy in identification, consistency and comparability in reporting lice numbers. Sampling occurred as described above with simultaneous counts by government auditors and farm personnel. Since the Broughton Region includes many but not all farms from two adjoining BCMAL fish health zones, the audit data collected from the farms in the study were selected out and compiled manually. The farm level mean sea lice abundance obtained by the auditors and the farm personnel on the day of the audit was compared using Student's *t*-test. The mean lice abundance values calculated from all farms audited for the region in each quarter were compared with the mean lice

abundance calculated from all data submitted by the industry for the same period. Comparisons were made for each quarter on chalimus, adult female *L. salmonis*, mobile *L. salmonis* and mobile *C. clemensi* abundance levels.

The analysis focused on providing simple descriptive summary statistics. Farm-level sea lice abundance data were evaluated in relation to a number of parameters including calendar year, time of year [between March and June (M–J); the period of wild juvenile salmon migrations and between March and December (M–D) the sampling period common amongst the 3 years examined], year class of population and lice treatment. The distribution of the sea lice data was not normal but skewed to the right and contained outliers. The logarithm of each value (value + 0.001) was computed to normalize the data. These log-transformed values were used in ANOVA followed by multiple comparisons using the Tukey HSD test. All two-sample statistical comparisons were carried out using Student's *t*-test on untransformed data. All analyses were carried out using STATISTIX for Windows[®] (Analytical Software). The level of significance was set at 5% ($P \leq 0.05$). In addition to mean values and standard deviation (SD), the report also provides median values. All figures presented in the report were prepared using EXCEL 2000[®] (Microsoft).

Results

During the 34-month study period (March 2003–December 2005), a total of 20 farms operated in the Broughton Archipelago region, 100% of which participated in the study. Thirteen farms operated as general production farms (both smolt and grow-out), two operated as smolt-only sites, three operated primarily as grow-out sites and two were designated as broodstock sites. With the exception of the two broodstock sites, all the farms were single year class sites. The number of operational sites varied through the course of the study depending on the farms' stocking and harvesting schedules: in 2003 and 2004 there were 18 Atlantic salmon farms active in the study area and during 2005 there were 19 farms in operation. Although the number of farms among the years was similar, there was a difference in age or year class distribution between the years. In 2003, almost two-thirds of the farms consisted of year class 1 (Yr1) populations (< 365 days in seawater), while in 2004 the situation was reversed with two-thirds of the farms holding year class 2 (Yr2) populations (> 365 days

in seawater). In 2005, there were approximately equal number of farms with Yr1 populations and Yr2 populations (10 and 9 respectively).

Monthly salinity (surface) and temperature (at 5 m) data were obtained from January 2003 to the end of 2005. Surface-water salinities ranged from 7.3 to 34 g L⁻¹ and water temperatures ranged from 6 to 13.2 °C. The lowest average surface salinities (mean 22.3 g L⁻¹ – range 8.23–33.0 g L⁻¹) and the warmest water temperatures (mean 11.2 °C – range 9.2–13.2 °C) in all 3 years were recorded in August. The highest average salinities were recorded in March (mean 30.1 g L⁻¹ – range 22.8–33.7 g L⁻¹). The coldest water temperatures were in January, with a mean 7.1 °C (range 6–8 °C).

Over 33 000 farmed salmon were examined for sea lice by farm personnel during the study period. In total, 431 farm-level lice evaluates were submitted for an average of 1.0 lice counts farm⁻¹ month⁻¹ between July and February and 1.6 lice counts farm⁻¹ month⁻¹ between March and June. One hundred per cent of the active farms reported in 23 months of the 34-month study period. For the other 11 months, the level of reporting ranged from 70% to 93%. Most of the omissions occurred in August, September and October; as a result of environmental problems such as plankton blooms or low dissolved oxygen levels when handling the fish presented a high risk.

Total lice numbers, the number/type of dislodged sea lice enumerated from the anaesthetic totes and the number of fish evaluated per pen were submitted by each farm to the BCSEA database. Data collection was carried out at the pen level, which permitted calculation of abundance levels (the average number of sea lice per salmon examined) but not prevalence (the proportion of salmon infested with sea lice) or intensity (the average number of sea lice on infested salmon).

Figure 2 shows the monthly pattern of sea lice abundance levels during the 34-month study period for the Broughton Archipelago region. In general, the lowest levels of lice were observed in the summer months (June–September) with levels increasing through the autumn/winter. The SDs associated with the higher mean abundance levels are very large – often twice the mean value – compared with the SDs of the smaller mean values. The large SDs resulted from the skewed data.

Table 1 summarizes the median and mean annual abundance level of the mobile stages of each louse species as well as the combined total of chalimus

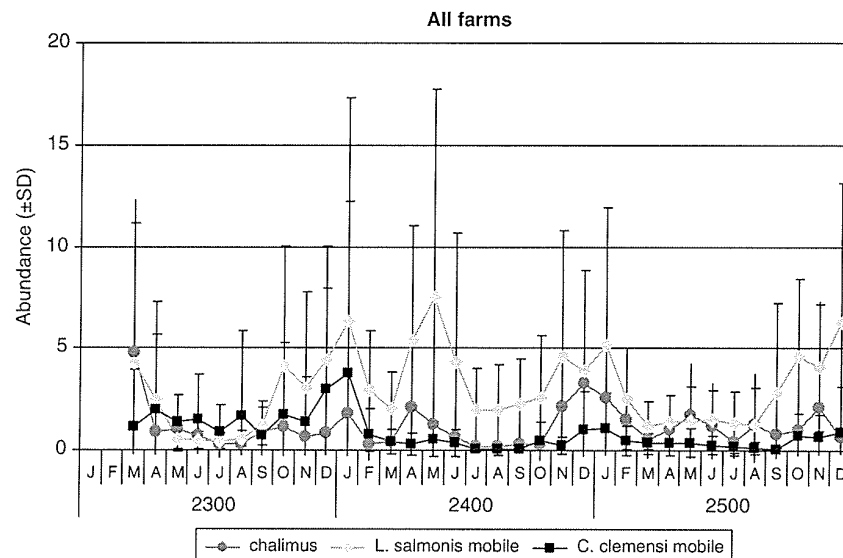


Figure 2 Mean monthly sea lice abundance with standard deviation (SD) for all farm months for the period of March 2003–December 2005.

Table 1 Median and mean with standard deviation (SD) annual sea lice abundance levels of all farms in operation in the Broughton Archipelago between March 2003 and December 2005, with the number of farm-level evaluates (*n*) for each year shown

Year (<i>n</i>)	<i>Lepeophtheirus salmonis</i> (mobile)			<i>Caligus clemensi</i> (mobile)			Chalimus		
	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD
2003*									
M–D (118)	0.7	2.2	4.3	0.4	1.6	2.9	0.3	1.1	2.8
2004 (160)	2.0	3.8	5.8	0.1	0.6	2.5	0.4	1.1	2.0
M–D (136)	2.0	3.7	5.4	0.1	0.4	0.8	0.4	1.1	2.0
2005 (153)	1.3	2.7	3.9	0.1	0.5	1.0	0.3	1.3	2.7
M–D (123)	1.3	2.5	3.4	0.1	0.4	0.9	0.3	1.1	2.3

For 2004 and 2005 the values calculated for the months March–December (M–D) are also provided.

*March–December only.

stages for both louse species for all active farms in the Broughton Archipelago. Table 2 provides a summary of lice levels on populations of Atlantic salmon that have been in seawater < 1 year (Yr1) and those that have been in seawater > 1 year (Yr2). In general, for the full sampling period, the mobile *L. salmonis* levels were higher in Yr2 populations than Yr1 populations, with levels significantly higher among Yr2 populations in 2003 (M–D), 2004 and 2005 ($P \leq 0.001$, 0.02 and 0.001 respectively). When the farm level data collected after October 2003 were examined (i.e. when the proportion of adult females was uniformly recorded by both companies), it was found that a higher proportion of the total mobile

L. salmonis levels in Yr2 populations was adult females (46.3%) than in Yr1 populations (29.5%) ($P < 0.01$). Mobile *C. clemensi* abundance levels were significantly higher in Yr2 populations compared to Yr1 populations in 2003 (M–D) ($P < 0.001$) but not in 2004 and 2005 ($P = 0.43$ and 0.71 respectively). There was no significant difference in chalimus levels between year classes in any of the 3 years examined.

To maintain consistency, only sea lice levels reported from March to December (M–D) during all 3 years were used to statistically evaluate for inter-annual variation within year classes. No significant inter-annual variation was observed in mobile *L. salmonis* levels within Yr1 or Yr2 populations

Table 2 Median and mean with standard deviation (SD) sea lice abundance levels of mobile *Lepeophtheirus salmonis*, *Caligus clemensi* and chalimus stages by year class (Yr1 and Yr2) for: the calendar year, the period March–December (M–D) and the out-migration period [March–June (M–J)] of each year, with the number of farm-level evaluations (*n*) shown

Year/months	Year class (<i>n</i>)	<i>L. salmonis</i> (mobile)			<i>C. clemensi</i> (mobile)			Chalimus		
		Median	Mean	SD	Median	Mean	SD	Median	Mean	SD
2003*	Yr1 (74)	0.5	0.9	1.1	0.2	0.6	0.9	0.3	0.7	1.0
M–D	Yr2 (44)	1.1	4.3	6.2	1.2	3.1	4.3	0.4	1.9	4.3
M–J	Yr1 (29)	0.5	0.7	0.6	0.4	0.8	0.9	0.4	1.0	1.2
	Yr2 (22)	0.7	3.6	6.2	1.1	2.4	3.6	0.6	2.8	5.9
2004	Yr1 (55)	1.2	2.6	3.4	0.1	0.5	1.5	0.4	0.9	1.1
	Yr2 (105)	2.2	4.5	6.7	0.1	0.7	2.9	0.3	1.1	2.3
M–D	Yr1 (45)	1.5	2.9	3.6	0.2	0.3	0.5	0.5	1.0	1.2
	Yr2 (91)	2.2	4.1	6.0	0.1	0.4	0.9	0.2	1.1	2.2
M–J	Yr1 (21)	2.4	4.1	4.5	0.3	0.4	0.6	0.7	1.4	1.2
	Yr2 (38)	2.4	5.2	7.8	0.1	0.4	0.7	0.3	0.9	1.5
2005	Yr1 (88)	1.1	1.5	1.6	0.1	0.4	0.8	0.3	1.1	2.9
	Yr2 (65)	2.7	4.5	5.2	0.1	0.5	1.3	0.5	1.6	2.5
M–D	Yr1 (73)	1.2	1.5	1.5	0.1	0.4	0.6	0.3	0.9	2.3
	Yr2 (50)	2.4	3.9	4.7	0.1	0.4	1.2	0.4	1.4	2.2
M–J	Yr1 (33)	1.2	1.4	1.3	0.2	0.4	0.5	0.3	0.9	1.0
	Yr2 (18)	0.5	1.3	1.7	0.0	0.2	0.6	0.3	1.7	2.7

*March–December only.

($P = 0.12$ and 0.40 respectively). This holds true even though the mean abundance level in Yr1 populations in 2004 was almost three times that of 2003 levels and almost twice that of 2005; however, the SD associated with the 2004 level was very broad, indicating a large variation in values. Significant inter-annual variation in mobile *C. clemensi* levels was observed among Yr2 populations ($P < 0.001$) with significantly higher levels occurring in 2003 than in 2004 or 2005. Inter-annual variation in mobile *C. clemensi* levels was not observed among Yr1 populations ($P = 0.12$). No significant inter-annual variation was found in the chalimus stages in either Yr1 or Yr2 populations among the 3 years ($P = 0.73$ and 0.18 respectively).

Lice levels on the farmed salmon were also examined for the period when wild juvenile pink salmon were migrating seaward [March–June (M–J)] (Table 2). The results of the focused comparisons differed from those of the broader comparisons. There was no significant difference between Yr1 and Yr2 populations in mobile *C. clemensi* or chalimus stages in all 3 years. Significantly higher mobile *L. salmonis* abundance levels were observed in Yr2 populations in 2003 ($P = 0.04$). However, in 2004 and 2005 there was no significant difference in mobile *L. salmonis* levels between year classes ($P = 0.47$ and 0.77 respectively). Significant inter-annual variation was observed only in mobile *L. salmonis* among Yr1 popu-

lations with levels reported in 2004 being significantly higher than in 2003 ($P = 0.002$) and in mobile *C. clemensi* in Yr2 populations where levels reported in 2003 were significantly higher than either 2004 or 2005 levels ($P < 0.001$).

Regulatory imposed treatment-trigger levels were established in 2004. There were 39 sea lice treatments during the study period: four in 2003 (February–December), 17 in 2004 and 18 in 2005. The mean abundance of mobile *L. salmonis* at the time of treatment for all populations was 8.69 (SD = 7.7) (median = 6.18). In all cases, treatment was provided as medicated feed using Slice[™] (emamectin benzoate, Schering Plough Animal Health, Point-Claire, Canada). Within the nine groups that started and completed their production cycle during the study period, there was an average of 1.6 sea lice treatments for the cycle.

Overall, for the 3-year study period, the majority of treatments (75%) in Yr2 populations occurred between October and March (Q4 and Q1 respectively). Among Yr1 populations, the majority of treatments (68%) in both 2004 and 2005 occurred between April and June (Q2). Over 60% (24 of 39) of the treatments occurred in Yr2 populations and the average age at first treatment was 266 days (SD = 153.8) (median = 280). Figure 3 illustrates the breakdown of treatments by calendar quarter for Yr1 and Yr2 populations. During 2004, the highest number of treat-

Figure 3 Shows the timing (in year/quarters) of sea lice treatments in year class 1 (Yr1) and year class 2 (Yr2) populations.

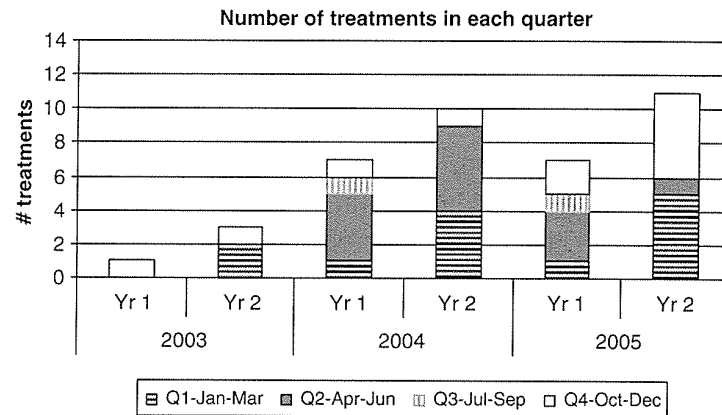
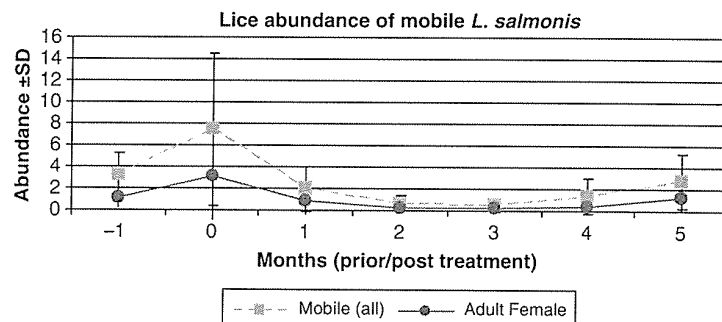


Figure 4 Mean sea lice abundance levels with standard deviation (SD) for 1 month before treatment (–1), the month of treatment (0) and for 5 months following treatment (+1 to +5) for sites ($n = 19$) that were treated during the period studied.



ments in Yr2 populations occurred between January and June (nine), while in 2005 most occurred in Q1 and Q4, each with five treatments. There were only three treatments in Yr2 populations in 2003: two occurring during Q1 and the third occurring during Q4.

The effect of treatment on mobile *L. salmonis* was evaluated by tracking lice abundance levels on populations that were in production for a minimum of 5 months following the treatment ($n = 19$). Farms treated after August 2005 ($n = 7$) were excluded from the evaluation since the 5 month post-treatment period extended into 2006 – beyond the limits of the present study. Farm populations harvested ($n = 11$) or moved to a different farm ($n = 2$) less than four months after receiving treatment were also not included. Figure 4 illustrates the mean abundance of all mobile *L. salmonis* lice (adult females included), as well as adult females separately before, during and for 5 months following treatment. The mean abundance levels at the time of treatment for all mobile stages of *L. salmonis* and adult female *L. salmonis* only were 7.45 (SD = 7.02) and 3.15 (SD = 4.01) respectively. There was a statistically significant decrease seen in

both the combined mobile *L. salmonis* and adult female levels 1 month following treatment: a 3.8 and 3.5 times decrease respectively. The levels remained significantly below pre-treatment levels for 5 months following treatment ($P < 0.001$). At that time the mean abundance levels, though no longer significantly different from pre-treatment, were still over 2.5 times lower than the levels reported at the time of treatment. Only one farm was re-treated within this period, at 5 months following the initial treatment.

Twenty-five farms in the Broughton Archipelago were audited by BCMAL, 11 in 2004 and 14 in 2005. The percentage of farms in the Broughton Archipelago audited during quarters when 25% of the industry was audited ranged from 13% to 21%. During the second quarter in 2005, when the level of audits increased to 50% of the industry, a total of 44% of farms operating in the region were audited. Farm level comparisons of audit and industry data collected in the Broughton Archipelago found no significant difference in the overall estimates of mobile *L. salmonis* abundance. However, during two audits (8%), Q2 and Q3 of 2005, a significant difference in estimates

Table 3 Comparison of sea lice median and, mean with standard deviation (SD) collected during BCMAL audits with data reported by all the farms in the Broughton Archipelago

Year	Quarter	Number of farms (audit/active)	Chalimus			<i>Lepeophtheirus salmonis</i> (all mobile stages)			<i>L. salmonis</i> (adult female only)			<i>Caligus clemensi</i> (all mobile stages)		
			Median	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD
2004	J–M	3	0.8	0.6	0.6	2.6	2.7	2.7	1.7	1.4	1.3	0.3	0.4	0.5
		16	0.4	0.8	1.7	1.7	3.6	6.5	0.8	1.8	3.5	0.2	1.6	4.9
	A–J	2	1.5	1.5	1.8	0.5	0.5	0.2	0.0	0.0	0.0	0.4	0.4	0.5
		16	0.6	1.3	1.6	3.3	5.8	7.6	1.0	2.3	4.3	0.1	0.4	0.7
	J–S	3	0.0	0.0	0.0	0.5	1.2	1.7	0.3	0.9	1.3	0.0	0.0	0.0
		16	0.1	0.2	0.3	1.5	2.1	2.1	0.5	0.9	1.1	0.0	0.1	0.1
	O–D	3	2.8	4.8	5.2	1.5	6.1	8.5	0.3	2.6	4.2	0.1	0.1	0.2
		14	0.6	2.0	3.1	1.8	3.8	4.9	0.6	1.9	2.7	0.0	0.6	1.2
	J–M	3	1.4	3.2	4.3	1.4	7.1	10.7	0.3	3.3	5.3	0.3	0.3	0.3
		16	0.3	1.7	3.5	1.4	3.2	4.8	0.6	1.7	2.9	0.1	0.7	1.2
2005	A–J	7	0.8	1.5	1.8	0.6	1.2	1.7	0.2	0.4	0.7	0.1	0.2	0.5
		15	0.5	1.3	2.0	1.0	1.4	1.5	0.3	0.5	0.7	0.1	0.3	0.6
	J–S	2	0.3	0.3	0.0	2.7	2.7	3.0	1.8	1.8	1.9	0.0	0.0	0.0
		15	0.2	0.8	1.6	0.8	1.8	2.9	0.3	0.9	1.7	0.0	0.1	0.2
	O–D	2	0.4	0.4	0.2	4.1	4.1	2.3	2.3	2.3	1.4	0.0	0.0	0.0
		14	0.5	1.3	3.3	3.0	4.9	4.7	1.9	2.8	3.2	0.1	0.7	1.5

BCMAL, British Columbia Ministry of Agriculture and Lands.

of adult female *L. salmonis* was found. In both situations, the farm abundance estimates were found to be significantly higher than audit estimates. There were significant differences in mobile *C. clemensi* found during three audits (12%). In 2005 Q1 and Q2 the industry abundance estimates of *C. clemensi* were found to be significantly higher than the audit while in 2004 Q2 the audit estimates were found to be significantly higher. Finally, during nine audits (36%), there was a significant difference in chalimus abundance levels; in all cases the industry abundance estimates were significantly higher than the audit estimates. This occurred in one audit in 2004 Q1, Q2 and Q4 and Q3 2005, in two audits in 2005 Q1 and in three audits in Q2 2005.

Table 3 provides a comparison of quarterly sea lice abundance estimates for the Broughton Archipelago as calculated from the provincial audit data and as reported by farms operating in the region. There was no significant difference between the audit and the farm-supplied data in 28 of 32 lice-by-quarter-by-stage comparisons. There were four occurrences where the audited values were found to be significantly different from the industry-reported values: *L. salmonis* mobiles and *L. salmonis* adult female levels in Q2 of 2004, *C. clemensi* in the last quarter in 2005 and chalimus levels in Q3 of 2004. In all cases, the levels reported by the industry were

significantly higher than the levels obtained during the audit.

Discussion

The study is the first detailed examination of sea lice on Atlantic salmon farmed in the Broughton Archipelago on the west coast of Canada. These farms represent approximately 25% of the total farmed Atlantic salmon production in BC. During the study period, when farms were monitored for sea lice on an average of once per month and as often as 1.6 times per month between March and June, *L. salmonis* and *C. clemensi* lice species were both observed. Similar to reports from Europe and Eastern Canada, *L. salmonis* was the predominant species of louse observed on farmed Atlantic salmon in the Broughton Archipelago. The most striking difference between sea lice levels on farms in BC compared with those reported in Europe and Eastern Canada is the actual difference in the total abundance of lice *L. salmonis*. The lice levels on farmed salmon populations in this study were two to three times lower than published reports on similar-sized Atlantic salmon raised in Europe (Wallace 1998; Copley, McCarney, Jackson, Hassett, Kennedy & Nulty 2001; Revie, Gettinby, Treasurer, Grant & Reid 2002; Revie, Gettinby, Treasurer, Rae & Clark

2002; Heuch, Revie & Gettinby 2003). The positive skewness of the mean abundance levels observed in the present study highlights the implications for accuracy when reporting only mean abundance levels, and also the relevance of reporting median values in similar studies.

The large SDs associated with the data suggest that there may be other variations within the farms operating in the Broughton Archipelago not captured in the present analyses. Some of these have been examined and will be discussed in later reports.

Statistically significant annual variations in abundance levels of *L. salmonis* were not found when similar data (i.e. March–December data) were compared for 2003, 2004 and 2005. However, during the wild salmon outmigration (March–June), significantly lower levels of mobile *L. salmonis* were observed among Yr1-farmed populations in 2003 than in 2004. This was not a function of treatment as therapeutants were not provided during this period in 2003. Inter-annual variations were found in the wild populations during this same period (Jones, Wosniok & Hargreaves 2006). When mandatory treatment-trigger levels were established in 2004, an artificial cap on lice abundance was created. It is possible that inter-annual variations may be masked by the required treatments; however, the existence of a natural annual variation in the farmed salmon populations may be difficult to prove as long as the mandatory treatment regulations are in place.

As in Europe, *L. salmonis* levels in the Broughton Archipelago increase the longer the salmon are exposed in seawater (Bron, Sommerville, Jones & Rae 1991; Tully & Nolan 2002; Revie, Gettinby, Treasurer, Grant *et al.* 2002; Revie, Gettinby, Treasurer, Rae & Clarke 2002). The present study did find that the proportion of adult females of the total mobile *L. salmonis* was higher in Yr2 than Yr1 populations. However, because both ovigerous and non-ovigerous adult females were grouped together, it could not be determined whether the proportions of ovigerous females differed between the year classes or by season as it has been reported in Europe, where the highest abundance of ovigerous females on farmed salmon have been reported to occur in the winter months (Tully 1989; Wallace 1998).

The second species of louse *C. clemensi* observed on the farmed salmon during this study is not unlike *C. elongatus*, reported on farmed salmon in Europe and Eastern Canada, as it has a broad host range, infesting salmon as well as other economically important species such as herring *Clupea pallasii* (Valenciennes)

in BC (Kabata 1972; Johnson, Treasurer, Bravo, Nagasawa & Kabata 2004). It was observed in one small study (unpubl. obs.) that the inclusion of mobile *C. clemensi*, found detached in the anaesthetic tote, can increase the abundance estimates substantially, by up to 30% compared with <6% for mobile *L. salmonis* or chalimus stages. This suggests that pre-adult and adult *C. clemensi* are highly mobile and most likely move freely on and off farmed Atlantic salmon. As a result, enumerating lice found detached within the anaesthetic tote is essential in obtaining an accurate abundance estimate for mobile *C. clemensi*.

In this study, mobile *C. clemensi* levels fluctuated annually; the mean abundance in 2003 in Yr2 populations was significantly higher than in either 2004 or 2005. In 2003, mobile *C. clemensi* made up 42% of the total mobile lice observed. However, the overall abundance of *C. clemensi* was still lower than *L. salmonis* on both year classes of fish. Unlike *L. salmonis* levels, which tended to be higher on Yr2 populations than Yr1 populations throughout the study, mobile *C. clemensi* abundance levels do not appear to be a predilection to any year class; with higher levels being observed on Yr2 as compared with Yr1 populations in 2003. These findings differ from reports of infestation with *C. elongatus* in Scotland, where the levels are consistent from year to year and with higher abundance on Yr1 populations than Yr2 populations (Revie, Gettinby, Treasurer, Grant *et al.* 2002; Revie, Gettinby, Treasurer & Rae 2002; McKenzie, Gettinby, McCart & Revie 2004).

Differentiation of the attached chalimus stages of *L. salmonis* and *C. clemensi* are not accurate unless examined microscopically. Therefore, for the purpose of routine farm monitoring, all attached stages of both *L. salmonis* and *C. clemensi* were grouped into one category – chalimus. In this study, reported chalimus levels did not vary among the 3 years, nor did levels vary significantly between year classes. In 2003, although *L. salmonis* was the predominant species of louse (58% of total mobiles), samples collected from farmed salmon by BCMAL identified approximately 70% of the chalimus as *C. clemensi* species (S. Johnson, pers. comm.). The overall chalimus stage levels reported in the present study appear to be significantly lower than those reported for the *L. salmonis* chalimus observed in Scotland (Revie, Gettinby, Treasurer, Grant *et al.* 2002).

In Canada, there are only two products available for the treatment of sea lice: Calicide[®] (teflubenzuron, Nutreco Aquaculture) and Slice[®] (emamectin benzoate, Schering Plough Animal Health) available under

Emergency Drug release (EDR). The in-feed product, Slice[®], is the only therapeutant used for sea lice treatment in BC. In the present study, three important differences between BC and Europe were noted with respect to treatment: BC had a lower frequency of treatment required for lice control, the temporal pattern of treatment varied from that reported in Europe and there was a difference in the reported efficacy of the sea lice treatments between BC and Europe.

For the Broughton Archipelago area, there were only 1.6 lice treatments per production generation (i.e. smolt to harvest), with the average farmed salmon population residing in seawater almost 9 months (266 days) before requiring their first treatment. Most treatments were required to meet regulated trigger levels as opposed to fish health concerns from lice infection [pers. comm., Association of Aquaculture Veterinarians of BC (AAVBC)]. These are a fraction of the treatment levels reported by Revie, Gettinby, Treasurer and Rae (2002) in Scotland (2.1 and 6.5 farm⁻¹ year⁻¹ in Yr1 and Yr2 populations respectively) and Norway (> 2 farm⁻¹ year⁻¹ in Yr2 populations) (Heuch *et al.* 2003). It is recognized that the treatment options reported in Revie, Gettinby, Treasurer and Rae (2002) differ and were likely less efficacious from the ones presently available.

The majority of sea lice treatments on BC farms examined occurred in the winter and spring (between October and March); close to 75% of the treatments in Yr2 populations occurred during this time. Many of these farms treated salmon populations that were near or at harvest weights. Treatments were timed on these farms first, to make sure that the mean mobile *L. salmonis* abundance levels were below three for the start of the spring wild juvenile Pacific salmon outmigration in March and also to ensure that required treatment-withdrawal periods for Slice[®] (originally set at 21 days and increased to 68 days by Health Canada in October 2005) were met for the scheduled harvest dates. In contrast, over 50% of the treatments in Yr1 populations occurred during the second quarter (April–June) and again were based on maintaining levels below the trigger levels. In comparison, in Norway and Scotland, the majority of treatments occur in the summer and fall months (Heuch *et al.* 2003). In Scotland, there are no established treatment trigger levels; hence, treatment would be in response to fish health concerns with rising lice numbers. Norway has established trigger values, but current literature does not differentiate reasons for treatment in Norway.

Finally, the data in this study showed that the effects of the Slice treatment last up to 5 months follow-

ing treatment in BC. This is a substantially longer efficacy than in Europe and Eastern North America, where the reported duration of efficacy ranged from 43 days to 14 weeks (Armstrong, MacPhee, Katz & Endris 2000; Stone, Sutherland, Sommerville, Richards & Endris 2000; Stone, Sutherland, Sommerville, Richards & Varma 2000; Treasurer, Wallace & Dear 2002). It is clear from the length of the 'lice-free' period in BC and the generation time for lice reproduction at ambient water temperatures in BC, that re-infestation from within a farm following a site-wide treatment is unlikely. In addition, the majority of treatments in Europe and Eastern Canada occur to control *L. salmonis* for fish health reasons, as *L. salmonis* infestations have caused significant damage to farmed salmon, resulting in health and production problems (Wootton, Smith & Needham 1982; Armstrong *et al.* 2000; Fast, Ross, Mustafa, Sims, Johnson, Conboy, Speare, Johnson & Burka 2002; Johnson *et al.* 2004). Clinical damage associated with sea lice is rare in BC-farmed salmon and was not observed in this study (pers. comm., AAVBC).

Reasons for the differences observed in sea lice abundance levels and control in BC, compared with other regions, do not appear to be attributable to differences in production strategies, site locations or local water-chemistry parameters in the different regions. For example, with the exception of the two broodstock farms, the farms in the Broughton Archipelago operated as single-year class sites with no overlap between generations. This management practice is similar to Scotland, where 100% of production sites are single-year class (Heuch *et al.* 2003). The water temperature and salinity profiles in the Broughton Archipelago are also similar to those reported in Scotland and Norway (Heuch *et al.* 2003).

A major difference, however, between BC and the other regions is the dissimilarity in the number of wild salmonids and their role in the natural lifecycle of the parasite. Norway is considered to have the largest wild Atlantic salmon population in Europe, estimated at between 2 and 2.5 million salmon (Heuch & Mo 2001). In BC, the average annual catch values (the number of salmon reportedly caught by the commercial fisheries) for wild Pacific salmon between 1992 and 2002 were 15.1 million year⁻¹ (Irvine, Bijsterveld & Nagy 2003), six times greater than the entire estimated population of wild salmonids in Norway. Furthermore, several reports have described sea lice infestations, particularly *L. salmonis*, on adult wild Pacific salmon (Kabata 1979; Nagasawa, Ishida, Ogura, Toadokora & Hiramatsu 1993; Johnson, Blay-

lock, Elphick & Hyatt 1996; Nagasawa 2001; Beamish, Neville, Sweeting & Ambers 2005). Although sea lice are found on all species of Pacific salmon, pink salmon with their high naturally occurring lice abundances and, to a lesser extent, chum salmon *O. keta* (Walbaum) with their steady population size in the ocean, are considered important natural hosts for *L. salmonis* in the Pacific (Nagasawa 2001). A 7-year survey conducted by Nagasawa (2001) reported an average of 5.5 adult female *L. salmonis* per adult pink salmon. Therefore, returning wild adult salmon may be a significant source of sea lice on farms located in regions with large runs. In addition, *L. salmonis* has recently also been found on a non-salmonid species, the threespine stickleback *Gasterosteus aculeatus* (Linnaeus), commonly found year round in near-shore waters (Jones & Nemat 2004). It is uncertain what role these species may play in the abundance and occurrence of lice on wild salmonids.

Surprisingly however, even with the large natural reservoir of lice on wild Pacific salmon and other potential hosts, the salmon farming industry in BC has not been plagued with the clinical manifestations of sea lice reported in Europe and the east coast of North America (Wooten *et al.* 1982; Hogans 1995; Copley *et al.* 2001; Revie, Gettinby, Treasurer, Grant *et al.* 2002; Tully & Nolan 2002; Heuch *et al.* 2003). It is not clear why this is the case. However, a recent study that assessed genetic differences in *L. salmonis* across a broad geographical area reported that although there was no genetic difference in those collected from wild and farmed salmon from Scotland, Norway and Eastern Canada, there were genetic differences in the *L. salmonis* from these regions to those collected from BC (Todd, Walker, Ritchie, Graves & Walker 2004). At this time it would be impossible to ascertain whether the differences in *L. salmonis* abundance reported in this study could be attributed to the small genetic variability; however, further work into differences in pathogenicity and/or host preference/specificity should be pursued.

Concerns have been raised by Heuch, Bjorn, Finstad, Holst, Asplin and Nilsen (2005) about the accuracy of the Norwegian farm sea lice data due to infrequent or no government auditing. In BC, the BCMAL established a quarterly programme where 25% or 50% of the industry would be selected to be audited for sea lice. As a result of the random selection process, between 13% and 44% of all the active farms located in the Broughton Archipelago study area were audited quarterly in 2004/2005 by government fish health personnel. The definition of active

farms used by BCMAL for its audit programme did not include farms with salmon populations <1 month in seawater or brood stock farms, but these were included in the industry-reported data. This discrepancy in the definition of active farms may provide an explanation to the lower-than-expected percentage of audits in the region during some quarters. Comparison of audit data with the industry-supplied data showed that there was no significant difference in the majority of the comparisons. Where significant differences were observed, the majority of abundance estimates provided by the industry were actually higher than the levels determined by BCMAL. This provides strong evidence that the sea lice levels reported by the industry are not an under-reporting but rather a valid reflection of the lice levels on farms in the Broughton Archipelago.

While there are some similarities of infestation patterns in BC with those observed in Europe and Eastern Canada such as higher lice loads on older fish groups, total sea lice abundance and overall infestation patterns in BC are not reflective of those observed on Atlantic salmon in other areas. Not only are sea lice levels on farmed salmon in BC lower, but the pathogenic impact of *L. salmonis* appears less. Sea lice levels can also be controlled with significantly fewer treatments. Even though the identical louse species (*L. salmonis*) on the same farmed salmon species (Atlantic salmon) are being examined, there are clear differences in pathology and control efficacy. This suggests that the European literature on the topic may not be directly applicable to the BC situation and illustrates the importance of conducting proper and relevant research in BC.

Acknowledgments

The authors would like to acknowledge the funding for this project provided by Aquaculture Collaborative Research and Development Programme (ACRDP), Fisheries and Oceans Canada, the British Columbia Salmon Farmers Association BCSEA, Heritage Salmon and Stolt Sea Farm. The authors would like to thank Lee Beile, Brad Boyce and Peter McKenzie for their assistance in collecting the farm data; Maria Coombs and Chris Diamond for collecting the audit data; the Association of Aquaculture Veterinarian of BC (AAVBC) and Stewart Johnson for information used in the manuscript and Alisdair McVicar, Richard Beamish, Chryst Neville, Rusty Sweeting, Darlene Hanson, Mia Parker, Barbara Nowak and

Crawford Revie for their comments and suggestions during the preparation of the manuscript.

References

- Armstrong R., MacPhee D., Katz T. & Endris R. (2000) A field efficacy evaluation of emamectin benzoate for the control of sea lice on Atlantic salmon. *Canadian Veterinary Journal* **41**, 607–612.
- Beamish R.J., Neville C.M., Sweeting R. & Ambers N. (2005) Sea lice on adult Pacific salmon in the coastal water of Central British Columbia, Canada. *Fisheries Research* **76**, 198–208.
- British Columbia Ministry of Agriculture and Lands (BCMAL) (2005) *Monitoring Program* <http://www.agf.gov.bc.ca/fisheries/health/sealice/MS.htm> (retrieved February 2006).
- British Columbia Salmon Farmers Association (BCSFA) (2002) *Production values* <http://www.agf.gov.bc.ca/fish.stats/pdf/SeafoodIndustry.YIR.2002.pdf> (retrieved February 2006).
- Bron J.E., Sommerville C., Jones M. & Rae G.H. (1991) Settlement and attachment of early stages of the salmon louse, *Lepeophtheirus salmonis* (Copepoda: Caligidae) on the salmon host, *Salmo salar*. *Journal of Zoology* **224**, 201–212.
- Copley L., McCarney P., Jackson D., Hassett D., Kennedy S. & Nulty C. (2001) The occurrence of sea lice (*Lepeophtheirus salmonis* Koyer) on farmed salmon in Ireland (1995 to 2000). In: *Marine Resources Series. No 127* p. 14. Marine Institute, Galway, Ireland.
- Fast M.D., Ross N.W., Mustafa A., Sims D.E., Johnson S.D., Conboy G.A., Speare D.J., Johnson G. & Burka J.E. (2002) Susceptibility of rainbow trout *Oncorhynchus mykiss*, Atlantic salmon *Salmo salar* and coho salmon *Oncorhynchus kisutch* to experimental infection with sea lice *Lepeophtheirus salmonis*. *Diseases of Aquatic Organisms* **52**, 57–68.
- Groot C. (1996) Salmonid life histories. In: *Principles of Salmonid Culture. Developments in Aquaculture and Fisheries Science*, Vol. 29 (ed. by W. Pennell & B.A. Barton), pp. 97–218. Elsevier Science B.V., Amsterdam, the Netherlands.
- Heuch P.A. & Mo T.A. (2001) A model of salmon louse production in Norway: effects of increasing salmon production and public management measures. *Diseases of Aquatic Organisms* **45**, 145–152.
- Heuch P.A., Revie C.W. & 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., Bjørn P.A., Finstad B., Holst J.C., Asplin L. & Nilsen E. 2005 A review of the Norwegian 'National Action plan against salmon lice on salmonids': the effect on wild salmonids. *Aquaculture* **246**, 79–92.
- Hogans W.E. (1995) *Infection dynamics of sea lice (Lepeophtheirus salmonis) (Copepoda: Caligidae) parasitic on Atlantic salmon (Salmo salar) cultured in marine waters of the lower Bay of Fundy*. Canadian Technical Report of Fisheries and Aquatic Sciences, No. 2067, 14pp.
- Irvine J.R., Bijsterveld L. & Nagy L. (2003) *An update on catch trends for Pacific salmon in British Columbia Canada*. North Pacific Anadromous Fish Commission, Document 709, 14pp.
- Johnson S.C., Blaylock R.B., Elphick J. & Hyatt K.D. (1996) Disease induced by the sea louse (*Lepeophtheirus salmonis*) (Copepoda: Caligidae) in wild sockeye salmon (*Oncorhynchus nerka*) stocks in Alberni Inlet, British Columbia. *Canadian Journal of Fisheries and Aquatic Sciences* **53**, 2888–2897.
- Johnson S.C., Treasurer J.W., Bravo S., Nagasawa K. & Kabata Z. (2004) A review of the impact of Parasitic Copepods on Marine Aquaculture. *Zoological Studies* **43**, 229–243.
- Jones S. & Némec A. (2004) *Pink salmon action plan: sea lice on juvenile salmon and on some non-salmonid species in the Broughton Archipelago in 2003*. Canadian Science Advisory Secretariat Research Document 2004/105. Fisheries and Oceans Canada, Ottawa, Canada, 87pp. ISSN 1499-3848.
- Jones S.R.M., Wosniok W. & Hargreaves N.B. (2006) *The salmon louse Lepeophtheirus salmonis on salmonid and non-salmonid fishes in British Columbia*. Proceedings of the 11th Symposium of the International Society for Veterinary Epidemiology and Economics, Cairns, Australia: ISVEE 11, 1131, 2006.
- Kabata Z. (1972) Developmental stages of *Caligus clemensi* (Copepoda: Caligidae). *Journal of the Fisheries Research Board of Canada* **29**, 1571–1593.
- Kabata Z. (1979) *Parasitic Copepods of British Fishes*, No. 152. The Ray Society, London, 468pp.
- McKenzie E.G., Gettinby G., McCart K. & Revie C.W. (2004) Time series models of sea lice *Caligus elongatus* (Nordmann) abundance on Atlantic salmon *Salmo salar* L. in Loch Sunart, Scotland. *Aquaculture Research* **35**, 764–772.
- Morton A., Routledge R., Peet C. & Ladwig A. (2004) Sea lice (*Lepeophtheirus salmonis*) infection rates on juvenile pink (*Oncorhynchus gorbuscha*) salmon in the nearshore marine environment of British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences* **61**, 147–157.
- Nagasawa K. (2001) Annual changes in the population size of the salmon louse *Lepeophtheirus salmonis*, (Copepoda: Caligidae) on high-seas Pacific Salmon (*Oncorhynchus* spp.) and relationship to host abundance. *Hydrobiologia* **453/454**, 411–416.
- Nagasawa K., Ishida Y., Ogura M., Toadokora K. & Hiramatsu K. (1993) The abundance and distribution of *Lepeophtheirus salmonis* (Copepoda: Caligidae) on six species of Pacific salmon in offshore water of the North Pacific Ocean and Bering Sea. In: *Pathogens of Wild and Farmed Fish: Sea Lice* (ed. by G.A. Boxshall & D. De-

- faye), pp. 166–178. Ellis Horwood, Chichester, West Sussex, UK.
- O'Donohoe P., Kennedy S., Kane E., Naughton O., Tierney D. & Jackson D. (2005) *National Survey of Sea Lice (Lepeophtheirus salmonis Kroyer and Caligus elongatus Nordmann) on Fish Farms in Ireland – 2004, Leaflet B22*. Marine Institute, Galway, Ireland pp. 1–33.
- Revie C.W., Gettinby K., Treasurer J.W., Grant A.N. & Reid S.W.J. (2002) Sea lice infestation on farmed Atlantic salmon in Scotland and the use of ectoparasitic treatments. *The Veterinary Record* **151**, 753–757.
- Revie C.W., Gettinby K., Treasurer J.W. & Rae G.H. (2002) The epidemiology of the sea lice, *Caligus elongatus* Nordmann, in marine aquaculture of Atlantic salmon, *Salmo salar* L., in Scotland. *Journal of Fish Diseases* **25**, 391–399.
- Revie C.W., Gettinby K., Treasurer J.W., Rae G.H. & Clark N. (2002) Temporal, environmental and management factors influencing the epidemiological patterns of sea lice, *Lepeophtheirus salmonis* infestations on farmed Atlantic salmon, *Salmo salar* L., in Scotland. *Pest Management Science* **58**, 576–584.
- Stone J., Sutherland I.H., Sommerville C., Richards R.H. & Endris R.G. (2000) The duration of efficacy following oral treatment with emamectin benzoate against infestations of sea lice, *Lepeophtheirus salmonis* (Kroyer), in Atlantic salmon *Salmo salar* L. *Journal of Fish Diseases* **23**, 185–192.
- Stone J., Sutherland I.H., Sommerville C., Richards R.H. & Varma K.J. (2000) Commercial trials using emamectin benzoate to control sea lice *Lepeophtheirus salmonis* infestations in Atlantic salmon *Salmo salar*. *Diseases of Aquatic Organisms* **41**, 141–149.
- Todd C.D., Walker A.M., Ritchie M.G., Graves J.A. & Walker A.E. (2004) Population genetic differentiation of sea lice (*Lepeophtheirus salmonis*) parasitic on Atlantic and Pacific salmonids: analysis of microsatellite DNA variation among wild and farmed hosts. *Journal of Fisheries and Aquatic Sciences* **61**, 1176–1190.
- Treasurer J.W. & Pope J.A. (2000) Selection of host sample number and design of a monitoring programme for ectoparasitic sea lice (Copepoda: Caligidae) on farmed Atlantic Salmon Aquaculture. *Aquaculture* **187**, 247–260.
- Treasurer J.W., Wallace C. & Dear G. (2002) Control of sea lice on farmed Atlantic salmon *S. salar* L. with oral treatment Emamectin benzoate (SLICE). *Bulletin of the European Association of Fish Pathologists* **22**, 375–380.
- Tully O. (1989) The succession of generations and growth of the caligid copepods *Caligus elongatus* and *Lepeophtheirus salmonis* parasitising farmed Atlantic salmon smolts (*Salmo salar* L.). *Journal of the Marine Biological Association of the United Kingdom* **69**, 279–287.
- Tully O. & Nolan D.T. (2002) A review of the population biology and host-parasite interaction of the sea louse (*Lepeophtheirus salmoni*) (Copepoda: Caligidae). *Parasitology* **124**, S165–S182.
- Wallace C. (1998). *Possible causes of salmon lice Lepeophtheirus salmonis (Kroyer, 1837) infestations on farmed Atlantic salmon, Salmo salar L., in a western Norwegian fjord-situated fish farms: implications for the design of regional management strategies*. Candidatus Scientiarum Thesis, University of Bergen, Norway.
- Wootton R., Smith J.W. & Needham E.A. (1982) Aspects of the biology of the parasitic copepods *Lepeophtheirus salmonis* and *Caligus elongatus* on farmed salmonids and their treatment. *Proceedings of the Royal Society of Edinburgh*. **81B**, 185–197.