North American Journal of Fisheries Management 27:187–197, 2007

DOI: 10.1577/M06-043.1

[Article]

Estimated Sea Louse Egg Production from Marine Harvest Canada Farmed Atlantic Salmon in the Broughton Archipelago, British Columbia, 2003–2004

CRAIG ORR*
Watershed Watch Salmon Society, Coquitlam, British Columbia V3K 3B7, Canada

Abstract.—Recent infestations of sea lice *Lepeophtheirus salmonis* on wild juvenile pink salmon *Oncorhynchus gorbuscha* and subsequent declines in the number of returning adult pink salmon have raised concern for the health of wild fish relative to salmon farming activities in the Broughton Archipelago, British Columbia. I used available (but limited) industry data to estimate sea louse egg production from Atlantic salmon *Salmo salar* farmed by Stolt Sea Farm (now Marine Harvest Canada, Inc., Campbell River, British Columbia) in 2003 and 2004. The 12 active farms contained between 1 and 5 million Atlantic salmon during the 2 years and about 800,000 fewer mature salmon at the start of 2003 than in 2004. Sea louse egg production peaked during winter–spring in both years prior to the seaward migration period of the area's small and vulnerable juvenile pink salmon and chum salmon *O. keta*. Marine Harvest Canada salmon hosted over 6 million gravid sea lice that produced 1.6×10^9 eggs during 2 weeks in the winter of 2003–2004. Only half as many eggs were produced from the fewer hosts present during this period in 2003. Sea lice on farmed fish were further reduced to near zero each year through multiple uses of emamectin benzoate (Slice). Fewer farmed Atlantic salmon and sea lice in 2003 coincided with lower abundance and prevalence of *L. salmonis* on juvenile pink salmon and chum salmon near farms. A recent agreement between industry and conservationists may help improve data quality, our understanding of the dynamics sea louse–salmon interactions, and our chances of conserving wild salmon.

Millions of salmon (mainly Atlantic salmon *Salmo salar*) are cultured annually in the world (Naylor et al. 2003). In Europe, farmed Atlantic salmon now outnumber wild Atlantic salmon by nearly 50:1 (Porter 2003). Consequently, farmed Atlantic salmon are now a major year-round host and producer of parasitic sea lice (mainly *Lepeophtheirus salmonis*) in the world's coastal marine waters (Tully and Whelan 1993; Holst et al. 2000, 2003; Heuch and Mo 2001; Butler 2002; Naylor et al. 2003; Morton et al. 2004; Heuch 2005; Heuch et al. 2005). Farmed Atlantic salmon now produce 78–97% of all sea lice in Scottish waters (Butler 2002) and similar levels have been documented in Ireland (Tully and Whelan 1993) and Norway (Heuch and Mo 2001).

For over a decade, farmed Atlantic salmon have been implicated in sea louse outbreaks on juvenile wild salmonids (Tully and Whelan 1993; Tully et al. 1999; Holst et al. 2000, 2003; Heuch and Mo 2001; Bjørn and Finstad 2002; Butler 2002; Morton et al. 2004, 2005; Heuch 2005; Heuch et al. 2005; Krkosek et al. 2005). Farmed fish hosting even small numbers of lice per individual can collectively produce large numbers of louse eggs and infectious larvae during the spring, precisely when juvenile salmonids leave natal rivers and enter coastal waters (Heuch and Mo 2001; Heuch et al. 2005). Heuch and Mo (2001) estimated that Norway's farmed Atlantic salmon produced nearly 1.45×10^{11} eggs in 1990 during the critical 2-month (April–May) spring migration of juveniles.

Parasitism of juvenile salmon in coastal waters is now one of the world's major resource policy and management challenges (Jackson et al. 1997; PFRCC 2002; Naylor et al. 2003; Dill and Pauly 2004; Morton et al. 2004; Heuch 2005; Heuch et al. 2005). In Canada, this issue garnered substantial attention after the first reported sea louse outbreak on juvenile pink salmon *Oncorhynchus gorbuscha*—and a subsequent major decline in returning adult pink salmon—in the Broughton Archipelago (Figure 1) area of British Columbia (PFRCC 2002; Morton and Williams 2004; Morton et al. 2004). After scrutiny focused on the 28 fish farm tenures distributed along the probable migration route of the area's emigrating juvenile salmon and on management policy (PFRCC 2002), the government announced a one-time "sea lice action plan" of early harvesting and partial fallowing of farmed fish in 2003 (MAFF 2003).

It seems logical that our ability to understand and minimize parasitism events can be improved by examining the dynamics of sea lice on nearby farmed fish (Heuch and Mo 2001; Revie et al. 2002;

* E-mail: corr@telus.net

Received February 3, 2006; accepted May 1, 2006
Published online February 19, 2007

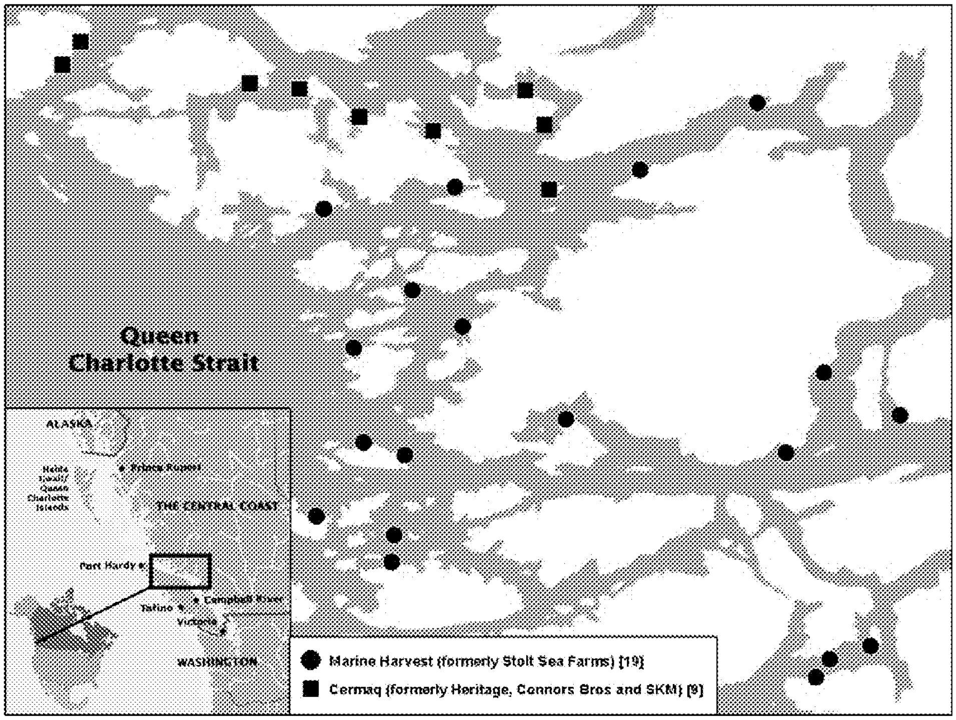

FIGURE 1.—Map of Atlantic salmon farm tenures in the Broughton Archipelago, British Columbia (modified from Living Oceans Society 2003).

McKibben and Hay 2004). However, information on numbers of cultured fish and sea lice in British Columbia is typically not made available. In September 2004, Stolt Sea Farm (now Marine Harvest Canada, Inc., Campbell River, British Columbia) became the first and only aquaculture company operating in British Columbia to publicly share data on fish and sea louse numbers (available at www.marineharvestcanada-westcoast.com). By following the methods of Heuch and Mo (2001) and Butler (2002), I examined those data (and the data limitations) for the 2 years (2003 and 2004) for which data were initially reported, and here I portray sea louse production on these active farms relative to numbers of cultured fish, management actions, and observed louse infestations on the area's juvenile salmon.

Methods

Study Site

The Broughton Archipelago consists of several hundred islands between northeastern Vancouver Island and British Columbia's mainland (Figure 1). The area's seven primary rivers may annually sustain returns of 3 million or more wild adult pink salmon (even-year dominance) as well as lesser numbers of the other five Pacific salmon species (PFRCC 2002; Morton et al. 2005). The archipelago hosts 28 (22%) of British Columbia's 129 Atlantic salmon farm tenures (PFRCC 2002; Statistics Canada 2004); 19 of them are leased by Marine Harvest Canada and 9 are leased by Mainstream Canada (Tofino, British Columbia; formerly Heritage Aquaculture, Ltd., Connors Brothers, Ltd., and SKM Enterprises). Data for sea louse and farmed Atlantic salmon numbers have not been made available by Mainstream Canada; thus, these farms were not included in the analysis.

Model Description

The model (Figure 2) was modified from Heuch and Mo (2001) and generated twice-monthly estimates of several biological parameters for Marine Harvest Canada operations in 2003 and 2004: (1) farmed Atlantic salmon abundance; (2) escaped farmed Atlantic salmon abundance; (3) gravid (egg-bearing)

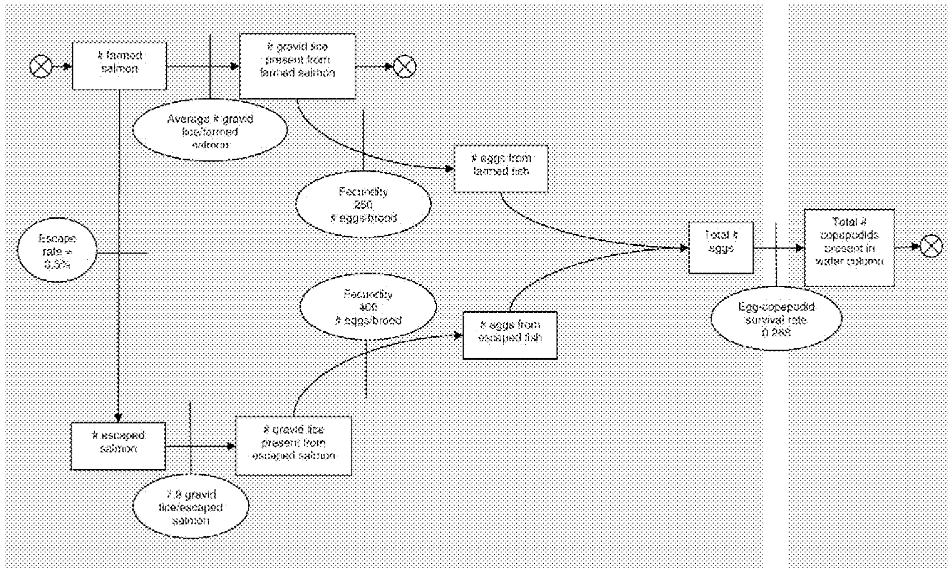

FIGURE 2.—Diagram of the model used to calculate sea louse production at Atlantic salmon farm tenures in the Broughton Archipelago, British Columbia (after Heuch and Mo 2001), in 2003 and 2004.

sea louse abundance on farmed fish; (4) gravid sea louse abundance on escaped farmed Atlantic salmon; and (5) sea louse egg production.

Assumptions

Farmed fish abundance.—Marine Harvest Canada first provided data in September 2004 on numbers of fish present per farm, generally in biweekly intervals, for January 2003 to August 2004 (available at www.marineharvestcanada-westcoast.com). Some data gaps existed, and to allow the portrayal of continuous estimates of sea louse production I estimated some numbers by interpolating from numbers before and after that time period. Where used, estimates are printed in bold.

Leakage rate of escaped Atlantic salmon.—The model assumes a continuous farmed Atlantic salmon "leakage rate" of 0.5%, the conservative end of the range (0.5–1.0%) reported by Lough and Law (1995) and Alverson and Ruggerone (1997).

Wild salmon abundance.—Wild salmon are normally abundant in the Broughton Archipelago during the fall (PFRCC 2002), but in late winter and spring the majority of British Columbia's wild salmon (i.e., potential sea louse hosts) resides in offshore waters (Groot and Margolis 1991); recent surveys in the Broughton Archipelago have also failed to locate concentrations of more than a few hundred adult salmon in the winter–spring (R. M. Sweeting, Institute for Ocean Sciences, unpublished). I estimated numbers of sea lice on returning wild adult salmon (based on Beamish et al. 2005 and DFO 2006), but wild salmon do not appear to be sea louse hosts of concern in spring and, thus, adult wild salmon are not included in the model.

Sea louse abundance.—The model uses the abundance of gravid sea lice on Atlantic salmon in active Marine Harvest Canada farms from January 14, 2003, to August 24, 2004. These numbers are reported as averages of gravid sea lice per fish; raw data and variation were not provided in online data sets.

Data were entered into the model in 2-week intervals (week 1: days 1–14; week 2: days 15–30 or 31), even though data were not always collected in regular intervals. Where two gravid sea louse counts were provided for one 14-d interval, the value used is an average of the two gravid sea louse counts, except when the second count occurred within 3 d of the end of a 14-d interval, and the subsequent interval did not have a gravid sea louse count. In this case, the second count from the first time interval was substituted for the missing count in the second time interval. Where data gaps existed, louse abundance was estimated as with Atlantic salmon, thus providing continuous data for gravid sea lice.

The average number of gravid sea lice per farmed fish was calculated by adding the number of sea lice per fish reported for each farm and dividing the total by the number of farms reporting data in that time period (e.g., if only farms A, D, and F reported the number of lice per fish for a given period, the calculation would be [farm A + farm D + farm F]/3). Total number of gravid sea lice on farmed fish was calculated for each farm by multiplying the number of fish by the number of lice per fish and then adding totals from each farm (e.g., [farm A fish × farm A lice per fish] + [farm B fish × farm B lice per fish], etc.). If no lice were reported, it was assumed that the farm's contribution to the total number of gravid sea lice was zero.

Sea louse fecundity.—Tully and Whelan (1993) found that sea lice on wild salmon had twice as many eggs as lice infecting farmed Atlantic salmon, mainly owing to the larger size of female lice on wild fish. I used a conservative published value of 250 eggs/louse for farmed Atlantic salmon to avoid overestimating fecundity and production. I used 400 eggs/louse for escaped farmed Atlantic salmon, a number in the upper range of values (and assumed to be equivalent to that of wild salmon) to avoid underestimating the contribution of escaped farmed Atlantic salmon to total sea louse production (Heuch and Mo 2001). These numbers are consistent with observations reported by Johnson and Albright (1991; 251–423 eggs/louse on farmed Atlantic salmon, farmed Chinook salmon *O. tshawytscha*, and wild Chinook salmon), Ritchie et al. (1993; 294–492 eggs/louse on farmed Atlantic salmon), and Tully and Whelan (1993; 251–583 eggs/louse on farmed Atlantic salmon and 977 eggs/louse on wild Atlantic salmon). While louse fecundity also varies seasonally (Ritchie et al. 1993), limited temperature data and limited information on the specific relationship between temperature and louse fecundity prevented a reasonable estimate of seasonal variation in the model's output. However, since the seasonal louse fecundity range reported by Ritchie et al. (1993) is higher than the 250 eggs/sea louse used in this study, a conservative estimate of sea louse production is maintained.

Abundance of gravid female sea lice per escaped farmed fish.—Given the lack of Broughton Archipelago-specific data, the model uses published values of 7.9 gravid sea lice per escaped farmed fish (Todd et al. 2000; Butler 2002).

Sea louse egg-to-copepodid survival (first infectious molt).—Heuch and Mo's (2001) model estimates the production of infectious copepodids using published egg-to-copepodid survival rates and temperature-dependent development times (Johnson and Albright 1991; Boxaspen and Næss 2000). No attempt was made to estimate the variation in copepodid production and survival for the Broughton Archipelago because of limited site-specific environmental data and the large variability in survival reported by Johnson and Albright (1991; 0.0–59.5%). For discussion purposes only, a rough estimate of total copepodid production was calculated using the average egg-to-copepodid survival rate of 0.268 reported by Johnson and Albright (1991).

Results

Farmed Atlantic Salmon and Gravid Sea Lice

Marine Harvest Canada (2004) provided an 18-month history of adult and smolt (immature) farmed Atlantic salmon abundance (Tables 1, 2) and counts of gravid sea lice (averages per fish; Table 3) for 12 of its farms in 2003 and 10 of its farms in 2004. Five farms containing 2.23 million adult Atlantic salmon were active at the beginning of 2003 (January 14; Table 2). Eight farms active at the start of 2004 had a total of 3 million adults and 489,000 smolts (Figure 3; Table 2). The total number of adult Atlantic salmon and smolts varied between 1,043,107 (August 31, 2004) and 5,198,568 (July 14, 2003), was generally lowest at the beginning of each year, peaked in July 2003 and May–June 2004, and declined as fish were harvested (Table 2; Figure 3).

Marine Harvest Canada's farm history reflects several management actions taken early in 2003 to comply with provisions of the sea lice action plan that was announced on February 7, 2003 (MAFF 2003) and designed mainly to reduce sea louse numbers in the Fife-Tribune Channel used by juvenile salmon (MAFF 2003; Morton et al. 2005). One farm (Wicklow Point; Table 2) was harvested and fallowed on February 3, 2003, while four others stocked with adult Atlantic salmon at the beginning of 2003 (Arrow Passage, 215,000; Blunden Passage, 584,000; Doctor Islets, 287,000; and Midsummer Island, 257,000 [transferred from Larsen and Blunden Passage]) were harvested and then fallowed between May 4 and July 23. Three other farms (Humphrey Rock, Larsen Island, and Sargeaunt Pass; Table 2) contained no adult fish at the beginning of 2003 and were stocked with smolts between February 16 and April 14.

Sea louse counts varied substantially when comparing immature and mature or adult fish. Four farms (Humphrey Rock, Larsen Island, Sargeaunt Pass, and Wicklow Point; Tables 2, 3) provided fish stocking and sea louse count data, suggesting that farmed fish did not host noticeable numbers of lice (Table 3) until they had been in marine pens for 168–214 d (average = 201 d). Certain individual farms containing mature or "adult" Atlantic salmon (that is, fish that had been in pens for nearly 200 d or more) reported highest numbers of gravid lice early in each year (averages only; Table 3).

TABLE 1.—Summary of stocking and harvesting at Marine Harvest Canada.

Date	Site	Disposition
Feb 3, 2003	Wicklow Point	Harvested and fallowed
Feb 6, 2003	Midsummer Island	Transfered from Larsen Island and Blunden Passage
Feb 6, 2003	Potts Bay	Transferred from Wicklow Point and Midsummer Island
Feb 16, 2003	Larsen Island	Stocked
Mar 9, 2003	Sargeaunt Pass	Stocked
Mar 22, 2003	Potts Bay	Transferred from Midsummer Island
Apr 14, 2003	Humphrey Rock	Stocked
May 4, 2003	Midsummer Island	Harvested and fallowed
May 23, 2003	Arrow Pass	Harvested and fallowed
May 23, 2003	Doctor Islets	Harvested and fallowed
Jun 9, 2003	Potts Bay	Transfered from Wicklow Point and Midsummer Island
Jun 15, 2003	Potts Bay	Partial harvest
Jul 20, 2003	Blunden Point	Transfered and fallowed
Jul 20, 2003	Glacier Falls	Transferred from other farms
Aug 17, 2003	Port Elizabeth	Partial harvest
Oct 21, 2003	Potts Bay	Transferred fish out
Nov 16, 2003	Swanson Island	Partial harvest
Dec 14, 2003	Larsen Island	Transfered and fallowed
Dec 14, 2003	Midsummer Island	Transfered from Larsen Island
Dec 15, 2003	Wicklow Point	Restocked
Feb 18, 2004	Larsen Island	Restocked
Feb 29, 2004	Potts Bay	Transfered from Swanson Island
Mar 14, 2004	Potts Bay	Transferred from Port Elizabeth
Mar 18, 2004	Swanson Island	Harvested and fallowed
Apr 2, 2004	Doctor Islets	Restocked
Apr 25, 2004	Port Elizabeth	Harvested and fallowed
Jun 7, 2004	Potts Bay	Partial harvest
Jun 23, 2004	Glacier Falls	Partial harvest
Jul 19, 2004	Sargeaunt Pass	Partial harvest

Potts Bay reported averages of 6–8 gravid (as opposed to adult) lice/farmed fish between February 14 and March 31, 2003, while Midsummer Island and Arrow Passage reported averages exceeding 3 lice/fish. Average numbers of gravid individuals ranged from 2.2 to 9.2 lice/fish in the late winter–early spring of 2003 and 2004 on Swanson Island, Gilford Island, and Potts Bay farms (Table 3). Trends in average and total estimated gravid sea louse numbers are shown in Figures 3 and 4. Collectively (all fish and all farms combined), farmed fish hosted an estimated peak abundance of 6 million gravid lice on December 31, 2003.

In addition to harvesting fish, Stolt Sea Farm also medicated Atlantic salmon with emamectin benzoate (Slice) on several farms that contained high numbers of sea lice (Figure 3). Slice is effective against lice (Stone et al. 2000; SPAH 2001) and is currently preferred as a treatment in Canada and elsewhere (SPAH 2001; Bright and Dionne 2004). Treatments reduced reported louse levels to zero or near zero during each year (Table 3; Figure 3). Five additional Slice treatments were also administered to Atlantic salmon on five farms between May 14 and June 21, 2004, despite relatively low louse numbers.

Wild Salmon and Gravid Sea Lice

As reported, there were too few wild salmon in winter–spring to reliably estimate this cohort's contribution of gravid sea lice. However, contributions of lice from returning salmon in the fall may have been seasonally significant. Based on Beamish et al.'s (2005) reported average of 51.1 lice/adult pink salmon (6% gravid lice) returning to the Queen Charlotte Strait and reported escapements in 2003 (about 200,000) and 2004 (about 1 million; DFO 2006), wild pink salmon potentially introduced approximately 600,000 gravid sea lice to coastal waters in 2003 and 3 million in 2004.

Estimated Sea Louse Egg and Copepodid Production

Estimated sea louse egg production in 2003 from all farms combined was highest in January–February and November–December (Figure 4). According to the model, active farms produced approximately 800 million sea louse eggs on January 31 and February 14. Numbers were near zero on May 31 (less than estimated egg numbers from sea lice on escaped farm fish) and approximately 1.4×10^9 and 1.6×10^9 eggs on November 14, 2003, and December 31, 2003, respectively (Figure 4). Egg production was approximately 100 million on April 30, 2004, and increased to nearly 440 million on May 14 before settling between biweekly estimates of approximately 100–400 million through June, July, and August 2004 (when reporting stopped; Figure 4). Thus, overall production of eggs at the beginning of 2003 (with 800,000 fewer farmed Atlantic salmon hosts) was about half the production

TABLE 2.—Total number of farmed Atlantic salmon reported at Marine Harvest Canada farms in 2003 and 2004 and adjusted to the time series used in this study. Values in bold italics are estimates.

Date	Blunden Passage	Arrow Passage	Doctor Islets	Glacier Falls	Humphrey Rock	Larsen Island	Swanson Island	Port Elizabeth	Potts Bay
Jan 14, 2003	***584,888***	215,754	***287,076***				571,358	574,165	
Jan 31, 2003	584,888	215,709	287,076				571,020	574,085	
Feb 14, 2003	696,328	***215,650***	***286,540***				***570,725***	573,952	26,626
Feb 28, 2003	***693,137***	215,591	286,003				570,429	570,526	***26,525***
Mar 14, 2003	689,946	215,473	227,182			767,936	560,173	577,771	***26,423***
Mar 31, 2003	682,336	215,431	151,097			807,029	570,092	577,582	26,322
Apr 14, 2003	676,503	215,357	113,116		0	***880,996***	569,820	577,435	29,918
Apr 30, 2003	673,575	215,071	112,838		25,936	954,963	569,651	577,271	29,898
May 14, 2003	671,584	214,968	50,668		638,576	945,520	569,538	577,096	29,870
May 31, 2003	669,484	214,749	0		634,299	936,133	569,254	577,301	29,844
Jun 14, 2003	662,747	214,399			633,339	928,436	568,928	570,851	29,817
Jun 30, 2003	660,632	***202,537***			630,567	923,994	567,913	570,480	29,626
Jul 14, 2003	659,493	***190,674***		655,980	625,131	917,877	557,606	570,079	29,570
Jul 31, 2003	0	178,812		***655,560***	***618,466***	914,950	550,327	***569,593***	23,123
Aug 14, 2003		0		655,140	611,801	911,086	548,430	569,107	6,704
Aug 31, 2003				654,739	***610,923***	***908,989***	***542,645***	***560,197***	***6,638***
Sep 14, 2003				654,544	***610,046***	906,891	***536,861***	***551,288***	***6,572***
Sep 30, 2003				***654,140***	609,168	***906,432***	***531,835***	542,378	6,506
Oct 14, 2003				***653,737***	***608,841***	***905,973***	***525,291***	***495,572***	***6,148***
Oct 31, 2003				653,333	608,514	905,514	519,507	448,766	5,789
Nov 14, 2003				***653,128***	608,243	747,026	518,926	***429,590***	5,570
Nov 30, 2003				652,923	***608,153***	***747,026***	505,693	410,413	***5,536***
Dec 14, 2003				***652,200***	***608,063***	0	***428,751***	356,394	5,501
Dec 31, 2003				651,476	607,973		351,809	***337,863***	***4,249***
Jan 14, 2004				***651,311***	607,526		***350,286***	***319,331***	***2,997***
Jan 31, 2004				651,145	***606,764***	0	348,763	300,800	1,745
Feb 14, 2004				650,843	606,001	***40,666***	***277,181***	***266,020***	***15,286***
Feb 28, 2004				***650,557***	***605,672***	40,666	205,598	231,239	28,827
Mar 14, 2004			0	650,270	605,343	***123,562***	69,054	220,510	***33,329***
Mar 31, 2004			***63,508***	649,857	605,064	206,458	0	***158,712***	37,831
Apr 14, 2004			63,508	649,180	604,525	***589,887***		***96,914***	37,791
Apr 30, 2004			298,619	648,320	604,130	973,316		35,116	37,368
May 14, 2004			678,998	647,832	603,135	1,120,665		0	37,283
May 31, 2004			673,271	647,386	602,503	1,112,317			37,076
Jun 14, 2004			671,836	646,794	600,436	1,093,625			29,035
Jun 30, 2004				640,580	599,727	1,082,434			15,803
Jul 14, 2004				634,918	***601,279***	1,071,500			***10,736***
Jul 31, 2004				632,796	602,831	1,067,912			5,669
Aug 14, 2004				***627,289***	599,253				***5,647***
Aug 31, 2004				621,782					5,625

from farmed Atlantic salmon at the start of 2004. An estimated total of approximately 4.0×10^9 copepodids were produced throughout the 2003–2004 study period.

Discussion

Infestations of sea lice occur regularly on juvenile wild salmonids in coastal marine waters containing Atlantic salmon farms (Tully and Whelan 1993; Holst et al. 2000, 2003; Bjørn et al. 2001; Heuch and Mo 2001; Bjørn and Finstad 2002; Butler 2002; McKibben and Hay 2004; Morton et al. 2004, 2005; Heuch 2005; Heuch et al. 2005; Krkosek et al. 2005). British Columbia's juvenile salmon are the latest of the world's wild salmon to exhibit such infestations, having high sea louse infections observed every spring since 2001 in the Broughton Archipelago's actively farmed waters (Morton and Williams 2004; Morton et al. 2004, 2005; Krkosek et al. 2005).

Stolt Sea Farm became the first aquaculture company operating in British Columbia to publicly share information on sea lice and farmed Atlantic salmon. There are clearly limitations in the data provided. Numbers of sea lice reported by industry are averaged for each farm, which limits assessment of patchiness or variability. Some gaps exist in online information sets, and there are few data for the entire smolt-to-adult phase of farmed fish. Nevertheless, and especially considering the total lack of farm-source data before 2003, these numbers are sufficiently robust to suggest that sea louse egg production from Atlantic salmon cultured in Stolt Sea Farm's 10–12 farms active in 2003 and 2004 was substantial and varied with fish numbers, seasonally, and as a result of management actions.

TABLE 2.—Extended.

Date	Midsummer Island	Sargeaunt Pass	Wicklow Point
Jan 14, 2003			
Jan 31, 2003			
Feb 14, 2003	256,877		
Feb 28, 2003	***243,520***		
Mar 14, 2003	230,163		
Mar 31, 2003	224,856		
Apr 14, 2003	182,513	469,444	
Apr 30, 2003	84,468	891,907	
May 14, 2003	0	1,003,675	
May 31, 2003		999,743	
Jun 14, 2003		999,031	
Jun 30, 2003		997,455	
Jul 14, 2003		992,158	
Jul 31, 2003		988,521	
Aug 14, 2003		978,674	
Aug 31, 2003		***977,795***	
Sep 14, 2003		***976,916***	
Sep 30, 2003		976,037	
Oct 14, 2003		***870,174***	
Oct 31, 2003		764,310	
Nov 14, 2003		768,100	
Nov 30, 2003		***767,729***	
Dec 14, 2003		***767,357***	
Dec 31, 2003	420,449	***766,986***	
Jan 14, 2004	420,290	766,614	
Jan 31, 2004	***420,179***	***766,361***	163,244
Feb 14, 2004	***420,067***	766,107	***439,112***
Feb 28, 2004	419,956	***765,598***	714,980
Mar 14, 2004	419,858	765,089	708,091
Mar 31, 2004	419,808	764,241	694,299
Apr 14, 2004	419,660	762,157	676,693
Apr 30, 2004	419,550	762,157	674,426
May 14, 2004	419,407	760,753	667,493
May 31, 2004	419,231	757,936	662,975
Jun 14, 2004	418,252	756,956	662,410
Jun 30, 2004	417,138	754,135	660,250
Jul 14, 2004	417,006	***733,284***	***659,654***
Jul 31, 2004	416,219	712,433	659,058
Aug 14, 2004	***415,960***		
Aug 31, 2004	415,700		

Atlantic salmon that had resided longer than nearly 200 d in marine waters probably contributed billions (i.e., 1 billion $= 1 \times 10^9$) of sea louse eggs to adjacent marine waters. These estimates of lice from farmed fish were also conservative for the Broughton Archipelago, since I used conservative fecundity values and because Marine Harvest Canada (or Stolt Sea Farm) reported only on gravid female lice, not on total adult females, many of which would have been near the egg-bearing stage. These production estimates also represent only about 13% of the 84 farms currently operating along British Columbia's coast. Seasonal contributions of lice from wild salmon in the late summer–fall may be significant, but overall contributions of lice from farmed Atlantic salmon hosts far overshadow those of wild and escaped farmed Atlantic salmon (combined) in spring, the period of concern during which wild juvenile fish are near the area's farms.

Seasonal variation in estimated sea louse production was influenced by numbers of fish in pens in January and February. With 800,000 fewer fish to start 2003 (compared with 2004), estimated louse production was only half in that year. In both years, louse production was highest in winter and spring and lowest in summer as fish were harvested and Slice became effective (Figures 3, 4). Slice has a reported efficacy of 89–93% at 5–6 weeks after use (Stone et al. 2000; SPAH 2001), and its early-winter use in both years appeared to reduce louse numbers to near zero over a period of weeks (Figure 3). Although seasonal variation in copepodid production was not estimated, the limited data available suggest that reductions in salinity between June and August (dipping below 30‰) may have also led to reduced copepodid survival rates (Johnson and Albright 1991).

Similar to the Broughton Archipelago, Revie et al. (2002) showed that sea louse levels on 33 Scottish farms were low in the first year of production after farms were stocked with uninfected smolts. McKibben and Hay (2004) also found sea louse larvae in Scotland's coastal waters only when Atlantic salmon farms were in the second year of their production cycle. In terms of infection risk near farms, Morton et al. (2004) found significantly greater numbers of lice on juvenile salmonids collected near Broughton Archipelago farms than on fish sampled in areas without farms. Krkosek et al. (2005) also estimated that infection pressure near a single farm in the Broughton Archipelago was 73 times greater than ambient levels and exceeded ambient levels for 30 km past that farm.

The evidence is consistent with the view that cultured salmon are the major source host of sea lice infecting wild juvenile salmon (Heuch and Mo 2001; Butler 2002; McKibben and Hay 2004; Heuch et al. 2005; Krkosek et al. 2005; Morton et al. 2005) and that certain management actions (e.g., reducing farmed salmon numbers, the application of sea louse biocides) may dramatically reduce louse numbers and, thus, infection risk. When fewer farmed Atlantic salmon and lice were present early in 2003, Morton et al. (2005) found that louse prevalence on juvenile salmon declined from 92% (2002) to 36% (2003) before increasing again to 94.5% (2004). Overall abundance of lice similarly declined by a factor of 8.9 between 2002 and 2003 and increased again by a factor of 7.2 in 2004. Morton et al. (2005), who found that patterns in louse abundance could not be explained by variations in marine water temperature or salinity, also showed that removing all Atlantic salmon from a single farm resulted in a 42-fold decrease in copepodids on juvenile fish near that farm.

In Europe, management is specifically mandated in

TABLE 3.—Average number of gravid sea lice per farmed fish reported at Marine Harvest Canada farms in 2003 and 2004 and adjusted to the time series used in this study. Values in bold italics are estimates; asterisks denote treatment with Slice. The following farms did not report data: Deep Harbour, Smith Rock, Carrie Bay, Northeast Eden Island, Upper Retreat, Mound Island, and Watson Cove.

Date	Blunden Passage	Arrow Passage	Doctor Islets	Glacier Falls	Humphrey Rock	Larsen Island	Swanson Island	Port Elizabeth	Potts Bay	Midsummer Island	Sargeaunt Pass	Wicklow Point
Jan 14, 2003		3.30					1.00	0.80*				
Jan 31, 2003	0.00	3.70	1.50				0.70	***0.50***				5.30
Feb 14, 2003	0.00	***3.25****	***1.55***				***0.65****	0.20	8.20	4.90		
Feb 28, 2003	***0.00***	2.80	1.60				0.60	0.00	***7.50***	***3.35***		
Mar 14, 2003	0.00	0.10	0.90			0.00	0.00	0.00	***6.80****	1.80		
Mar 31, 2003	0.00	0.10	1.80			0.00	0.00	0.00	6.10	7.00		
Apr 14, 2003	0.00	0.00	1.40			***0.00***	0.00	0.00	1.40	3.30	0.00	
Apr 30, 2003	0.10	0.00	1.90			0.00	0.00	0.00	0.75	5.50	0.00	
May 14, 2003	0.00	0.10			0.00	0.00	0.00	0.10	1.80		0.00	
May 31, 2003	0.00	0.00			0.00	0.00	0.00	0.00	0.00		0.00	
Jun 14, 2003	***0.05***	0.10			0.00	0.00	0.00	0.00	0.30		0.00	
Jun 30, 2003	0.10				0.00	0.00	0.00	0.00	0.10		0.00	
Jul 14, 2003	0.10			0.05	0.00	0.00	0.00	0.00	0.10		0.00	
Jul 31, 2003				***0.03***	***0.00***	0.00	***0.10***	***0.15***	0.00		***0.00***	
Aug 14, 2003				0.00	0.00	0.00	0.20	0.30	0.00		0.00	
Aug 31, 2003				0.10	***0.00***	***0.10***	***0.48***	***0.23***	***0.50***		***0.02***	
Sep 14, 2003				***0.30***	***0.00***	0.20	***0.76***	***0.17***	***1.00***		***0.04***	
Sep 30, 2003				***0.50***	0.00	***0.15***	***1.00***	0.10	***1.50***		***0.06***	
Oct 14, 2003				***0.70***	***0.00***	0.10	***1.32***	***0.85***	***2.00***		***0.08***	
Oct 31, 2003				0.90	0.00	***0.20***	1.60	1.60	2.50		0.10	
Nov 14, 2003				1.50	0.10	0.30	6.80	1.50	0.20		0.00	
Nov 30, 2003				1.70	***0.10***		3.30	***1.55***	***0.80***		***0.00***	
Dec 14, 2003				***1.60***	***0.10***		***4.05***	1.60	1.40		***0.00***	
Dec 31, 2003				1.50	***0.10***		4.80	***1.80***	***4.00***	6.90	***0.00***	
Jan 14, 2004				***0.80***	0.10		***6.00***	***2.00***	***6.60***	0.70	0.00	
Jan 31, 2004				0.10	***0.10***		7.20	2.20*	9.20	***0.60****	***0.00***	
Feb 14, 2004				0.00	0.10		***4.05****	***1.53***	***6.55****	***0.50***	0.00	
Feb 28, 2004				***0.00***	***1.55***		0.90	***0.87***	3.90	0.40	***0.00***	
Mar 14, 2004				0.00	3.00			0.20	***2.10***	0.10	0.00	0.00
Mar 31, 2004				0.00	0.60				0.30	0.00	0.40	0.00
Apr 14, 2004				0.10	0.20				0.60	0.10	0.70	0.00
Apr 30, 2004				0.00	0.29				0.00	0.00	0.30	0.00
May 14, 2004			0.00	0.10	2.00*	0.00			0.00	0.10	0.60*	0.00
May 31, 2004			0.00	0.00	0.90	0.00			0.00	0.00	1.20	0.10
Jun 14, 2004			0.00	0.50	0.10	0.00			0.00	0.00	0.30	0.80*
Jun 30, 2004			0.00*	***0.85****	1.00	0.00			0.10	0.10	0.00	0.30
Jul 14, 2004				1.20	0.00	0.00			***0.15***	0.30	0.00	0.00
Jul 31, 2004				0.40	0.00	0.00			0.20	0.40		
Aug 14, 2004				0.00		0.00			***0.15***	1.20		
Aug 31, 2004									0.10	2.00		

Note: Values in bold italics are estimates; asterisks denote treatment with Slice. The following farms did not report data: Deep Harbour, Smith Rock, Carrie Bay, Northeast Eden Island, Upper Retreat, Mound Island, and Watson Cove.

spring (April–March) to minimize farm-source sea louse production during the time when the majority of wild juvenile salmonids migrate past farms (Heuch and Mo 2001; Heuch 2005; Heuch et al. 2005). The effectiveness of such actions may be eventually offset, however, by increases in Atlantic salmon production, even as treatment thresholds for sea lice are continuously lowered (Heuch 2005; Heuch et al. 2005). In Canada, to be effective, louse management must also be sensitive to the life histories of the area's wild salmon. Pink salmon fry hatched in Broughton Archipelago rivers emerge from the gravel of natal streams around March 1 (Morton et al. 2005) and along with juvenile chum salmon *O. keta*, they quickly enter marine waters (Groot and Margolis 1991; Morton et al. 2005). Therefore, efforts to reduce sea louse numbers (and, thus, infection risk) before juveniles appear must begin weeks earlier than March 1 to account for the prolonged (at 7°C water temperature) development of louse eggs and larvae that may be present (e.g., Johnson and Albright 1991; Boxaspen and Næss 2000). Management challenges will be exacerbated by the exceptionally small size and apparent vulnerability (to sea lice) of pink salmon and chum salmon juveniles, which average just 0.30 and 0.36 g, respectively (Morton et al. 2005). Recent studies suggest that these exceptionally small juvenile salmon—nearly 10 times smaller than their juvenile

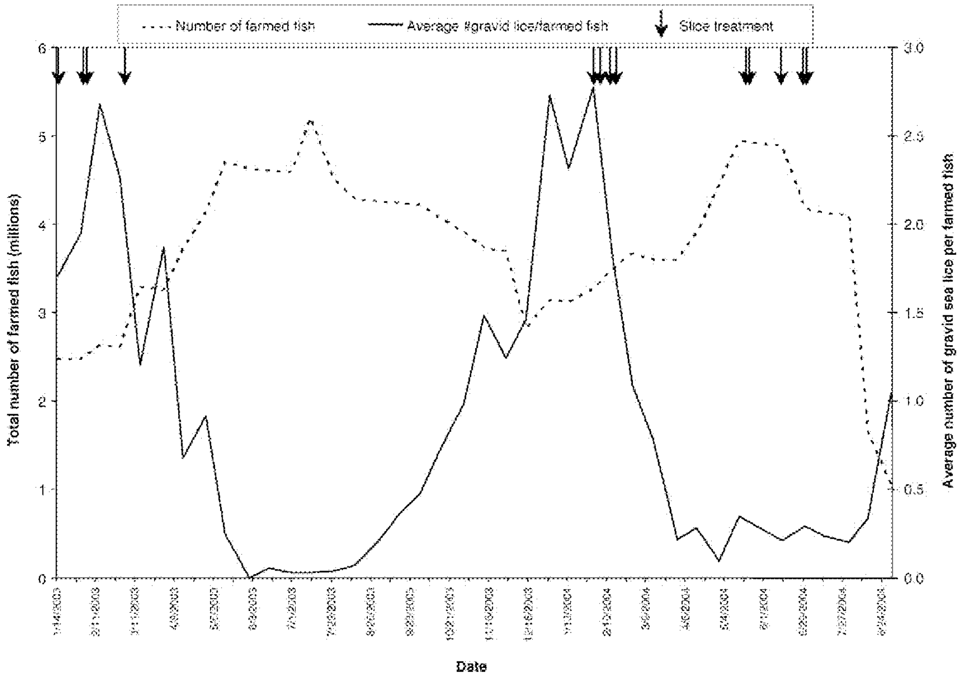

FIGURE 3.—Total number of farmed Atlantic salmon, average number of gravid sea lice per farmed fish, and timing of Slice treatments (arrows) at Marine Harvest Canada farms in the Broughton Archipelago, British Columbia, 2003 and 2004.

Atlantic salmon counterparts—may not be able to survive after being infected by even a single louse (Bjørn and Finstad 1997; Finstad et al. 2000; Morton and Routledge 2005, 2006).

Clearly, our ability to assess and manage infection risk will be improved by more accurate data on farm sea louse dynamics and environmental influences on louse production and dispersal. Broughton Archipelago currents, for instance, play a major role in the transport of louse larvae and the movement of small wild salmon (Foreman et al. 2006). The lack of accurate data, in turn, has prompted a debate on how quickly sea lice are transported away from farms, thus influencing the level of risk posed by farm-source lice (Brooks 2005; Krkosek et al. 2006). Therefore, it is useful to note that a recent research and monitoring agreement has been reached between Marine Harvest Canada and several conservation and aboriginal groups (Simpson 2006) that may help improve the availability and quality of farm-source and environmental data. This, in turn, may improve our understanding of the host–parasite dynamics of sea lice and salmon in Canada's Broughton Archipelago and increase our chances of conserving wild salmon.

Acknowledgments

I thank Karen Leslie and, especially, Trish Hall for their work on the model and other help; Alex Morton for sharing findings, insights, and in press papers; the Living Oceans Society for a map; and Marine Harvest Canada for sharing its data. Rick Routledge, Neil Frazer, Alex Morton, Brendan Connors, Peter Heuch, and three anonymous reviewers provided useful comments on the paper. The Vancouver Foundation, David and Lucile Packard Foundation, Gordon and Betty Moore Foundation, and David Suzuki Foundation provided financial support.

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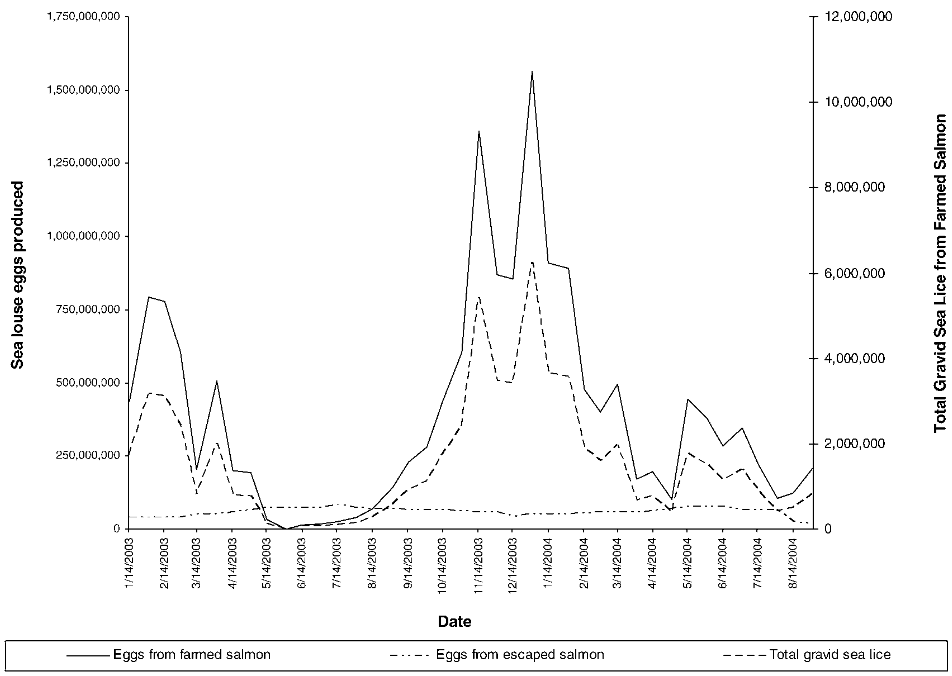

FIGURE 4.—Total number of gravid sea lice on farmed Atlantic salmon and sea louse eggs produced from farmed and escaped fish originating from Marine Harvest Canada farms in the Broughton Archipelago, British Columbia, in 2003 and 2004.

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