

# Relationship of farm salmon, sea lice, and wild salmon populations

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Increased farm salmon production has heightened concerns about the association between disease on farm and wild fish. The controversy is particularly evident in the Broughton Archipelago of Western Canada, where a high prevalence of sea lice (ectoparasitic copepods) was first reported on juvenile wild pink salmon (*Oncorhynchus gorbuscha*) in 2001. Exposure to sea lice from farmed Atlantic salmon (*Salmo salar*) was thought to be the cause of the 97% population decline before these fish returned to spawn in 2002, although no diagnostic investigation was done to rule out other causes of mortality. To address the concern that sea lice from fish farms would cause population extinction of wild salmon, we analyzed 10–20 y of fish farm data and 60 y of pink salmon data. We show that the number of pink salmon returning to spawn in the fall predicts the number of female sea lice on farm fish the next spring, which, in turn, accounts for 98% of the annual variability in the prevalence of sea lice on outmigrating wild juvenile salmon. However, productivity of wild salmon is not negatively associated with either farm lice numbers or farm fish production, and all published field and laboratory data support the conclusion that something other than sea lice caused the population decline in 2002. We conclude that separating farm salmon from wild salmon—proposed through coordinated fallowing or closed containment—will not increase wild salmon productivity and that medical analysis can improve our understanding of complex issues related to aquaculture sustainability.

Because salmon aquaculture production has rapidly increased over the past three decades, the potential for environmental impacts of salmon farms has generated heightened scientific and public interest (1, 2). One concern about salmon farms is that they are the source of ectoparasitic sea lice infestations that might reduce the marine survival of wild salmon (3, 4). In the Broughton Archipelago region of Western Canada (Fig. S1), farming of Atlantic salmon (*Salmo salar*) began in the late 1980s, and annual farm salmon production increased steadily to 17 Gg by 1999 (Fig. S2). Pink salmon (*Oncorhynchus gorbuscha*) is the most abundant wild salmon species in the Broughton Archipelago; they enter the marine environment at a very small size (0.2 g), and they return to natal streams to spawn 2 y after their parents (5). Because age at maturity never varies, they have distinct even- and odd-year populations (Fig. S2 and SI Text). Record high numbers of pink salmon returned to spawn in rivers of the Broughton Archipelago in 2000 and 2001 (Dataset S1), but these returns were followed by population decline of 97% in 2002 and 88% in 2003 (Figs. S2 and S3 and SI Text). When juvenile pink salmon in the Broughton Archipelago were first examined for sea lice in June 2001, more than 90% were infested—leading to the hypothesis that sea lice from fish farms were the cause of population collapse in 2002 (4).

Adult pink salmon are a natural host for the sea louse species *Lepeophtheirus salmonis* (6), and in Western Canada, *L. salmonis* is generally common on all mature salmon returning to the coast (7, 8). In contrast, *L. salmonis* is rare on juvenile pink salmon in areas with no fish farms (9). *L. salmonis* occurs in the Atlantic and Pacific oceans, but the Pacific form is clinically less pathogenic

than the Atlantic form (10), and the two forms have significant genetic differences (11, 12). One other sea louse species, *Caligus clemensi*, occurs on pink salmon, but it is more common on other fish hosts (13). Unlike *L. salmonis*, *C. clemensi* is sometimes common on juvenile pink salmon away from fish farms (13).

Several studies have attempted to explain the impact of sea lice and salmon farming on pink salmon population decline, but these studies have been limited by lack of access to fish farm data (14–17). In one series of studies, juvenile pink salmon of unknown history were captured from the wild (2004–2007), separated by lice infestation status into field-based enclosures, and held for several weeks to assess differences in mortality (14, 18, 19). Results from these studies were used to support the conclusion that “recurrent louse infestations of wild juvenile pink salmon (*Oncorhynchus gorbuscha*), all associated with salmon farms, have depressed wild pink salmon populations and placed them on a trajectory toward rapid local extinction” (3). However, the field mortality studies were not able to differentiate whether sea lice were the cause of mortality or whether sea lice had preferentially attached to fish that were destined to die from some other cause. To overcome this deficiency, other research exposed juvenile pink salmon of known history to Pacific forms of *L. salmonis* under controlled laboratory conditions (20); results were used to estimate that sea lice killed no more than 4.5% of juvenile pink salmon in any given year from 2005 to 2008 (21). Conclusions from these studies remain controversial, in part because they depend on experimental results from confined wild fish. Pink salmon sometimes adapt poorly to confinement (22) and change their behavior when exposed to sea lice (23); therefore, experimental results might overestimate or underestimate mortality among lice-infested fish in the wild. To overcome limitations inherent in using experimental studies to estimate population outcomes, we use a combination of approaches common in medical science and mathematical modeling to analyze actual farm data in relation to wild salmon information.

The primary objective of our study was to assess interrelationships between wild pink salmon, sea lice, and farmed Atlantic salmon in the Broughton Archipelago. Most importantly, we wanted to determine whether farm-source sea lice negatively impacted wild salmon population productivity (measured by the number of returning fish per spawner). Our approach was to

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Conflict of interest statement: None of the authors received compensation from any source for this analysis. S.M.S., as part of her private veterinary practice over the past 15 y, has done contract work for all three fish farm companies that operate in the study area (these companies are cited in the acknowledgments, and this relationship was vital for obtaining all proprietary farm medical records for this study); S.M.S.'s spouse started working for closed-containment aquaculture operation in September 2010.

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farm fish the next April decreased over the years 2004, 2006, and 2008 (Fig. 1).

**Relationship of Sea Lice on Farm Fish and Juvenile Pink Salmon.**

*L. salmonis* prevalence on outmigrating juvenile pink salmon in May shows a strong curvilinear relationship with adult female *L. salmonis* abundance on farm fish in April ( $r^2 = 0.981$ ,  $a = 107.7$ ,  $b = 1.04 \times 10^{-7}$ ) (Fig. 3B). This relationship remained stable as progressively earlier farm lice treatments truncated the timing of the annual peak in farm fish *L. salmonis* abundance from the spring (in 2002) back to late fall (by 2008/2009). The *L. salmonis* prevalence on juvenile pink salmon was not determined in May 2001, but the reported prevalence of 96% in June and July 2001 (4) is within the 95% prediction interval based on our estimate of 15.6 million female *L. salmonis* on farm fish in June 2001 (Figs. 1 and 3B). Collectively, these findings support the hypothesis that farm fish are the main source of *L. salmonis* infesting juvenile pink salmon, and they are consistent with indirect evidence from several other studies that did not have access to farm data (14, 16, 26, 27).

Because farm-source sea lice accounted for 98% of the variability in wild salmon sea lice prevalence from 2002 to 2009 and sea lice were sometimes common on farmed Atlantic salmon during the 1990s, farm-source sea lice probably infested juvenile pink salmon many years before they were first examined for sea lice in 2001 (1). As evidence, we show that sea lice were abundant on farm fish in 2000 (Fig. 1). Before 2000, farm fish sea lice were usually not quantified, but infestations were common enough that sea lice treatment options were investigated in the early 1990s (28), and publicly available records confirm that those treatments were used as early as 1996 (figure 25 at [http://www.agf.gov.bc.ca/ahc/fish\\_health/Fish\\_Health\\_Report\\_2003-2005.pdf](http://www.agf.gov.bc.ca/ahc/fish_health/Fish_Health_Report_2003-2005.pdf)). No evidence exists to indicate that sea lice are not moving through net cages

in both directions between farm and wild fish (16), and net cages have not changed over the past two decades.

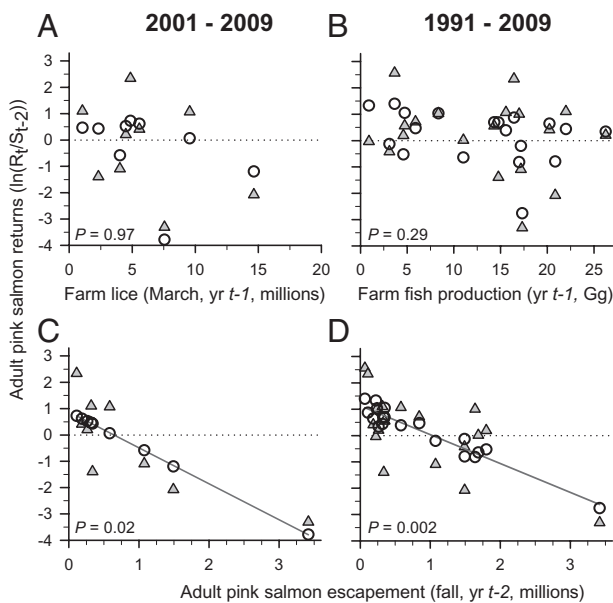
**Relationship of Farm Fish Production and Farm Sea Lice to Pink Salmon Productivity.**

Despite the strong correlation between sea lice infestation of farm salmon and wild salmon, pink salmon productivity is not consistently associated with either farm fish adult female *L. salmonis* numbers (March) or farm fish production ( $Gg \cdot yr^{-1}$ ) during the year of juvenile outmigration (Fig. 4). Instead, pink salmon returns per spawner (year  $t$ ) are significantly associated with escapement of the parent generation ( $t - 2$ ) for returns of the odd- and even-year runs combined in (i) 2001–2009 (the period corresponding to sea lice counts;  $P = 0.02$ ) and (ii) 1991–2009 (the period corresponding to fish farm production data;  $P = 0.002$ ) (Fig. 4). When odd- and even-year populations are analyzed separately, the relationship of pink salmon returns to parental escapement is significant during odd years from 1991 to 2009 ( $P = 0.02$ ) and almost significant during even years from 1992 to 2008 ( $P = 0.08$ ). For all combinations of years and runs (even or odd year), pink salmon adult returns (year  $t$ ) were never significantly associated with year  $t - 1$  farm fish production ( $P \geq 0.27$ ). The only significant relationship with farm adult female *L. salmonis* numbers was a positive correlation with the even-year run from 2002 to 2008 ( $P = 0.04$ ) (Dataset S1). Positive contributions of sea lice to pink salmon productivity have not been investigated, but sea lice might be a food source. As evidence, juvenile pink salmon held in captivity feed on sea lice attached to cohorts (19).

**Medical Analysis of Potential Causes of Pink Salmon Mortality.**

The data from Broughton Archipelago pink salmon populations and sea lice experiments best fit the conclusion that the majority of pink salmon deaths are caused by something other than sea lice, and our farm data supports the conclusion that farm lice did not significantly decrease pink salmon productivity over the past decade. Historically, mortality from fry to adult for central British Columbia stocks is about 95% (29), and most of this mortality occurs during the first 6 wk in the ocean (30). When lice-infested juvenile pink salmon of unknown health status were captured from the marine environment and held for several days in field-based enclosures, mortality was consistently higher among fish that began the experiment infested with sea lice; however, the parasites were shed from the majority (19) or all (14, 18) of the fish that eventually died. Koch's fourth postulate states that, to confirm a parasite as the cause of disease, presence of the parasite must be confirmed on the diseased host (31). Because most or all of the initially infested fish shed their lice before they died, the cause of death remains unknown, and the evidence points to something other than sea lice killing most of the fish. These experiments did not include diagnostic methods (e.g., bacteriology, virology, or histopathology) to identify other causes of death. In some cases, Koch's postulates need not be fulfilled to establish disease causation (e.g., with bacteria and viruses that cannot be cultured), but sea lice are routinely isolated for exposing lice-free fish under controlled laboratory conditions (23, 32).

To better determine the role of sea lice in pink salmon mortality (e.g., do they contribute to or cause mortality?), controlled laboratory experiments exposed lice-free juvenile pink salmon of known history to Pacific-source *L. salmonis*. Infested fish had increased jumping activity and a slight preference for fresh water (23), and infested juvenile pink salmon shed most lice within about 3 wk (32); mortality was limited to heavily infested fish weighing  $<0.7$  g (20, 32). Therefore, because of their rapid growth rate, pink salmon are susceptible to lethal sea lice infestations only during their first 1 mo at sea (21). Based on extrapolations from controlled laboratory studies, infestation levels associated with our estimate of 9.5 million farm-source female *L. salmonis* in February 2005 (Fig. 1) might have killed 8% of the juvenile



**Fig. 4.** Observed values (closed triangles), predicted values (open circles), and  $P$  values for the two multiple linear regressions of pink salmon production [generational survival;  $\ln(R_t - 2/S_t)$ ]. (i) For 2001–2009 data, the relationship of generational survival to farm-source adult female *L. salmonis* sea lice was not significant (A), but the relationship of generational survival to parental escapement ( $S_{t-2}$ ) was significant (C). (ii) For 1991–2009 data, the relationship of generational survival to farm fish production was not significant (B), but the relationship of generational survival to parental escapement was significant (D). Dotted lines denote where returns equal parental escapement. For emphasis, solid trend lines are shown for significant relationships (C and D).

salmon outmigrating in March 2005 (21). However, generational escapement for these fish returning as adults in 2006 was similar for the Broughton and reference populations (Fig. S3), suggesting that, if louse-induced mortality occurred, it was compensatory (i.e., death caused by sea lice exposure replaced death caused by other causes, resulting in no net change in generational survival).

**Assessment of the Potential for Management Options to Improve Pink Salmon Abundance.** Two management options are being considered for decreasing the impact of farm salmon on wild salmon (1, 2, 19): (i) coordinated fallowing of juvenile salmon migration corridors and (ii) removal of all farms from direct contact with the marine environment (e.g., through transition from open net cages to closed containment aquaculture). After severe pink salmon population decline was confirmed in the Broughton Archipelago in the fall of 2002, government regulators worked with fish farm companies to follow a migration pathway during the outmigration months of March, April, and May of 2003 (16, 33). As a result of this voluntary program, three farms in the Tribune-Fife corridor (Fig. S1) that had been stocked in March 2002 were fallowed from March through June 2003. The Knight Inlet corridor (Fig. S1) was not fallowed in 2003, and total numbers of farm fish in the Broughton were about the same in March 2002 (6,717,000), 2003 (7,142,000), and 2004 (7,223,000) (Fig. S5 and Movie S1). The three farms fallowed in 2003 were restocked with young fish by March 2004, and thereafter, the Tribune-Fife corridor was not fallowed. The second option (closed containment) has not been tested at commercial production levels.

The year of coordinated fallowing (2003) was associated with decreased sea lice prevalence on juvenile pink salmon in the fallowed corridor (16) and in the corridor that was not fallowed (34), and sea lice numbers on all Broughton farm salmon were generally less in 2003 than in either 2002 or 2004 (Fig. 1). Among several hypotheses to explain these changes in sea lice prevalence, the strength of the relationship between *L. salmonis* on wild and farm fish best supports the hypothesis that the decrease in 2003 was a result of the precipitous decline of the parent generation in 2002 (16) and fewer numbers of lice per returning fish. In support, escapement of the pink salmon parent generation was less in 2002 (110,300) than in either 2001 (1,490,000) or 2003 (186,800), and even-year pink salmon populations are associated with significantly fewer lice per fish than odd-year populations (Fig. 3A). Decreased sea lice prevalence was not a result of increased treatment of farm fish, because farm fish received fewer emamectin benzoate treatments during the fallow year (September 2002 through August 2003) than in the preceding or following year, and sea lice numbers on treated fish during the fallow year were less than either the preceding or next year (Fig. 2) (10). Finally, the increase in sea lice prevalence in 2004 and some years thereafter could not have resulted from lack of fallowing after 2003, because the three farms that were fallowed in 2003 hosted almost no sea lice from 2004 to 2007 (Fig. S5). Only in 2008 were farm lice numbers relatively high in the previously fallowed corridor (Fig. S5), when fish treatment at one farm was delayed until March (Dataset S1) because of lack of availability of emamectin benzoate from the manufacturer. In March 2008, this farm hosted 43% of the 1.0 million adult female *L. salmonis* on all Broughton farm fish, but adult returns (in 2009) for juvenile pink salmon migrating through the Broughton in 2008 were nearly triple that of their parent generation (in 2007) (Fig. S2).

## Conclusion

Adult pink salmon returns the previous fall are a good predictor of sea lice prevalence in the spring, but farm sea lice numbers are not a good predictor of wild salmon survival. Indeed, we estimate that farm-source sea lice numbers were greater during juvenile pink salmon outmigration in March 2000 than in March 2001 (9.1 vs. 7.5 million) (Fig. 1), providing no intimation of record high adult

returns in 2001 vs. the 97% population collapse in 2002 (Fig. S2). Based on the lack of evidence for a significant negative relationship between farm fish and pink salmon productivity, the data do not support the hypothesis that separating farm fish from wild fish will increase pink salmon marine survival. Determination of the cause(s) of salmon population decline requires investigation of other variables. For example, in 2001, sick juvenile pink salmon frequently had “bleeding at the base of the fins” (4), but this lesion does not occur in pink salmon exposed to Pacific-source *L. salmonis* under controlled laboratory conditions (20, 32). Instead, reddening of the fins is commonly associated with stressful environmental conditions or bacterial and viral infections (35, 36); however, none of these differentials were investigated in 2001, and their potential role in fish mortality that year remains unknown. Adding medical analysis to multidisciplinary investigations of fish population decline can increase our understanding of the cause and help government agencies develop cost-effective regulations to sustain healthy wild salmon populations.

## Methods

To determine the relationship of farm-source sea lice and pink salmon productivity, we obtained data from all salmon farms and major pink salmon rivers in the Broughton Archipelago region of Western Canada. Annual farm fish production ( $Gg \cdot y^{-1}$ ) data are from 1990 to 2009 (Dataset S1). Monthly farm data (from 2000 to 2009) include: inventory (number of fish per farm), sea lice counts (number of adult female *L. salmonis* and *C. clemensi* per fish), and medical treatments for sea lice (Dataset S1). We used these data to estimate the monthly total of adult female sea lice on all farm fish in the Broughton Archipelago from as early as March 2000 (SI Methods), more than 1 y before sea lice were first reported on wild juvenile pink salmon. Data were compared with pink salmon escapement (number of wild salmon that return to a river to spawn in the fall) and commercial harvest data obtained from the Department of Fisheries and Oceans Canada from 1950 to 2009 (Dataset S1).

To test whether returning adult pink salmon could be a source of sea lice on farm fish, we compared adult pink salmon returns (escapement plus commercial harvest) with farm adult female *L. salmonis* numbers the next April. Separate linear regressions were done for returns to the Broughton Archipelago for all years (1999–2008) and for the even- and odd-year runs separately followed by significance testing of differences in the slope of each run's regression (37). A multiple linear regression was done for returns to the Broughton Archipelago and the nearby Fraser River for all years, with both runs combined.

To test whether sea lice infestation of juvenile pink salmon from 2002 to 2009 is related to the number of *L. salmonis* on farm fish, we compared farm fish adult female *L. salmonis* numbers in April with the prevalence of *L. salmonis* on juvenile pink salmon in mid-May (16, 21, 34, 38, 39). The 1-mo lag accounts for the time needed for a louse egg to develop into an infectious copepodid stage (24). We considered comparing farm lice numbers in March with juvenile pink salmon lice prevalence in April, but we did not do so because pink salmon lice data are not available for April 2002: the year of greatest farm lice numbers during March or April. Visual inspection of the data suggested a curvilinear relationship, and therefore, data were fitted to a von Bertalanffy curve:  $y = a(1 - e^{-bx})$ , where  $y$  is the *L. salmonis* prevalence on wild outmigrating juvenile pink salmon,  $x$  is the number of adult female farm *L. salmonis*,  $a$  is the maximum prevalence, and  $b$  is the rate of increase in prevalence.

To test the relationship between pink salmon returns and farm fish variables, we used a generalization of the classic Ricker spawner–recruit model, which relates returns of one generation to escapement of the previous generation (40). It predicts that returns are a dome-shaped function of the spawning population because of density-dependent effects. The generalized model also includes effects of the farm fish variables. Our approach is similar to a previous study that implicated sea lice in wild salmon declines (3), except that our study uses data from fish farms. We tested the impact of fish farms on pink salmon productivity (in year  $t$ ) in the Broughton Archipelago using two variables to represent fish farm effects: March adult female *L. salmonis* numbers (year  $t - 1$ ) and annual farm fish production (year  $t - 1$ ). Because total March adult female *L. salmonis* numbers on farm salmon were not correlated with same year farm fish production from 2000 to 2009 (linear regression,  $P = 0.99$ ), these variables provide different measures of the potential effects of fish farms on pink salmon. The other variable in the linear regression analysis is escapement 2 y earlier (year  $t - 2$ ). A complete derivation of this relationship from assumptions about mortality during early life history is described in SI Methods.

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