SCIENCE AND SEA LICE

WHAT DO WE KNOW?

Prepared for the
B.C. Pacific Salmon Forum

February 22, 2008

Brian Harvey
1755 Emerson St.
Victoria, B.C. V8R 2C2
bjharvey@telus.net

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The human understanding is no dry light, but receives infusion from the will and the affections; whence proceed sciences which may be called "sciences as one would." For what a man had rather were true he more readily believes. Therefore he rejects difficult things from impatience of research; sober things, because they narrow hope; the deeper things of nature, from superstition; the light of experience, from arrogance and pride; things not commonly believed, out of deference to the opinion of the vulgar. Numberless in short are the ways, and sometimes imperceptible, in which the affections colour and infect the understanding.

Francis Bacon, in the *Novum Organum* (1620)

Author's note

The B.C. Pacific Salmon Forum engaged me to create an independent overview of recent research on the interaction between sea lice and juvenile Pacific salmon in the Broughton Archipelago. I was to draw the bulk of my information from published scientific papers, while referring to unpublished work where it seemed to bring important new insights. An annotated bibliography was chosen as the best way of providing an impartial summary of the available scientific research. The responsibility for which papers to include in the bibliography, what information to include in each entry, and for any mistakes in interpretation, is mine.

I did not formally interview any of the cited researchers during the preparation of this bibliography, although I am grateful to many colleagues, and to all the people at the Pacific Salmon Forum, for alerting me to publications I might otherwise have missed. Members of the Science Advisory Committee of the Pacific Salmon Forum provided detailed reviews of an earlier draft; their excellent suggestions greatly improved the document.

Hatsumi Nakagawa helped me obtain papers from various providers, organize them and maintain a standard format.

Brian Harvey
February, 2008

Introduction

Science increasingly concentrates on the small picture. At the same time, science is becoming more political. "Science-based" has become a catch-phrase for politicians, policy-makers and advocates; it's supposed to mean the same thing as "true."

Unfortunately for those who want credibility for policy, science still works best on minutiae. Using it to justify big-picture decisions causes predictable problems. The respected journal *Science* is considering a trial policy of requiring its authors to write a summary in plain English, because scientists even slightly outside their own field can't understand the papers any more. If the scientific generalist can no longer understand the literature, what hope has the policy maker?

The question of where the sea lice on juvenile wild salmon come from – what happens to a mobile parasite and a mobile host in a highly fluid environment – is a tantalizing scientific one. So is climate change, and in fact the two issues have something in common. Both cry out for more data, rely in the interim on complicated mathematical models, and engender polarization and rancour. Getting a definitive answer will take less time for sea lice, but the question of "how long?" is a good one. Some people say it's been long enough; others say we need more research.

The public (not the scientific) debate about sea lice is often hard to separate from the more general issue of salmon farming in B.C. But behind all the shouting, the science works away as it always has. The question is, how do you look at the product of that science at any moment in time and say what it all means?

That's what the present bibliography tries to do, and the answer depends on where we are in the investigation. In my opinion, the sea lice transmission issue isn't a baby any more – we've learned to feed it with research grants and clothe it in international conferences – nor is it quite a mature adult we can leave to its own devices. Instead, it's somewhere in late adolescence, still gangly and unpredictable and hard to approach.

The reader should make no mistake: this is a daunting field, because it's actually many fields – epidemiology, oceanography, meteorology, mathematics, natural history and genetics – all mixed up together. Scientists are being asked to unravel a skein of biological interactions in an enormous aquatic arena of channels and shallows, eelgrass and rocks, and currents that fluctuate in three dimensions. The scientific method is expected to predict the fate of microscopic particles in a chaotic world where three right feet in running shoes can wash up on three different islands and nobody can even begin to say where they came from.[1] The two quite different species of louse and their many life stages are sensitive to salinity, temperature, rainfall, tides, winds, alternate hosts, and ceaseless currents. Working conditions for the researchers feature rain, high winds and equipment breakdowns. A complete lack of forensic tools makes it difficult to test even the simplest hypothesis, and impossible to point to a smoking gun.

[1] This happened in August, 2007, on Jedediah and Gabriola Islands. Parksville Qualicum Beach News, December 14, 2007. The third foot appeared on Valdes Island in early 2008.

Because I believe in science the process (not science the credibility-bestower), I think the only way to review the sea lice question is to let science do the talking. A scientific report is a set of conclusions backed by data and methods; all three can be shot down by a subsequent report. This back and forth eventually stabilizes around a scientific consensus, and scientists move on to new questions. This is what Carl Sagan, one of the most impassioned defenders of the scientific method of this century and one of the greatest communicators of science, called "a built-in self-correcting mechanism."[2] He was referring not only to the peer review process (which, as can be seen from some of the references in this bibliography, is showing some signs of strain)[3] but also to the fundamental tenet that a hypothesis only exists to be tested. If it fails the test of further scientific research, it'll be thrown out. That's why we couldn't do open heart surgery a hundred years ago, or make a phone call from a bicycle, but we can now. Sea lice will be similarly sorted out. Before that consensus has been reached, the only way to understand the issue is to let each scientific report speak for itself.

That is what I have done in this annotated bibliography. In it, the recent scientific papers on sea lice, salmon farms and wild salmon are not *critically reviewed*, they are *summarized*. Everything is boiled down to a standard format that tells the reader what the report is about, what kind of work it is, who funded it, what it concludes, and why it's relevant. Nothing about its flaws or omissions; that's the job of a reviewer, and in a field as politicized as sea lice, reviews are often biased. My belief is that the reader, who should be able to get through the whole bibliography in a couple of hours, will get the sweep of science as it tackles this daunting question, and come to his or her own conclusions. The following "Analysis and Comment" helps in that process, but it's only my analysis. Someone else could write a completely different one.

[2] Sagan, C. 1996. The Demon-Haunted World: Science as a Candle in the Dark. Ballantine Books. 457 pp.
[3] Longhurst (2007)

Analysis and Comment

Between the landward end of Knight Inlet, where the Klinaklini River enters the sea, and the nearest salmon farm at Sargeaunt Passage, are seventy nautical miles of deep, turbulent and windy fjord, including an underwater sill at Hoeya Head that's long been studied for its disruption of water circulation. Towing a plankton net along the shoreline often produces no more than one sea louse larva per living room-full of water, yet somehow the lice keep turning up on pink salmon, chum salmon, even on the completely unrelated three-spined stickleback whose life history is nothing like the salmon's. And the consequences of all those encounters seem to be grave: a recent mathematical simulation predicts the pink salmon in the Klinaklini and other rivers will go extinct in four generations because of infestation from sea lice produced on salmon farms.[4]

Implicating salmon farms in sea louse infestations on wild pink and chum juvenile salmon in the Broughton Archipelago makes good sense. It's hard to imagine otherwise: there are lots of salmon farms; amplification of louse numbers inside the sea cages is undisputed; simple calculations reveal that more than a billion eggs are produced in those cages.[5] If you find juvenile salmon carrying lice in the Broughton, it's hard to imagine some of those lice didn't come from a farm – especially when the louse pool inside the net cages is so big, and so little is known about wild sources of the parasite.

The plausibility of salmon farm involvement makes a good starting point for science, but has social implications too. Net-cage farming of Atlantic salmon is a hot button in B.C. In recent years, a number of farming practices have been identified as environmentally harmful; sea lice is one of them. To pretend that some sea lice researchers do not fall into one camp or the other would be naïve; not to say it is to pretend that scientists are as impartial as we expect them to be. The writing in scientific papers may aspire to a kind of dry, Olympian objectivity, but it is impossible to read the papers on sea lice, one after the other, day after day, without picking up the body language of the authors. Many of the scientists publish repeatedly, and they have a style. Emotions creep in.[6] This comes out most in the Discussion sections of published papers, which can have a whiff of the soapbox. The Methods and the Results are where the meat is, but it's in the Discussion that the real hypothesizing is to be found. Other scientists reading these papers know that the words "may" and "suggest" are hedges, but do the media and the public? Because it's these hypotheses – minus those inconvenient hedges – that usually end up in the news.

So reviewing, or even simply summarizing, this literature involves more than the usual effort to separate the known from the speculated, especially when the paper one is reading has already been consumed by the media and regurgitated in a dozen different forms – many of them

[4] Krkošek et al. 2007b
[5] Orr (2007)
[6] The quotation from the philosopher Francis Bacon, which I included at the beginning of this report, shows scientists have been human since at least 1620.

unrecognizable and unlikely to be called back. As the legendary showman said, "There's no such thing as bad press, as long as they spell your name right."[7]

Coming to grips with the literature

The question of sea louse transmission in the Broughton Archipelago is, scientifically speaking, the kind any beginning graduate student would die for. It covers salmon biology, sea louse biology, parasitology, epidemiology, oceanography and meteorology and, until someone manages to develop a forensic test of the origin of the lice found on wild juvenile salmon, the evidence is largely circumstantial.[8] It makes excellent sense that sea lice from farmed salmon would hitchhike onto wild salmon, make them sick, even drag down their populations over the years – it's just that the evidence is infuriatingly indirect, and scientists can't agree on the importance of infections from farmed salmon compared to infections from wild sources. The scientific challenge is so daunting that, in 2006, the Pacific Salmon Forum took the unusual step of commissioning peer-reviewed technical guidelines for scientists tackling the subject, covering technical matters as wide-ranging as field sampling and identification, assessment of heath effects, louse treatment and methods for estimating the size of salmon populations.[9]

Inevitably, there are two research approaches: use the data you have, or get more data. Getting more data that prove sea lice from salmon farms do or don't contribute enough to the louse loads on wild salmon to affect their survival is preferable; the smoking gun would be revealed. But that kind of research is expensive and time-consuming, so there's an alternative: use statistical tools and simulation models to draw inferences and make predictions. Much of the current controversy over sea lice in the Broughton comes from using different mathematical models on different portions of the available data. Each model has its proponents, who feed their models with different data. Hence all the conclusions that flow from the models – farms contribute most of the sea lice, farms are a minor contributor, and everything in between – are equally "right."

When I was asked to read, summarize and analyze scientific research relevant to the Broughton and sea lice, I knew no more about sea lice than I had picked up through media reports and casual conversations with other scientists. My qualifications for independently reviewing the literature included a respectable number of peer reviewed publications on fish physiology and conservation, many popular articles on fisheries plus a forthcoming book on rivers, and plenty of experience writing scientific reports and recommendations for government agencies, many of them on aquatic species at risk in Canada. I was no longer affiliated with any organization, although ten years spent running a fish-conservation NGO on Canada's west coast gave me insight into the world of advocacy and fundraising (two things that figure largely in the sea-louse world). I had worked with conservationists and fish farmers for years, and in many places around the world, for example developing rural aquaculture of local species in South America

[7] generally attributed to P.T. Barnum
[8] Juries and policy makers, of course, often have to make decisions based on circumstantial evidence
[9] This 108 page Reference Manual can be found on the Pacific Salmon Forum website at http://www.pacificsalmonforum.ca/wild/index.php

while advising the Convention on Biological Diversity about the adverse effects of farming in the ocean.[10] So I was able to see both sides.

I was, however, wary of attempting a critical scientific review of the literature on sea lice. For one thing, there appeared to be just too much of it; for another, even a cursory look at a dozen recent papers made it clear that "the literature on sea lice" covered many fields of science. More important, one of those fields was mathematical modeling, and that was well outside my area of expertise. So an annotated bibliography, which can be tedious to produce and even more tedious to read, began to look remarkably appropriate. There is one big reason for this: a great deal of the controversy about sea lice stems from the lack of data and the difficulty of getting good data, so many of the published papers drift toward hypothesis and discussion. This is not normally a bad thing in science (hypotheses get tested), but the degree of media attention to sea lice meant that the take-home message from each new paper was often just the hypothesis, not the actual findings of the scientists. Maybe, if I concentrated in my summaries on what the authors actually found, and scrupulously reproduced their own hedges when they hypothesized about what it all meant, a reader could cover the field quickly enough that he or she could come to their own conclusions.

Finally, one of the great strengths of the annotated bibliography is that the reader knows exactly what sources were consulted; if important papers were missed (I'm sure I missed some), it will be easy to add them and to keep the list up to date. Plus an annotated bibliography is easy to correct for errors in interpretation, which I hope the authors will tell me about.

The format for each summary

The first three categories (citation, geographic area and topic) are self-explanatory. "Kind of Research" tells the reader whether the study was done in the field (at sea or on a farm), in the laboratory, or as a "desk study" – my term for a review of already-published literature. These three categories get a bit fuzzy for papers that combine lab results with fieldwork (if you sit at a desk to run a mathematical model that uses field data, is that a desk study?), but are still helpful for general orientation.

"Kind of Document" is, again, self-explanatory and, with the exception of the Work in Progress appendix, most are peer reviewed articles in scientific journals. I like this limitation because it keeps the review manageable and defensible. Calling up a scientist and chatting about their unpublished work is easy and often edifying, but it's also unfair if you only contact one or two: everyone's views should be equally valid, and there are just too many of them. Sea lice is a fertile field for journalism, but this isn't the occasion.

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[10] Harvey, B., A. Baer and C. Ross. 2002. The Effects of Mariculture on Biodiversity. Background document for the Ad Hoc Technical Expert Group on Mariculture Rome, 1-5 July 2002. 50 pp.

I included a category called "Funder" because science has changed. Not so long ago (say, twenty years ago, when salmon farming was starting up in B.C.), most scientific research was funded by government. Now, industry, associations and foundations are just as important, and one would be naïve to pretend that many of these funders don't have an agenda. The process of science is supposed to function independently of the source of money, so there can be no harm in including this information. All funders appreciate recognition, and most peer reviewed papers now include a statement about the backers of the research. It's reproduced in the bibliography.

The "Rating" category has nothing to do with the quality of scholarship. A shoddy paper that should never have gotten through the review process can get a Must Read rating, and an elegant one languish as a Can Read. My ratings reflect one criterion only: How important are the findings to the controversy surrounding the source and effect of sea lice in the Broughton?

This brings us to the next two categories, namely the specific question the paper sets out to answer (self-explanatory), and the findings themselves – the "Main Message." The hardest part in writing the summaries was separating the actual findings from the author's interpretation of what these findings might mean. This is the real difference between a summary and a critical review, which often takes issue with the author's use of his own results. Not wanting (or having time) to do that, I tried simply to use language that made it clear what was interpretation, reproducing the "mays" and the "suggests" along with the "shoulds" and the "musts" that telegraph the arrival of the next hypothesis. Many times, these hypotheses turn out to be true; sometimes they don't. The "Main Message" section is my attempt to summarize what the paper said, not comment on its strengths and weaknesses as science and argument.

If there is any scientific editorializing at all in my summaries, it's in the final two categories. "Importance to Broughton" was hard to keep under control, because it could so easily slide into critical review (which this annotated bibliography is *not*). But the category is necessary if only because of the reliance (at least in 2004-2005, and progressively less so after that) on research in Europe. "See Also" is my attempt to remind the reader of connections – similar work, or a diametrically opposed study – without veering off into discussion of the merits of each.

Selecting the papers to summarize

The bibliography was begun around the time of one of the periodic spikes in media interest in the effect of sea lice on wild salmon. On September 17 2007, eighteen concerned scientists wrote an open letter to Prime Minister Stephen Harper and Premier Gordon Campbell stating that the debate over sea lice was over: the peer-reviewed science was clear in showing sea lice from Atlantic salmon farms to be threatening the survival of wild pink and chum salmon in the Broughton. The "debate is over" part of the letter – if it refers to the discussions of scientists – is disingenuous. As of early February 2008, while I write this, the scientific debate is as vigorous as ever. And, rather than one side backing down and saying "You win," what's more likely to happen is that the two sides will quietly coalesce. There is already plenty of evidence of this, as researchers have begun to work in partnerships that would have been unthinkable a few years ago.

The scientists' letter appeared while I was in the early stages of preparing this annotated bibliography for the Pacific Salmon Forum, who saw the need for an impartial review. Most interesting to me was the statement "the science is clear," which became a useful focus for the job at hand. Was it or wasn't it?

First, I had to identify "the science." I took the informal advice of one of the signatories to the September 17 letter, and did a search for "salmon farms and sea lice" on Google Scholar. Sure enough, the promised 1,200 or so references appeared. Back-dating the search only to 2004 and adding the word "wild" reduced the papers to a more manageable 282, but this still worked out to reading, understanding and summarizing a numbing ten papers a day in the time I had available. Still too many.

So I printed out the search and ticked off the ones that looked relevant. As it turned out, Google's ability to rank the results in order of relevance to the search terms was surprisingly close to my own selection; the last few pages of references had hardly any ticks at all. Many of the papers I'd chosen were already available from the Pacific Salmon Forum and its partners,[11] and I obtained the rest through the University of Victoria Library. The resulting pile of paper was only about eight inches high – the 1,200 papers had been whittled down by a factor of ten. Even some of these never made the final cut; the reference to sea lice might be interesting, like whether they attached to gills or skin, but added nothing to our understanding of natural dynamics in the Broughton. I read them but didn't include them in the bibliography.

I also summarized several batches of PowerPoint presentations made at dedicated sea lice workshops in 2007. There should be no misunderstanding about these summaries, which are provided here as an appendix: they are highly preliminary and don't pretend to represent the author's final conclusions. Some presentations were not even summarized, because they were just not in a usable format. But they do give a flavour of the most current research (which is well ahead of what's actually published), and are a fascinating postscript to the peer reviewed articles. In the end, the whole annotated bibliography consists of around a hundred references. Even with this pruning, the reader will experience some déjà vu with many of the papers of 2004 and 2005; questions posed have already been answered, which is at least a comforting reminder of how science works.

The papers summarized here include scientific work ranging from the elegant to the pedestrian. A few were unimpressive, but there were also some unexpected pleasures. Who would have imagined escaped Atlantic salmon transferring sea lice to their wild relatives in the oceanic feeding grounds off the Faroe Islands?[12] Or that the promiscuous mating habits of *L. salmonis* might actually matter in their control?[13] And that their eggs were so hard to kill?[14]

[11] The Pacific Salmon Forum provided me with a number of bibliographies on sea lice, including one by the Centre for Aquaculture and Environmental Research (2006), as well as a more comprehensive one on the Broughton Archipelago in general.
[12] Jacobsen and Gaard (1997)
[13] Todd et al. (2005)
[14] Pietrak and Opitz (2004)

The summaries are written, as far as possible, in plain language. I present the most recent papers first, on the theory that most readers want to start with the latest information. Within each year, the papers are ordered, as far as possible, by their date of acceptance for publication. Readers who prefer detective stories can read the summaries in reverse order.

Is a hundred or so references enough to tell whether the science is clear or not? In my view, it's more than enough. Otherwise there's something fundamentally wrong with the scientific method, and I don't think there is.

Is the science clear?

After reading, re-reading, thinking about and summarizing these papers, my conclusion is that the science on whether sea lice from farmed salmon are causing the demise of wild pink and chum populations in the Broughton isn't clear. Not to me, not yet. You have only to go to a scientific meeting on sea lice to realize this: if the science is so clear, why are the scientists arguing so much? Publishing so much? In other words, acting normally?

The burden of proof – that sea lice from farmed Atlantic salmon *don't* cause population decline in wild salmon – is with the salmon farming industry. Yet if this were a trial, and a jury was asked, *solely on the basis of the scientific evidence*, to convict Atlantic salmon of harming wild Pacific salmon using sea lice, I'm not sure they could. Too much of the evidence is circumstantial; lots of correlations, but no cause and effect, and there are vigorous defenders of both positions. So vigorous, in fact, that the jury in this imagined trial would probably be swung by the eloquence of those making the arguments. The scientific evidence would not be the only thing on their minds. Juries have to make decisions, even if some of the evidence isn't clear.

Reasons for the lack of clarity

It's fairly clear what each paper is saying; the lack of clarity is because there is so little overall agreement between different papers. In many cases, the papers are not even talking the same language. For example, it's extremely difficult to compare the results obtained from different mathematical models of louse dispersal and spread of infection (in some cases, these two kinds of models are themselves confused), and things get even worse when the models are run using different data sets. Another good example is the reliance, at least until recently, on studies from Europe using different species living in different conditions – even, as it has recently turned out, harbouring different species of lice. This last discovery – that *Lepeophtheirus salmonis* from the Atlantic is probably a different species from *L. salmonis* in the Pacific, may be behind observations that lice in the two oceans seem to behave in subtly different ways.[15] Then there's the curious concentration of most of the research on one species, pink salmon, when chum salmon are also susceptible to sea lice. The following are some other reasons why it's hard to find consensus among the scientists working on sea lice.

[15] Observations on the species status of *Lepeophtheirus* are courtesy of Ben Koop (pers. comm.)

Confusing terminology

The scientific papers are generally clear about the way they describe the severity of a louse infestation, but the terms they use – abundance, intensity and prevalence – all mean different things. Occasional reference to "numbers of sea lice" makes matters even worse, as does the fact that you have to be very clear about *what* you're describing as abundant (or prevalent, or intense). Sea lice in B.C. come in two genera (*Lepeophtheirus salmonis* and *Caligus clemensi*), and each exists in many different developmental stages. If one paper talks about "abundance of *L. salmonis* egg-bearing females" and another refers to "prevalence of *C. clemensi* copepodid larvae", these are apples and oranges. Once either report gets into the media, however, you can be sure it will all be reduced to "numbers of sea lice."

Lack of baseline biological data

Science is trying to fill in the gaps in our knowledge of what's "normal" for sea lice and salmon. Until fish farms came along, sea lice were just another crustacean parasite. It's now the most-studied parasite on fish, but there is still a lot to learn before anyone can say anything definitive about the normal louse burden on wild salmonids of various life stages in the nearshore area. We know something about louse loads on adult salmon at sea, but there's almost no historical information on juveniles closer to land. We also know far too little about the life history strategy of the two species of louse found in B.C. There's currently a spurt of interest in the role of sticklebacks as an alternate host for *L. salmonis* – something that didn't even figure in our understanding two years ago, but really shouldn't be a surprise, since lice were reported on a stickleback-like species in Japan back in 1994.[16] And the louse larvae released into the water column during the winter, outside of the normal spring pulse from salmon farms – where do these come from? The more biological baseline data we get – on life history, behaviour of lice and fish, and the effects of their interactions – the better the mathematical models will represent the true situation. Where lice are found still depends on where you look, and a fjord like Knight Inlet, if you were to search all its shoreline irregularities, is a big haystack. Salmon populations are highly influenced by temperature, climate and ocean conditions, so we have to understand these factors too.

Lack of access to industry data

Many of the papers reported here are hobbled by lack of access to industry data on things like louse infection levels, ocean conditions, louse treatments and fish health. To return to the courtroom analogy, it's as though investigators have access to some of the suspects (they can measure louse levels all they want outside the farms), but they can't talk to others. This situation is slowly being rectified, but for scientists trying to get a complete picture (which should mean *all* scientists) open data can't come soon enough. [17] When more data from industry are available,

[16] it was the Japanese dace, *Tribolodon hakonensis*

[17] The Pacific Salmon Forum is working to get agreement from more companies to release data to researchers

there won't be such an obvious hole in bibliographies like the present one, where you won't find much about how, and how well, lice are being controlled on farms in the Broughton Archipelago.

Complicated water dynamics

Moths can scent mates kilometers away; whales can call to each other through miles of ocean; salmon can find their way to their home rivers; and a single sea louse larva in a few cubic metres of water can latch onto a passing fish. These are all wonders, and their explanation requires insight and evidence from many fields of science, not just biology. In the case of transport of larval sea lice, we can't hope to predict their movements from A to B without understanding the movement of water and the movement of the larvae themselves. More and more findings of louse concentrations upstream of farms (that is, against the prevailing currents, which can be over-ruled by winds) make it clear that intuition is no predictor of louse movement.

Predicting water movement is a huge challenge: we can construct all the mathematical models we want, but they ultimately depend on real measurements in the real world, and the ocean environment in the Broughton is actually many environments, in three dimensions, acted on by winds, rainfall, unseen underwater topography and the pull of the moon. Any boater will tell you that travel in the Inside Passage is at the grace of the tides and the currents (which are not the same thing), and that there are many times when the predicted tides, current directions and strengths are simply wrong. That's because they're either based on old computer models that need updating, or because factors beyond the table-creator's control (rainfall and winds, mainly) override the predictions. Boaters see the evidence of currents on the macro scale all the time, in convergence zones where junk collects; imagine what a louse larva sees.

Dependence on mathematical models

Models are useful for predicting all kinds of biological and physical behaviours (climate change is a good example). The problem is that models are based on mathematics, and mathematics is like musical notation: it's not a spoken language. Science may use bewildering terms, but if these are in a spoken language they can eventually be puzzled out. However, if the arguments in a paper are expressed in a chain of mathematical formulae, non-mathematicians are at a loss. This is why, if the conclusions of the paper are reported in the media, it can seem as though no math was involved at all. There is still a healthy degree of disagreement between the proponents of the several mathematical models used to predict the movements in space and the infectivity of sea lice (these are not, by the way, the same things).[18] Disagreement is not a bad thing in science, and the models are being rapidly refined. It *will* get sorted out, but for the moment, competition between mathematical models is one big reason why "the science" is not yet "clear."

More good data means better (and probably fewer) models. Unfortunately, the sea louse question is a lot like other areas where statistics have "shown" something important, like the

[18] Dispersion models tell you where particles might end up; infectivity models tell you how an infection can spread.

famous study linking wine drinking with a reduction in heart disease. Many researchers furiously dispute that there's any causal link here, but the public remembers what it wants to remember, which may or may not be good for our hearts. The alcohol controversy will eventually be solved by more basic biology and epidemiology; sea lice will be solved by more field biology and oceanography.[19]

Is anything *clear?*

If there are still all these impediments to a clear picture of sea louse infection in the Broughton, what is the bright side? What has been accomplished between 2004 and February 2008, the period covered in this bibliography? The short answer is that the standard for research on sea lice has been raised. There is a community of scientists, largely from B.C., who are watching each other very closely. Better still, they are collaborating, in teams whose members might not have spoken to each other just a few years ago. Now they go into the field together, attend the same workshops, publish joint papers. The Pacific Salmon Forum can take a lot of credit for fostering this détente, but there's another, more fundamental reason that gets back to the nature of science: both sides need each other. If they're going to publish good science, what the other guy knows about "his" turf is part of the puzzle. Scientists are supposed to seek the truth about nature, but they also need publications. Even if they have to collaborate.

In terms of the scientific picture we now have, it's this:

- Salmon farms in the Broughton produce large numbers of sea louse larvae;
- Encounters between those farm-produced larvae and juvenile pink and chum salmon cannot yet be observed but are completely plausible biologically and in all current mathematical models;
- The percentage of sea lice on wild salmon that come from salmon farms can't be quantified;
- The role of alternate, "natural" sources of sea lice needs to be understood and quantified;
- Drawing a direct link between sea lice produced on salmon farms and the status of wild salmon populations will be a lively area of research.

Will there be a definitive answer?

Scientists can argue about whether pink salmon stocks in the Broughton will go extinct from sea lice in four generations – or forty, or never – but that's not the only issue. Practical decisions have to be made. Pink salmon stocks enjoy the protection of the Governments of Canada and British Columbia, through various legislation and policies. The people whose job it is to apply those policies and laws need an answer on sea lice, because there is biodiversity at stake. If sea lice infection can contribute to a salmon population crash, we need to know.

[19] That doesn't mean doing away with models, only that the models will get better, and use better data.

Similarly, the salmon farming industry needs to know how to run its business; jobs and profits are at stake. Argument over which is more important – biodiversity or money – touches every organism, ecosystem and human activity on this planet and will probably never end, but the discussion is more civilized when there's something other than emotion to fuel it.

The scientific results flowing out of sea lice research in the Broughton don't, in my opinion, provide enough clarity for a definitive answer. But they will, and soon. Crude approaches have yielded to much more sophisticated ones. In the last few years we've weaned ourselves off dependence on European research; we've started to look hard, in the field, at the life history not only of the lice but also of its wild salmon hosts; and we've refined the models that predict louse dispersion and infectivity, making them much better at accepting real-world data on water movements and biology. When a new cohort of graduate students takes on a problem like sea lice, as they have in B.C. universities and colleges, it's a good sign. The publication pipeline is full of new insights, and researchers are racing to work up already-collected data. With this kind of effort and cooperation, science gets a chance to do its stuff.

The real question is whether society is prepared to wait while it does. Science, as a process, may theoretically be disinterested, but when it comes to sea lice and wild salmon, that's not always true. The public is engaged; non-scientists need to make decisions. I hope the summaries that follow will help.

Summaries of Peer-reviewed Articles

2008

Ford, J., and Myers, R. A. 2008. **A global assessment of salmon aquaculture impacts on wild salmonids.** PLoS Biol 6(2): e33. doi:10.1371/journal.pbio.0060033.
Geographic area*:* Scotland, Ireland, Atlantic and Pacific Canada
Sea lice topic: effects of net-pen culture of Atlantic salmon on wild salmon populations
Kind of research: laboratory and field
Kind of document*:* peer reviewed online journal
Funder(s)*:* Lenfest Ocean Program, Census of Marine Life; NSERC
Rating: Can Read (useful background)
Question: Is there correlation between wild salmon population numbers and the presence of Atlantic salmon farmed in net cages?
Main message: Existing data on marine survival and returns of sea trout, Atlantic salmon, coho salmon, pink salmon and chum salmon were statistically analyzed for wild populations that did or did not swim past salmon farms during their early life. The start date of the analysis varied from 1960 (for Scotland) to the late 1980s (for B.C. coho). Reductions in survival or abundance associated with salmon farming varied for location and species. In many cases, reductions in survival or abundance were above 50%. Atlantic salmon populations and Irish sea trout were depressed more than were Pacific salmon populations (only coho, chum and pink were analyzed); greater effects on Atlantic salmon may reflect interbreeding and disease. In B.C., of the three salmon species analyzed, only pink salmon showed significant declines correlated with aquaculture. Estimated reduction in wild salmonid survival would be expected to increase with aquaculture production, but better management should reduce the impact on a per tonne basis.
Importance to Broughton: A big-picture meta-analysis that indicates significant detrimental effects of net-cage culture of Atlantic salmon. The study does not isolate mechanisms of impact, although it lists sea lice, other diseases, density effects, interbreeding and competition with escapees as known interactions.

Brooks, K.M, and Jones, S.R.M. 2008. **Perspectives on pink salmon and sea lice: scientific evidence fails to support the extinction hypothesis.** Reviews in Fisheries Science 16: 1-10.
Geographic area*:* Broughton Archipelago
Sea lice topic: effect of farm-origin sea lice on pink salmon population dynamics
Kind of research: critical review of previous research
Kind of document*:* peer reviewed journal article
Funder(s)*:* not stated
Rating: Must Read (critical to debate)
Question: Do Krkošek et al. (2007b) get it right when they predict extinction of several Broughton pink salmon populations within four generations?

Main message: Pink salmon returns in the Northeast Pacific, including the Broughton Archipelago, are naturally so highly variable as to make it hard to forecast future returns. The major pink salmon producing system in the Broughton Archipelago (Glendale River) should not have been excluded from the Krkošek et al. analysis. The mathematical model used in their study significantly overestimated the risk of death from sea louse infection. Linking improved pink salmon returns to a fallow migration path in Tribune Channel in 2003 was not justified. In terms of natural history, there are many wild sources of sea lice, including stickleback and several species of over-wintering juvenile Pacific salmon, whose importance relative to the lice shed by farmed salmon is not known. The Krkošek et al. study did not consider recent research on louse salinity preferences and recent dispersion models that account for this and other factors such as wind and river discharge. The production of sea lice on farms was overestimated and did not take into account the use of emamectin benzoate to manage louse infestations since 2004. Finally, the techniques used for statistical analysis and modeling were inappropriate and incomplete, and made selective use of data on pink salmon returns to show a cause-and-effect relationship between salmon farming and population declines. An alternative statistical analysis of all eleven Broughton watersheds in the DFO escapement database shows the trend since 2003 to be positive, suggesting population recovery rather than imminent extinction; current returns are within the area's historic variability.
Importance to Broughton: Presents many of the key issues in the lively scientific debate over the natural history and dynamics of sea louse infestation in the Broughton Archipelago, and shows that the scientific community remains polarized.
See also: Krkošek et al. 2007b (the paper commented on here). The fallowing experiment referred to is described in Morton et al. (2005).

Rosenberg, A. 2008. **The price of lice.** Nature 451: 23-24.
Geographic area*:* Broughton and global
Sea lice topic: environmental costs of net-pen aquaculture
Kind of research: opinion and comment
Kind of document*:* appeared in peer reviewed journal
Funder(s)*:* not stated
Rating: Can Read (useful background)
Question: What lesson can we take from Krkošek et al. 2007b, who predict extinction of several Broughton pink salmon populations within four generations?
Main message: Siting an aquaculture facility in a complex ecosystem can disrupt that ecosystem. Policy makers need to factor such ecosystem effects into their decisions about farm location and expansion, not only for Atlantic salmon but for other farmed species as well. Aquaculture systems that reduce or eliminate environmental impacts can be designed.
Importance to Broughton: An opinion piece in which predicted effects of sea lice on wild pink salmon are used as an example of ecosystem effects that could be reduced.
See also: Krkošek et al. 2007b (the paper commented on here).

2007

Krkošek, M., Ford, J.S., Morton, A., Lele, S., Myers, R.A., and Lewis, M.A. 2007b. **Declining wild salmon populations in relation to parasites from farm salmon**. Science 318: 1772-1775.
Geographic area*:* Broughton and Central Coast
Sea lice topic: population-level effects of sea lice
Kind of research: laboratory and field
Kind of document*:* peer reviewed journal article
Funder(s)*:* NSERC; Canadian Mathematics of Information Technology and Complex Systems National Centre of Excellence; National Geographic Society; Tides Canada Foundation; University of Alberta Bill Shostak Wildlife Award; Lenfest Ocean Program, Census of Marine Life; Canada Research Chair
Rating: Must Read (critical to debate)
Question: What is the effect of sea louse infestation on the population dynamics of pink salmon from rivers close to, and remote from, active salmon farms?
Main message: The effects of salmon lice on pink salmon population dynamics were investigated through a mathematical treatment of Fisheries and Oceans Canada historic escapement data for 64 Central Coast rivers distant from salmon farms and seven Broughton Archipelago rivers whose pink salmon populations must migrate past at least one salmon farm. Rivers such as the Glendale, whose populations are substantially enhanced, were not included. To obtain population growth rates from data on escapements (the number of adults that reach the spawning grounds), the 1954 Ricker equation for population growth rate was modified and applied to pooled populations from 1970 to 2006. The degree to which pink salmon mortality was caused by lice was estimated by further iterative modification of the Ricker model, and provided estimated louse-caused mortalities between 16 and 97% for the seven exposed rivers between 2002 and 2006. The mortality attributed to lice varied significantly between rivers and between years; on average, it was highest in 2002 and 2005, lowest in 2004, and roughly midway between those extremes in 2003 and 2006. Statistical analysis of population viability showed that some populations exposed to lice decreased to less than 1% of their historic abundance, while others exceeded their historic abundance. Although salmon farming was introduced to the Broughton in 1987, a lack of population declines before 2001 may be explained by a latent period during which farm-derived louse abundance reaches a critical host density threshold. Although the results of this modeling study were based on a short time series for infested populations (five years of data), waiting for larger data sets carries a 99% risk of population collapse within four generations if louse exposure is maintained.
Importance to Broughton: Represents an important trend in sea louse research, namely the use of mathematical analysis to try to answer the "big picture" questions of how much wild salmon mortality is caused by sea lice, and how much that mortality affects the survival of wild salmon populations.
See also: Hvidsten et al. 2007, where a different statistical approach applied to a single wild Atlantic salmon population remote from salmon farms in Norway showed no significant correlation between sea louse mean intensity and the number of returning adults caught the following year. Brooks and Jones (2008) provide a critical review that takes issue with many of the study's conclusions.

Krkošek, M., Gottesfeld, A., Proctor, B., Rolston, D., Carr-Harris, C., and Lewis, M.A. 2007a. **Effects of host migration, diversity and aquaculture on sea lice threats to Pacific salmon populations**. Proceeding of the Royal Society of London Series B. 274: 3141-3149
Geographic area: Skeena River estuary
Sea lice topic: Infection rates on wild salmon juveniles in an area where there are no salmon farms
Kind of research: field and desk study
Kind of document: peer reviewed journal article
Funder(s): Bill Shostak Wildlife Award; NSERC Graduate Scholarship; Canada Research Chair; National Geographic Society; David Suzuki Foundation; Canadian Sablefish Association; National Research Council Canada; B.C. Pacific Salmon Forum; B.C. Aquaculture Research and Development Council
Rating: Must Read (critical to debate)
Question: What are the lice levels on juvenile pink salmon in the area around the mouth of the Skeena River? What can a mathematical model tell us about wild salmon population dynamics given various levels of infestation?
Main message: In the Skeena River estuary area, juvenile pink salmon do not encounter adult salmonids until late May or June, when chinook salmon return to spawn. Prevalence of both *L. salmonis* and *C. clemensi* on juvenile pinks in 2004-2006 increased significantly in July; the ratio of the two louse species, while still favouring *C. clemensi*, became more even in July. *C. clemensi* was seen on several non-salmonid species as well as on pink salmon, and is probably maintained by a reservoir on nearshore non-salmonid hosts while *L. salmonis* is "brought in" by returning adult salmon. The only non-salmonid species parasitized by *L. salmonis* was three-spined stickleback. In a separate theoretical analysis, a mathematical model suggested that pink salmon populations could collapse at abundances of 1.5-5 *L. salmonis* per fish, and that this eventuality should be reflected in planning any aquaculture development in the Skeena region.
Importance to Broughton: Gives an idea of "background" sea lice infestation on juvenile pink salmon in an area with no salmon farms, while offering an explanation for the source of the parasite.
See also: Jones et al. 2006a regarding a role for stickleback as temporary hosts for *L. salmonis;* Krkošek et al. 2007b extends the mathematical modeling concept to pink salmon returns in a portion of the Broughton Archipelago.

Gillibrand, P.A., and Willis, K.J. 2007. **Dispersal of sea louse larvae from salmon farms: modeling the influence of environmental conditions and larval behavior.** Aquatic Biology 1: 63-75.
Geographic area: Scotland
Sea lice topic: modeling louse dispersal
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Must Read (critical to debate)

Question: Does inclusion of environmental factors (e.g. wind) and louse behaviour improve the mathematical models for dispersal?
Main message: Previous models for sea louse dispersal lack key physical and hydrodynamic parameters as well as input regarding larval behaviour; for this reason, they have serious shortcomings for predicting dispersal from a point source such as a salmon farm. A coupled hydrodynamic/louse transport model applied to an idealized (that is, not real) rectangular coastal inlet 30 km long was used to gauge the effects of the following variables: wind, freshwater river runoff, tidal currents, temperature-dependent growth, mortality, salinity preference and daily vertical migration of larvae. Running the model with and without different larval behaviour patterns made it easy to see the effects of environmental factors on larvae released from a single point source near the landward end of the idealized "inlet". Wind forcing and vertical migration were especially strong modifiers of dispersal; in combination with the effects of runoff, they were able to concentrate copepodids near the head of the inlet – confirming field observations. Making larval behaviour (vertical migration) part of the model increased retention of copepodids in the "inlet" and raised surface distribution above that for passive particles. Vertical migration, which has the effect of toggling larvae from landward-flowing to seaward-flowing currents, also reduced the mean distance larvae are transported, a finding highly relevant to interpretating the results of the mathematical models presently being used to describe larval dispersal in the Broughton Archipelago. "Shoreline" concentrations, while possibly an artefact, could explain vulnerability of migrating salmonids in nearshore areas. Models that depict larvae as passively dispersing particles are overly simplistic and should not be used as management tools. The present model, when run in an idealized inlet, concurs with field observations that suggest fish farms are a major source of sea lice in coastal inlets.
Importance to Broughton: The model described here is the first to couple three-dimensional water circulation with larval behaviour. It is potentially a significant advance in mathematical modeling of louse dispersal, and one that should stimulate research on larval behaviour and ways to incorporate it into models.
See also: Unpublished results incorporating wind forcing into a model for the Broughton (Stucchi and Foreman 2007, summarized in "Unpublished or In Progress" below).

Trudel, M., Jones, S.R.M., Thiess, M.E., Morris, J.F.T., Welch, D.W., Sweeting, R.M., Moss, J.H., Wing, B.L., Farley, E.V., Murphy, J.M., Baldwin, R.E., and Jacobson, K.C. 2007.
Infestations of motile salmon lice on Pacific salmon along the west coast of North America.
American Fisheries Society Symposium 57.
Geographic area: coastal Oregon to Alaska
Sea lice topic: spatial and temporal variation in louse infestations in coastal waters
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Fisheries and Oceans Canada; Bonneville Power Administration; NOAA Ocean Carrying Capacity Program; U.S. GLOBEC; Yukon River Drainage Fisheries Association
Rating: Must Read (critical to debate)
Question: What is the degree of infestation of different species and sizes of Pacific salmon in coastal waters throughout their North American range?
Main message: Based on surface trawl data obtained from ongoing research programs, *L. salmonis* infestation rates on "small" (less than one year at sea) and "large" (ocean age one-plus)

sockeye, coho, chinook, pink and chum salmon were measured in 2002 and 2003. Both size classes were infested year-long, from the Oregon coast to the Arctic Ocean, with larger salmon consistently higher in prevalence and abundance. For small salmon, prevalence and abundance were highest for pink and coho salmon. Sources of lice on juvenile salmon in coastal waters could include returning spawners, farmed Atlantic salmon, and resident coho and chinook. Large catches of infested small pink and chum apparently over-wintering in coastal waters, and the presence of lice in the Alaska and Bering Sea samples (where there are no salmon farms), suggest further research on the relative contribution of these sources. Salmon louse transmission appears to occur in both coastal and oceanic waters throughout the salmon life cycle, so lice on salmon that over-winter in coastal waters could be a pool of infective copepodids. There was no consistent north-south gradient in louse infestation.
Importance to Broughton: While not specifically targeting or comparing infestations in the Broughton Archipelago, this big-picture study provides food for thought on the potential pool of infective lice represented by over-wintering salmonids, and also provides background data on infestation in areas remote from salmon farms.
See also: Beamish et al. (2007) on over-wintering salmonids as a copepodid pool; Krkošek et al. (2007a) provide background louse infestation in the Skeena estuary, an area without salmon farms.

Hvidsten, N.A., Finstad, B., Kroglund, F., Johnsen, B.O., Strand, R., Arnekleiv, J.V., and Bjørn, P.A. 2007. **Does increased abundance of sea lice influence survival of wild Atlantic salmon post-smolts?** Journal of Fish Biology 71: 1639-1648.
Geographic area: Trondheimsfjord, Norway
Sea lice topic: correlation between sea louse levels and wild salmon population strength
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Norwegian Directorate for Nature Management
Rating: Must Read (critical to debate)
Question: Can sea louse infection rates on wild Atlantic salmon smolts be related to population size?
Main message: In an area presumably uninfluenced by salmon farms, data on sea louse infestation rates of wild Atlantic salmon smolts (1992-2004) were correlated with official catch statistics for one-sea-winter adults returning to a major affluent, the Orkla River. (The Orkla is a regulated river producing a mixture of wild and hatchery fish). Louse prevalence, abundance and intensity varied widely over the 12 years of sampling. After correcting catch statistics for ocean mortality, no significant correlation was found between sea louse mean intensity and the number of one-sea-winter adults caught the following year in the Orkla River. Other factors, such as temperature and high variation in marine survival, may explain variation in wild catch; different sampling methods and locations may also have affected the outcome of the study.
Importance to Broughton: Highlights the difficulty of making correlations between infestation and wild population size in complex marine ecosystems where there are many factors other than sea lice burden that can affect populations. Presumably represents the “control” scenario where salmon farms do not contribute to the louse load on wild Atlantic salmon smolts.

See also: For another study attempting to describe the correlation between louse load and wild salmon populations, this time in an area of salmon farms in the Broughton, see Krkošek et al. 2007b.

Nowak, B.F. 2007. **Parasitic diseases in marine cage culture – An example of experimental evolution of parasites?** International Journal for Parasitology 37(6): 581-588.
Geographic area: global
Sea lice topic: touches on sea lice as part of a more general review
Kind of research: desk study
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Should Read (part of the puzzle)
Question: What do we know about the kind, number and effects of parasites on marine fish cultured in cages?
Main message: Based on a review of recent literature from around the world, cage culture introduces novel hosts, ecological niches and diets into natural marine systems, and the effects on parasites that normally infect wild fish are unpredictable. Free-living organisms not known to be parasitic in the wild may infest cultured fish (that is, cage culture can contribute to new parasitic diseases); others may be acquired from the wild, amplified in culture, and released to the wild again (recent research and transmission hypothesis in the Broughton Archipelago are provided as an example). Farmed fish, especially exotic species, usually have fewer parasites than do wild fish species, probably because they are fed a prepared diet. The balance between endoparasites (internal) and ectoparasites (external) also shifts toward the latter in farmed fish. Cultured fish can't avoid parasites as easily as can wild fish (worm-free sticklebacks, for example, avoid infected sticklebacks, at least in the laboratory). When the dominant parasite in culture is also present in wild populations, adverse effects are greater in the farmed fish.
Importance to Broughton: While not confined to sea lice, this review is an excellent primer on how hard it is to predict the effects of introducing novel environments and hosts into marine ecosystems. The cited studies argue collectively for a precautionary approach to marine cage culture; in so doing, they also illustrate how difficult it is to describe parasite behaviour in disturbed systems when we know so little of their life in the "natural" state.
See also: Sepúlveda et al. 2004 provides more detail on the differences in parasite kind and number between farmed and wild fish.

Webster, S.J., Dill, L.M., and Butterworth, K. 2007. **The effect of sea lice infestation on the salinity preference and energetic expenditure of juvenile pink salmon (*Oncorhynchus gorbuscha*).** Canadian Journal of Aquatic Sciences 64: 672-680.
Geographic area: relevant to any coastal area used by Pacific salmon
Sea lice topic: effects of sea lice on physiology and behaviour of juvenile salmon
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): Weston Foundation/B.C. Packers Graduate Fellowship; NSERC
Rating: Should Read (part of the puzzle)

Question: Is infection of pink salmon post-smolts with *L. salmonis* a possible explanation for the reported phenomenon of "premature return" to fresh water? Do fish infected in the laboratory choose lower salinity, and behave in ways that might rid them of sea lice?
Main message: Infected pink salmon post-smolts preferred fresh water to salt water. It was unclear whether this choice was made in order to regain osmotic balance or to remove attached lice, although increased leaping and rolling behaviour in infected fish may have been in order to dislodge lice. Whatever the reason for freshwater preference and leaping/rolling, both behaviours are likely to have negative effects on survival.
Importance to Broughton: confirms that pink salmon juveniles infected with sea lice can change their behaviour in ways that may affect survival; provides data on pink salmon "premature return" (previously all such data have been from sea trout).
See also: Premature return in lice-infected sea trout (Bjørn et al. 2006).

Bergh, Ø. 2007. **The dual myths of the healthy wild fish and the unhealthy farmed fish**. Diseases of Aquatic Organisms 75: 159-164.
Geographic area: global
Sea lice topic: public perceptions of aquaculture and fish health
Kind of research: desk study
Kind of document: peer reviewed critical essay
Funder(s): not listed
Rating: Can Read (useful background)
Question: How do people perceive diseases and parasites on wild and farmed fish?
Main message: Fish health in aquaculture is often oversimplified by assuming that wild fish are disease-free. High host abundance in culture may simply amplify a host-parasite relationship that already exists in nature. Sea lice is a good example; farmed salmon in Norway now outnumber wild hosts by about 100 to one; unprotected wild fish become more susceptible than farmed ones.
Importance to Broughton: Sea lice used as a case study for ethical debate on the acceptable tradeoffs of fish farming

Longhurst, A. 2007. **Doubt and certainty in fishery science: Are we really headed for a global collapse of stocks?** Fisheries Research 86: 1-5.
Geographic area*:* global
Sea lice topic: the peer-review process
Kind of research: viewpoint
Kind of document*:* appeared in peer reviewed journal
Funder(s)*:* not stated
Rating: Must Read (critical to debate)
Question: Does the peer review process still work?
Main message: While this opinion piece concerns recent reports of global fisheries collapses, not sea lice, one of the main arguments is that the rise of what Hilborn (2006b) dubbed "faith-based fishery science" has resulted in a community of scientists whose espousal of social issues related to their research has affected its credibility. Some scientists are losing confidence in what

is presented as unbiased investigation and disinterested peer review, especially in respected journals like *Science* and *Nature* that now cultivate media interest in forthcoming papers.
Importance to Broughton: The involvement of sea lice from salmon farms in infestations on wild Pacific salmon juveniles is a contentious topic of great social interest that receives considerable media attention. Reliance on peer-reviewed science for eventual policy decisions means the review process must remain impartial.
See also: Hilborn (2006b).

Beamish, R.J., Neville, C.M., Sweeting, R.M., Jones, S.R.M., Ambers, N., Gordon, E.K., Hunter, K.L., and McDonald, T.E. 2007. **A proposed life history strategy for the salmon louse, *Lepeophtheirus salmonis* in the subarctic Pacific.** Aquaculture 264(1-4): 428-440.
Geographic area: Central North Pacific; Queen Charlotte Strait, Broughton Archipelago
Sea lice topic: natural history of *L. salmonis*
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Innovation Council of B.C., Aquaculture Collaborative Research and Development Program
Rating: Must Read (critical to debate)
Question(s): How does *L. salmonis* survive in nature, and what can that tell us about possible routes of infection for juvenile pink salmon?
Main message: Based on sampling in the central Pacific and Queen Charlotte Strait, the distributions of juvenile and adult Pacific salmon can overlap in coastal and nearshore areas. This coincidence in space and time gives the offspring of sea lice from adult salmon a chance to infect juveniles. Infected coho and chinook juveniles, which spend a year in coastal and nearshore areas, could be acting as an overwintering host for sea lice and might subsequently infect juvenile salmon entering the ocean the next spring. This suggested louse life history strategy may be an evolutionary compensation for reduced host densities in the open ocean, and could mean that sea louse infection of juvenile Pacific salmon is a natural phenomenon in coastal areas.
Importance to Broughton: Proposes a natural mechanism for infection of pink salmon post-smolts. Better understanding of sea lice natural history will make it easier to judge the importance of different infection routes.
See also: Krkošek et al. 2006a for another view, namely that distribution of wild adult and juvenile salmon do not overlap in coastal areas.

Orr, C. 2007. **Estimated sea louse egg production from Marine Harvest Canada farmed Atlantic salmon in the Broughton Archipelago, British Columbia, 2003-2004.** North American Journal of Fisheries Management 27: 187-197.
Geographic area: Broughton Archipelago
Sea lice topic: source of sea lice in Broughton
Kind of research: desk study
Kind of document: peer reviewed journal article
Funder(s): Vancouver Foundation; David and Lucille Packard Foundation; Gordon and Betty Moore Foundation; David Suzuki Foundation

Rating: Must Read (critical to debate)
Question: How many infective sea lice are produced by salmon farms in the Broughton?
Main message: Based on raw data provided by Marine Harvest Ltd. for numbers of farmed fish and gravid sea lice per fish for 12 salmon farms (2003) and 10 farms (January-September 2004), a mathematical model was built to incorporate assumptions about numbers of escaped fish, sea louse fecundity and sea louse survival to the infective stage. The model showed sea lice egg production reached 1.5 billion eggs from around 6 million gravid females before treatment with Slice (emamectin benzoate) dramatically reduced louse counts. Additional data on stocking dates suggest that farmed salmon hosted few lice until about 200 days after they were introduced to seawater. Findings support the view that farmed Atlantic salmon are the main source of sea lice infection of wild juvenile Pacific salmon.
Importance to Broughton: Shows that high numbers of sea lice eggs can be released into Broughton waters from farmed Atlantic salmon, and that these numbers can be dramatically reduced by chemical treatment.
See also: Differs from Beamish et al. (2007) in assuming that, during spring, the wild salmon that may also be a source of sea lice infection are relatively scarce.

Sivertsgård, R., Thorstad, E.B., Økland, F., Finstad, B., Bjørn, P.A., Jepsen, N., Nordal, T., and McKinley, R.S. 2007. **Effects of salmon lice infection and salmon lice protection on fjord migrating Atlantic salmon and brown trout post-smolts**. Hydrobiologia 582: 35-42.
Geographic area: Romsdalsfjord, Norway
Sea lice topic: behavioural effects of sea lice on salmon post-smolts
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): European Commission; Aquanet Canada (RSM); Norwegian Institute for Nature Research; Statkraft Energy AS
Rating: Can Read (useful background)
Question: Does experimental infection of Atlantic salmon and brown trout post-smolts affect their migration out of the fjord?
Main message: Atlantic salmon and brown (sea) trout smolts tagged with acoustic transmitters were infected with sea lice or exposed to a sea lice prophylactic treatment before being tracked on their progress through Romsdalsfjord toward the open ocean (80 km). Atlantic salmon smolts took an average six days to exit the fjord; while trout stayed longer in the fjord. Survival or rate of migration was not affected by lice infection or lice prophylaxis for either species. The speed of the Atlantic salmon migration probably meant that sea lice didn't have time to develop into an infectious stage before they exited the fjord; for trout, a low recovery rate of tagged fish made it difficult to reach a definitive conclusion. The study was not designed to test whether trout could have returned to fresh water after infection.
Importance to Broughton: Geography is similar, but the fish are older and larger, and experimental design limits relevant conclusions.
See also: Laboratory study of effects of sea lice infection on pink salmon smolts (Webster et al. 2007).

Øines, Ø., and Heuch, P.A. 2007. ***Caligus elongatus* Nordmann genotypes on wild and farmed fish.** Journal of Fish Diseases 30(2): 81-91.
Geographic area: S.E. Norway
Sea lice topic: louse genetics and host preferences
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Rating: Can Read (useful background)
Question: How are different louse genotypes distributed between various hosts?
Main message: The two described genotypes of *Caligus elongatus* appear to differ in their distribution with regard to time of year and geography. In wild fish, Genotype 1 predominated in March-June; the second genotype was more common in autumn. Closer to salmon farms, Genotype 2 was more common in autumn.
Importance to Broughton: Not only confirms multiple genotypes in a single sea louse species, but also shows those genotypes vary with season and fish. May offer some support for the idea of forensic DNA identification of lice found on pink salmon juveniles.
See also: Saksida et al. (2007) hypothesized that different genotypes of *L. salmonis* might have differing effects on salmon in Europe and B.C.

Saksida, S., Constantine, J., Karreman, G.A., and Donald, A. 2007. **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.** Aquaculture Research 38(3): 219-231.
Geographic area: Broughton Archipelago
Sea lice topic: number of sea lice on salmon farms
Kind of research: desk study
Kind of document: peer reviewed journal article
Funder(s): Aquaculture Collaborative Research and Development Program; Fisheries and Oceans Canada; B.C. Salmon Farmers' Association; Heritage Salmon; Stolt Sea Farm
Rating: Must Read (critical to debate)
Question: How many sea lice are there on farmed salmon in the Broughton Archipelago?
Main message: Summarizes and analyzes data provided by the industrial sea lice monitoring program and the B.C. Ministry of Agriculture and Lands regulatory audit between March 2003 and December 2005 for all Broughton farms. The report describes the monitoring procedures and how they differ from those in similar programs in Norway, Scotland and Ireland. Because treatment of infected fish was compulsory (post-2004) at agreed-on trigger levels of infection, the data do not represent a controlled experiment; rather, the reported levels of sea lice reflect a situation where sea lice levels are artificially capped, and any natural seasonal variation is obscured. The data do, however, show lice levels two to three times lower than those reported for farmed salmon in Europe, despite fewer treatments per production generation and a different timing of treatments. Slice treatment in B.C. farms appeared to last longer than in Europe. Explanations for lower sea lice abundances and greater Slice efficacy in B.C. doesn't appear related to differences in production strategies, site location or water quality parameters; genetic differences in *L. salmonis* may be one explanation, and should be investigated.
Importance to Broughton: Uses government-audited industry data on lice levels and treatment efficacy in B.C. to argue that European literature may have limited relevance to the B.C. situation.

See also: Uses some of the same industry data as Orr (2007), but also includes 2005; focuses on numbers of sea lice rather than modeling of potential egg production. Koop (see 2007 In Progress) offers genetic evidence for there being separate Pacific and Atlantic *L. salmonis* species.

2006

Jones, S.R.M., Kim, E., and Dawe, S. 2006a. **Experimental infections with *Lepeophitheirus salmonis* (Krøyer) on threespine sticklebacks, *Gasterosteus aculeatus* L. and juvenile Pacific salmon, *Oncorhynchus* spp.** Journal of Fish Diseases 29:489-495.
Geographic area: Broughton Archipelago
Sea lice topic: role of sticklebacks as sea lice hosts
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): B.C. Innovation Council; Fisheries and Oceans Canada
Rating: Must Read (critical to debate)
Question: Do *L. salmonis* complete their development on three-spined stickleback? What role does the stickleback play in the life cycle of the louse?
Main message: Controlled laboratory infection of wild stickleback and hatchery-raised pink and chum salmon smolts affected the three species differently. Adult stages appeared on both salmon species after 20 days, but not on sticklebacks. Initial abundance was higher on chum than on pink salmon; intensity of infection was, however, consistently highest on stickleback. The fact that, despite this initially greater susceptibility, stickleback did not support lice development through to adult stages confirmed earlier field observations. In nature, stickleback may be temporary hosts for early louse development, and may transfer lice to juvenile salmon.
Importance to Broughton: Provides more information on the role of a potential "sentinel species" that may also be involved in carrying or amplifying sea lice.
See also: Follow-up research to Jones et al. (2006b).

Jones, S.R.M., Prosperi-Porta, G., Kim, E., Callow, P., and Hargreaves, N.B. 2006b. **The occurrence of *Lepeophitheirus salmonis* and *Caligus clemensi* (Copepoda: Caligidae) on threespine stickleback *Gasterosteus aculeatus* in coastal British Columbia.** Journal of Parasitology 92: 473-480.
Geographic area: Broughton Archipelago
Sea lice topic: occurrence of sea lice on stickleback
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Fisheries and Oceans Canada
Rating: Must Read (critical to debate)
Question: How does lice abundance on stickleback vary with time and location of collection, and with surface salinity?

Main message: Beach and purse seines were used to collect three-spined stickleback, a non-migratory species recently found to be a host for *L. salmonis* and *C. clemensi*, from 11 sampling zones in the Broughton Archipelago. Both species of lice were found on 84.3% of sticklebacks, including those from areas upstream of salmon farms. More lice were found in zones with higher salinity, confirming laboratory observations of the limiting effect of low salinity. DNA evidence was used to identify the predominantly early stages of *L. salmonis*, confirming that this is the first evidence of the species being a frequent parasite on stickleback. Rare occurrence of adult stages may mean that *L. salmonis* often fails to complete development on stickleback; infections appeared to have minimal impact. As a resident species, stickleback may be a useful "sentinel" for monitoring year-round abundance of sea lice over a wide geographic area.
Importance to Broughton: Provides more information on a previously unrecognized alternate host for sea lice that could be used to assay for lice levels in different locations in the Broughton Archipelago; provides further confirmation of sea louse susceptibility to low salinity.
See also: Jones et al. 2006a for comparison of lice levels on salmon and stickleback; Nagasawa (2004) for identification of another euryhaline, non-migratory alternate host (dace) in northern Japan.

Bricknell, I.R., Dalesman, S.J., O'Shea, B., Pert, C.P., and Luntz, A.J.M. 2006. Effect of environmental salinity on sea lice *Lepeophtheirus salmonis* settlement success. Dis. Aquat. Org. 71: 201-212.
Geographic area: Scotland
Sea lice topic: copepodid salinity tolerance
Kind of research: laboratory study
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Should Read (part of the puzzle)
Question: How do *L. salmonis* copepodids respond to changes in salinity?
Main message: High concentrations of copepodids around river mouths in spring raises the issue of their salinity tolerance, including ability to infect salmon at lower salinity. A series of laboratory experiments testing infection and copepodid survival at various salinities showed that, if given an option, copepodids selected full strength sea water (35 ppt), and that their survival dropped significantly below 29 ppt. Their ability to infect Atlantic salmon was even more sensitive to salinity change, dropping by nearly half at 26 ppt. Lower salinity reduced copepod activity and the ability to respond to host cues. Being in a lower-salinity environment will compromise both survival and the ability to infect fish, which suggests that infection of newly migrating smolts occurs away from river mouths.
Importance to Broughton: Salinity changes in the Broughton Archipelago, with location, rainfall and season. Its effect on *L. salmonis* behaviour and ability to infect fish is a frequently-debated variable when predicting zones of contact between farm-origin sea lice and wild salmonids. Salinity tolerance is an important parameter in some of the mathematical models used to predict infection.
See also: Genna et al. (2005) on salinity effects on intensity and distribution of copepodids; Brooks and Stucchi (2006) on effects of salinity on survival and distribution of copepodids (and linked papers by Krkosek et al. that form part of the rebuttal and response); Jones et al. 2006c on lice abundance vs. surface salinity.

Bjørn, P.A., Finstad, B., Kristoffersen, R., McKinley, R.S., and Rikardsen, A. H. 2006. **Differences in risks and consequences of salmon louse, *Lepeophtheirus salmonis* (Krøyer), infestation on sympatric populations of Atlantic salmon, brown trout, and Arctic charr within northern fjords.** ICES Journal of Marine Science 10: 1093.
Geographic area: northern Norway
Sea lice topic: occurrence of sea lice on wild salmonids
Kind of research: field study
Kind of document: peer reviewed journal article
Funder(s): Norwegian Research Council; Norwegian Directorate for Nature Management; European Commission
Rating: Should Read (part of the puzzle)
Question: When three species of salmonid occur together in a fjord area where there is salmon farming, do they respond differently to sea louse infection?
Main message: Atlantic salmon, brown trout and Arctic charr appear to have markedly different behaviours once they leave fresh water as post-smolts. Atlantic salmon seem to exit fjords relatively quickly while trout and charr linger in nearshore areas before returning to freshwater; the pattern of louse infestation seems to reflect these behavioural differences, with Atlantic salmon smolts uninfested in July, compared to increasing levels for trout and charr in the same period. Migration timing and seawater residence (both still poorly understood) are probably behind these different infestation levels, although there may also be differences in each species' susceptibility.
Importance to Broughton: Because the "wild" salmon species sampled are all different from Pacific salmon and all behave differently once in salt water, it's hard to draw parallels to the Broughton – especially because salmon farm locations are not provided in the present study (nor is the status of the fish sampled, ie. wild or hatchery).
See also: Any of the Broughton studies on infection on wild pink and chum salmon.

Krkošek, M., Lewis, M.A., Morton, A., Frazer, L.N., and Volpe, J.P. 2006a. **Epizootics of wild fish induced by farm fish.** Proceedings of the National Academy of Sciences 103(42): 15506-15510.
Geographic area: Broughton Archipelago
Sea lice topic: louse transmission dynamics and survival of infected juvenile salmon
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): NSERC; Tides Canada Foundation; National Research Council of Canada; David Suzuki Foundation; Canadian Sablefish Association; B.C. Wilderness Tourism Association
Rating: Must Read (critical to debate)
Question: What is the impact of *L. salmonis* from salmon farms on wild juvenile salmon?
Main message: Two separate data sets (one on infection dynamics of juvenile salmon and one on survival of infected juvenile salmon reared in experimental ocean enclosures) were analyzed using coupled mathematical models. The models permitted estimating the impact of salmon farms in the Broughton on wild pink and chum juveniles. Estimated mortality was high (9-95%) but consistent with field observations. Juvenile salmon enter the ocean lice-free, months before

wild, louse-carrying adult salmon occupy the same waters. However, farm fish undermine this natural protective mechanism by providing a novel source of infective lice, thus eliminating the temporal refuge and paving the way for high epizootic mortality.
Importance to Broughton: Provides predictions of louse movement and associated mortality of juvenile salmon that can be tested through further field studies.
See also: Beamish et al. (2007) for another view, namely that the distributions of juvenile and adult Pacific salmon normally overlap in coastal and nearshore areas in the Broughton.

Wells, A., Grierson, C.E., MacKenzie, M., Russon, I.J., Reinardy, H., Middlemiss, C., Bjørn, P.A., Finstad, B., Bonga, S.E.W., Todd. C.D., and Hazon, N. 2006. **Physiological effects of simultaneous, abrupt seawater entry and sea lice (*Lepeophtheirus salmonis*) infestation of wild, sea-run brown trout (*Salmo trutta*) smolts.** Canadian Journal of Fisheries and Aquatic Sciences 63: 2809-2821.
Geographic area: Scotland, Ireland, Norway
Sea lice topic: physiological effects of sea lice on sea trout smolts
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): European Commission
Rating: Must Read (critical to debate)
Question: is there a minimum target sea lice burden for sea trout smolts?
Main message: A new laboratory assay exposes 37g sea trout smolts to seawater shortly before challenging them with various levels of *L. salmonis*, thus mimicking migration into sea water shortly before encountering sea lice in the wild. Recordings of a suite of physiological responses for 28 days following exposure indicated a sublethal threshold of 13 mobile lice per fish at 21 days after infection, beyond which significant physiological stress occured. This threshold value may have value as a management tool for conserving wild salmonid stocks.
Importance to Broughton: Some significant differences: sea trout do not occur in B.C.; their smolts are much larger than pink or chum salmon; and the assumption is made that sea trout are exposed to a pulse of copepodids shortly after leaving the river. Nevertheless, the methodology for developing threshold infection levels is relevant.
See also: Jones et al. (2006c) provides louse levels on juvenile pink salmon in the Broughton, and the data are extended in unpublished work (Hargreaves 2007, see "Unpublished or In Progress" below). Compare to the prediction of pink salmon population extinction at 1.5 -5 lice/fish (Krkošek et al. 2007a).

Boxaspen, K. 2006. **A review of the biology and genetics of sea lice.** ICES Journal of Marine Science 63(7): 1304-1316.
Geographic area: global
Sea lice topic: biology and genetics
Kind of research: desk study
Kind of document: critical scientific review
Funder(s): not stated
Rating: Should Read (part of the puzzle)

Question: What is the state of our understanding of sea lice biology and genetics as seen from the scientific literature 1999-2005?
Main message: Many aspects of sea lice biology are relevant to its presence on wild salmon near salmon farms. Over-wintering of *L. salmonis* on salmonid hosts, for example, has implications for transmission. Genetic advances are particularly relevant to understanding transmission dynamics; for example, recent studies showing no population substructure in the Atlantic Ocean suggest long-distance transfer of lice (the Pacific Ocean population is, however, distinct from the Atlantic one). This overall lack of genetic population structure doesn't hold promise for forensic identification of lice on farmed fish; however, recent studies on elemental analysis show some potential for tools to identify louse origin. There is a useful summary of monitoring programs and the variables that affect their results.
Importance to Broughton: background review
See also: Costello (2006) reviews on transmission dynamics; Koop ("Unpublished and in Progress", below) provides evidence that the Pacific form of *L. salmonis* is in fact a different species.

Beamish, R.J., Jones, S., Neville, C-E., Sweeting, R., Karreman, G., Saksida, S., and Gordon, E. 2006. **Exceptional marine survival of pink salmon that entered the marine environment in 2003 suggests that farmed Atlantic salmon and Pacific salmon can coexist successfully in a marine ecosystem on the Pacific coast of Canada.** ICES Journal of Marine Science 63: 1326-1337.
Geographic area: Queen Charlotte Strait and Broughton Archipelago
Sea lice topic: coexistence of farmed and wild salmon
Kind of research: field and desk study
Kind of document: peer reviewed journal article
Funder(s): B.C. Innovation Council; Aquaculture Collaborative Research and Development Program
Rating: Must Read (critical to debate)
Question: Can sustainable wild populations of pink salmon coexist with salmon farms in the Broughton Archipelago?
Main message: One way to assess the impact of sea lice on juvenile pink salmon is to look at their population dynamics. Juvenile pink salmon from brood year 2002 were in the area of salmon farms in 2003 and returned to spawn in 2004. Based on catch statistics and escapement data for six major pink salmon producing rivers covering much of the archipelago, estimated marine survival for that cohort of pink salmon was much higher than for the preceding even-year (+1480%). Sampling for pink salmon juveniles both in nearshore areas (March to June) and, for older juveniles, in coastal areas (August), showed that sea lice remained on salmon in coastal areas and are likely eventually transported to the open ocean. Irrespective of the difficulties of sorting out the various sources of sea lice that can infect juvenile pink salmon, ecosystem conditions that produced high marine survival made it possible for offspring of the 2002 brood year to coexist with salmon farms. In the case of the smolts entering the Broughton in 2003, salmon farming in the area was at roughly the same level as in 2001 and 2002, when pink salmon survival was low. Decadal shifts in precipitation may either improve ocean conditions for sea lice production (in the case of reduced river runoff) or make it harder for sea lice to survive (in the case of increased runoff, which reduces salinity).

Importance to Broughton: argues that salmon population dynamics, which are one important indicator of the overall effect of sea lice on pink salmon in the Broughton, are also affected by ocean conditions.
See also: Morton et al. (2004) for the original postulated link between sea lice and declines in the pink salmon population in the Broughton Archipelago for the 2000 brood year. Krkošek et al. (2007b) use statistical analysis of pink salmon population dynamics in and outside the Broughton to argue that sea lice will cause local extinction of five of the six populations used in the Beamish study. Morton et al. (2005) present evidence that fallowing of some farms in 2003 resulted in reduced numbers of copepodids on wild pink and chum salmon juveniles within 1 km of farms.

Skilbrei, O.T., and Wennevik, V. 2006. **Survival and growth of sea-ranched Atlantic salmon, *Salmo salar* L., treated against sea lice before release.** ICES Journal of Marine Science 63(7):1317-1325.
Geographic area: Hordaland County, western Norway
Sea lice topic: population effects of sea lice on wild salmon
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Institute of Marine Research; Research Council of Norway; Directorate for Nature Management; Governor of Hordaland County; BKK Production AS
Rating: Must Read (critical to debate)
Question: Do sea lice affect marine survival of salmon?
Main message: After tagging hatchery-produced Atlantic salmon smolts, treating half with Slice, and releasing them all near the river mouth, the number and weight of returning, tagged adults was significantly greater for fish that were protected from sea lice. Protected smolts grew faster at sea, a clear sublethal effect of sea lice. Despite the drawbacks of using hatchery raised smolts for the experiment (they may perform more poorly than wild), it is still reasonable to conclude that Slice protected the smolts and that sea lice can have population effects in the wild.
Importance to Broughton: Shows that protecting out-migrating smolts from sea lice increases their chances of returning to spawn, and demonstrates sublethal effects of sea lice in the field.
See also: Beamish et al. (2006) used catch and escapement data for wild pink salmon to describe their marine survival in light of ocean conditions (ie no controls on early stage sea lice infection). The telemetry study of Sivertsgard et al. (2007) used different methods of infecting and protecting the released smolts, and found no differences in rate of migration of Atlantic salmon (but did not continue the study until return of the adults).

Hilborn, R. 2006. **Salmon-farming impacts on wild salmon.** Proceedings of the National Academy of Sciences 103(42): 15277.
Geographic area: Broughton Archipelago
Sea lice topic: population-level impacts of sea lice on wild salmon
Kind of research: desk study
Kind of document: critical essay
Funder(s): not stated
Rating: Can Read (useful background)

Question: Is the experimental design of Krkošek et al. (2006a) flawed? Is there any evidence for population effects of sea lice?
Main message: There is adequate evidence that migrating juvenile salmon are infected with sea lice as they pass salmon farms in the Broughton. The next step should be to monitor wild populations in corridors without farms, and compare their mortality estimates with those from farm-containing areas to arrive at theoretical population-level impacts.
Importance to Broughton: Suggests a useful research strategy.
See also: Krkošek et al. 2006 a, b; Krkošek et al 2007b for the kind of analysis Hilborn suggests.

Jones, S.R.M., Wosniok, W., and Hargreaves, N.B. 2006c. **The salmon louse *Lepeophtheirus salmonis* on salmonid and non-salmonid fishes in British Columbia.**
Proceeding of the 11th International Symposium on Veterinary Epidemiology and Economics. 7pp. www.sciquest.org.nz.
Geographic area: Broughton Archipelago
Sea lice topic: occurrence of sea lice on juvenile salmon and other fishes
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Fisheries and Oceans Canada
Rating: Must Read (critical to debate)
Question: How does lice abundance on juvenile salmon vary with time and location of collection, and with surface salinity?
Main message: Beach and purse seines were used for three years to collect two species of juvenile salmon (chum and pink) and stickleback from 11 sampling zones in the Broughton Archipelago during the time juvenile salmon are migrating from stream to ocean. There were more lice on all three species in 2004, a finding that cannot yet be explained. Lower surface salinity in the collection area generally coincided with lower lice abundance. In all years, chum salmon carried significantly more *L. salmonis* than did pink salmon, so this lice species may have a preference for chum. Unexpectedly, sticklebacks had more lice than either salmon species, for all years, suggesting a role in sea louse dynamics in the region. Although sampling covered areas both with and without salmon farms, spatial variations in louse abundance were not analyzed for this variable.
Importance to Broughton: A systematic attempt to sample a wide range of sites in the Broughton over a three year period; turned up a surprising finding about sticklebacks, a possible alternate host for sea lice, as well as field evidence of the regulating role of salinity.
See also: Saksida et al. (2007) presents salmon farm data for 2003-2005 regarding louse levels; Brooks (several papers) for discussion of salinity effects on lice abundance.

O'Donohoe, P., Kane, F., Kennedy, S., Naughton, O., Nixon, P., Power, A., and Jackson, D. 2006. **National Survey of sea lice (*Lepeophtheirus salmonis* Krøyer and *Caligus elongatus* Nordmann) on fish farms in Ireland – 2005**. Irish Fisheries Bulletin 24: 1-32.
Geographic area: NW Ireland, W Ireland, SW Ireland
Sea lice topic: effectiveness of control of sea lice on farmed salmonids
Kind of research: field
Kind of document: Government agency report

Funder(s): not stated
Rating: Can Read (useful background)
Question: How well were sea lice controlled on Irish fish farms in 2005?
Main message: This is an annual agency report on the Irish national program for sea lice monitoring and control in saltwater farms, covering three regions (West, Northwest, Southwest), two species (Atlantic salmon and rainbow trout) and 32 sites. Findings reflect the performance of control measures (fallowing and triggered treatment with Slice and three other licensed pharmaceuticals). For one-sea-winter farmed Atlantic salmon, the trend for increasing total mobile lice/fish and egg-bearing female lice/fish that began in 1998 continued in 2005. Treatment trigger levels were often exceeded in the West and Northwest regions, including in the critical spring period. For all stocks, means greater than 20 *L. salmonis*/fish were up over 2004. Levels in May (egg-bearing and total mobile lice) were both at the highest levels in five years. Slightly higher water temperature may explain some of the increases, in combination with treatments that worked less well than expected and insufficient fallowing.
Importance to Broughton: Useful comparison of treatment trigger levels and efficacy of treatment for Atlantic salmon.
See also: Saksida et al. (2007) summarizes the corresponding findings from the sea lice monitoring and control program in the Broughton Archipelago.

Costello, M.J. 2006. **Ecology of sea lice parasitic on farmed and wild fish.** Trends in Parasitology 22(10): 475-483.
Geographic area: global
Sea lice topic: aspects of sea lice biology that affect transmission
Kind of research: desk study
Kind of document: critical scientific review
Funder(s): European Commission; National Research Council Canada; Fisheries and Oceans Canada
Rating: Should Read (part of the puzzle)
Question: How can the last decade of research on sea lice behaviour (roughly 1995-2005) help us understand its transmission dynamics?
Main message: Generalizations about sea lice, their transmission and pathogenicity are difficult to make because of different locations, populations and species (in other words, many observations in one situation cannot be replicated in another). A good example is temperature dependency and the different temperature regimes in salmon farming areas around the world. Carbon-nitrogen isotope ratios or elemental "signatures" may be useful for forensic discriminations of source of lice on wild fish. Estuarine concentration of infective stages may be by passive transport depending on winds and currents, or deposition by returning wild salmon; either way, sea louse behaviour seems to facilitate interception of migrating salmonids. A transmission model for how sea louse larvae could be transported and concentrated in shallow coastal and estuarine waters is proposed.
Importance to Broughton: Broughton region is one case of transmission to wild salmon; unfortunately, this review is mostly confined to transmission to juvenile Atlantic salmon and does not consider non-salmonid hosts.

Hansen, L.P., and Windsor, M.L. 2006. **Interactions between aquaculture and wild stocks of Atlantic salmon and other diadromous fish species: Science and management, challenges and solutions.** ICES Journal of Marine Science: Journal 63(7): 1159-1161.
Geographic area: North Atlantic
Sea lice topic: summary of presentations on sea lice
Kind of research: desk study
Kind of document: summary of conference on wild-farmed interactions in North Atlantic
Funder(s): not stated
Rating: Can Read (useful background)
Question: What did conference attendees have to say about farmed-wild salmon interactions with regard to sea lice?
Main message: Understanding of louse biology is critical to management and development of vaccines. Infestation levels on out-migrating juvenile salmon are highly site-dependent, and risk varies with hydrographic conditions. Sea trout are highly susceptible; for salmon and sea trout, lice burden is a predictor of mortality in areas with farms. Management still needs to improve; wrasse should be pursued as a control agent.
Importance to Broughton: Summary of sea louse effects in an area where farmed salmon density is higher than in Broughton; different species of wild salmon.
See also: Boxaspen (2006) review of the scientific literature.

Brooks, K.M. and D.J. Stucchi. 2006. **The effects of water temperature, salinity and currents on the survival and distribution of the infective copepodid stage of sea lice (*Lepeophitheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia (Brooks, 2005) – A response to the rebuttal of Krkosek et al. (2005a).** Reviews in Fisheries Science 14: 13-23.
Geographic area: Broughton Archipelago
Sea lice topic: dispersion of sea louse larval stages in Broughton Archipelago
Kind of research: desk study
Kind of document: critical review of published literature
Funder(s): not stated
Rating: Must Read (critical to debate)
Question: Is the rebuttal of Krkošek justified?
Main message: Brooks (2005) considered sea louse biology and oceanographic conditions when predicting zones of infection in the waters of the Broughton Archipelago. The mathematical model of Krkošek is flawed because it does not adequately consider sea louse life history (for example molting rate and the time-dependence of development to the copepodid stage), low survival to copepodid stage at salinities less than 30 ppt, effects at salinities less than 25 ppt or empirical evidence of hydrodynamics in Knight Inlet and Tribune Channel, especially around the site of the Doctor Islets farm. The author presents a conceptual model of larval dispersion and reiterates that infection is unlikely to occur near the point of larval hatching.
Importance to Broughton: Emphasizes the gaps in our knowledge of sea louse life history, and the resulting different predictions of various mathematical models.
See also: Krkošek et al. 2006a, b. *Note: 2006b is the paper to which Brooks and Stucchi are responding here.*

Krkošek, M., Lewis, M.A., Volpe, J.P., and Morton, A. 2006b. **Fish farms and sea lice infestations of wild juvenile salmon in the Broughton Archipelago – A rebuttal to Brooks (2005).** Reviews in Fisheries Science 14: 1-11.
Geographic area: Broughton Archipelago
Sea lice topic: dispersion of sea louse larval stages in Broughton Archipelago
Kind of research: desk study
Kind of document: critical review of published literature
Funder(s): NSERC Canada graduate scholarship; D. Allen Birdsall Memorial Scholarship; NSERC Discovery Grants
Rating: Must Read (critical to debate)
Question: Where does Brooks (2005) go wrong?
Main message: In his 2005 review, Brooks ignores relevant published literature, interprets published literature in a selective and misleading way, and presents a flawed mathematical model for louse dispersal that overestimates the distance from salmon farms at which larval lice from those farms become infective. The salinity survival cut-off of 30 ppt used by Brooks is too high, and should be 25-30 ppt. A different mathematical model places the appearance of infective lice much closer to the presumed originating farms (0.5-1 km) and agrees with published field studies of louse abundance on salmon sampled near farms that were misinterpreted by Brooks. Juvenile salmon and sea lice interact in the nearshore environment, which Brooks' model does not handle well. There is thus a strong association between salmon farming and recurrent sea lice infestations on wild juvenile salmon.
Importance to Broughton: A good example of how different conclusions can be drawn from the same published studies, and the dramatically different conclusions that arise from using different mathematical models.
See also: Brooks (2005).

Foreman, M.G.G., Stucchi, D.J., Zhang, Y., and Baptista, A.M. 2006. **Estuarine and tidal currents in the Broughton Archipelago**. Atmosphere – Ocean 44(1): 47-63.
Geographic area: Broughton Archipelago
Sea lice topic: passive transport of sea lice in the archipelago
Kind of research: mathematical modelling
Kind of document: peer reviewed journal article
Funder(s): Aquaculture Collaborative Research and Development program
Rating: Should Read (part of the puzzle)
Question: How well do mathematical models describe the observed currents in the Broughton Archipelago, and can they provide insights related to the siting and impacts of aquaculture operations?
Main message: Better knowledge of ocean circulation is critical for siting salmon farms and understanding transport of sea lice. Results obtained using two numerical models for estuarine and tidal circulation are compared with field observations for several locations in the Broughton Archipelago. The main transport mechanisms are estuarine flow from river and glacier runoff, and strong winds. The two models tested have strengths and weaknesses and agree with field current observations in some but not all areas. They did conform well with field observations that bottom water enters Knight Inlet by way of Fife Sound and Tribune Passage (instead of up

the mouth of Knight inlet), and that surface waters coming down Knight Inlet split as they hit the southeast corner of Gilford Island.
Importance to Broughton: Models of ocean circulation are important for predicting transport of sea lice larvae, especially in the area of Tribune Channel.
See also: Brooks (2005), Brooks and Stucchi (2006) and Krkošek et al. (2006b) for a back and forth discussion of louse transmission models that depend on our knowledge of ocean currents.

Jonsson, B., and Jonsson, N. 2006. **Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish.** ICES Journal of Marine Science 63(7): 1162-1181.
Geographic area: North Atlantic
Sea lice topic: not specifically on sea lice
Kind of research: desk study
Kind of document: critical review of published literature
Funder(s): not stated
Rating: Can Read (useful background)
Question: How do cultured Atlantic salmon interact with wild fish?
Main message: Hatchery-raised Atlantic salmon are released intentionally in European waters (for stocking, enhancement, ranching) and unintentionally (escapes from farms). They compete for food, space and breeding partners with wild Atlantic salmon, but their performance and reproductive success are poorer, and reflect short term and long term adaptations to hatchery life.
Importance to Broughton: Escaped Atlantic salmon in the Broughton Archipelago may bear sea lice and may be significant contributors to louse transmission to wild juvenile Pacific salmon; knowing more about their performance in nature is useful.

Colla, S.R., Otterstatter, M.C., Gegear, R.J., and Thomson, J.D. 2006. **Plight of the bumble bee: Pathogen spillover from commercial to wild populations.** Biological Conservation 129(4): 461-467.
Geographic area: southern Ontario
Sea lice topic: pathogen spillover from farmed to wild animals
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: Do commercially produced bumble bees spread pathogens to wild bees?
Main message: Commercially produced bumble bees can escape and interact with their wild counterparts. Infection rates for four common bee pathogens were higher on wild bees collected near commercial greenhouses than on wild bees collected distant from greenhouses. The likely pathogen spillover has implications for bumble bee conservation. (Reviewed in Abstract only).
Importance to Broughton: An interesting example of putative amplification of disease in a captive population, and subsequent transfer to the wild population; sea lice is used in this paper as another example.

Tjensvoll, K., Glover, K.A., and Nylund, A. 2006. **Sequence variation in four mitochondrial genes of the salmon louse *Lepeophtheirus salmonis*.** Diseases of Aquatic Organisms 68(3): 251-259.
Geographic area: North Atlantic and North Pacific
Sea lice topic: population genetics
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: What is the degree of genetic separation between *L. salmonis* from Scotland, Russia, Norway, Japan and Atlantic Canada?
Main message: There is little evidence of genetic variation between the three Norwegian samples, or between sea lice from Norway, Scotland and Russia. Slight genetic separation exists between those samples and lice collected in New Brunswick. However, the Japanese *L. salmonis* was highly different from all the others.
Importance to Broughton: An interesting result that shows significant genetic differences between Atlantic and Pacific populations of *L. salmonis*. Unfortunately, the Pacific samples were from Japan, not B.C., and there is no suggestion of whether the genetic differences observed could imply behavioural differences significant enough to mean the Pacific Canadian population is actually a different species.
See also: Koop (2007 "Unpublished", below) which strongly suggests that Pacific and Atlantic *L. salmonis* are in fact different species.

Øines, Ø., Simonsen, J.H., Knutsen, J.A., and Heuch, P.A. 2006. **Host preference of adult *Caligus elongatus* Nordmann in the laboratory and its implications for Atlantic cod aquaculture.** Journal of Fish Diseases 29(3): 167-174.
Geographic area: Norway
Sea lice topic: *C. elongatus* as a possible pest in cod culture
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: Does *C. elongatus* infest lumpfish, sea trout, Atlantic cod, saithe and plaice?
Main message: Dislodging *C. elongatus* from wild lumpfish and saithe, then presenting the lice with a variety of possible hosts in the laboratory, showed that the lice strongly preferred lumpfish and cod. The two sources of lice had different genotypes, which differed slightly in their host preferences. Atlantic cod seems to be an attractive host for lice from the two wild species tested, confirming its catholic tastes and potential to be a pest in farmed cod. (read in Abstract only).
Importance to Broughton: Confirms the ability of *C. elongatus* to infect a wide variety of fish species; *C. clemensi*, found in the Broughton, may behave similarly.

2005

Weir, L.K., and Grant, J.W. 2005. **Effects of aquaculture on wild fish populations: a synthesis of data.** Environmental Reviews 13(4): 145-168.
Geographic area: mostly areas with Atlantic salmon
Sea lice topic: sea lice is one of many interactions reviewed
Kind of research: desk study
Kind of document: critical scientific review
Funder(s): Aquanet N.C.E.
Rating: Can Read (useful background)
Question: What do the published quantitative (not predictive or qualitative) papers say about interactions between escaped farmed Atlantic salmon and wild salmon?
Main message: Twenty recent quantitative scientific articles were analyzed with respect to interactions between farmed Atlantic and wild salmon in seven subject areas, ranging from demographic effects on wild populations to general ecosystem impacts. While "transfer of diseases and parasites" ranked sixth in importance, the best evidence of pathogen transfer from farmed to wild fish was judged to come from studies in the Broughton Archipelago.
Importance to Broughton: Points out the lack of specific quantitative papers for interactions in general and sea lice in particular, and recommends the kind of detailed research now happening in the Broughton. Relevant to Broughton because escaped farmed salmon probably amplify the numbers of lice entering the area.
See also: The more general review of Hansen et al. (2006) and the commentary of Hilborn (2006).

Beamish, R.J., Neville, C.M., Sweeting, R.M., and Ambers, N. 2005. **Sea lice on adult Pacific salmon in the coastal waters of Central British Columbia, Canada.** Fisheries Research 76: 198-208.
Geographic area: West coast of B.C.
Sea lice topic: prevalence of sea lice on wild Pacific salmon
Kind of research: field
Kind of document: peer reviewed research article
Funder(s): B.C. Innovation Council; Aquaculture Collaborative Research and Development Council
Rating: Must Read (critical to debate)
Question: How many sea lice are there on adult Pacific salmon returning to the B.C. coast?
Main message: The study was prompted by a lack of data on sea lice infestation of wild Pacific salmon returning to spawn along the coast of B.C. The five major species of Pacific salmon were sampled by hook and line in Queen Charlotte Strait (where there are active salmon farms) and Rivers and Smith Inlets (where there aren't). While the numbers of fish of each species caught in each area varied due to differences in migration timing, virtually 100% of all salmon examined bore sea lice. *L. salmonis* was more common than *C. clemensi*. Presence of many adult stages of the former species indicates the fish were infected offshore; *C. clemensi*, on the other hand, was likely acquired in coastal areas. Sea lice appear to be common on wild adult

salmon returning from the sea, and are likely transported into nearshore areas where they can in turn infect farmed salmon and juvenile Pacific salmon. Roughly similar numbers of sea lice seem to be transported into areas with and without salmon farms.
Importance to Broughton: Establishes a significant pool of gravid adult sea lice entering the Broughton Archipelago that is distinct from the lice produced on farmed Atlantic salmon.
See also: Beamish et al. (2007) for further development of these conclusions into a proposed life history strategy for sea lice in B.C.

Tjensvoll, K., Hodneland, K., Nilsen, F., and Nylund, A. 2005. **Genetic characterization of the mitochondrial DNA from *Lepeophtheirus salmonis* (Crustacea, Copepoda).** Gene 353: 218-230.
Geographic area: North Atlantic
Sea lice topic: Basic genetic characterization of *L. salmonis*
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): Research Council of Norway
Rating: Can Read (useful background)
Question: What is the structure of the mitochondrial genome of *L. salmonis*?
Main message: The structure of the mitochondrial genome (which is distinct from the nuclear genome) has great value in determining genetic relationships between species and providing genetic markers for population studies. The mitochondrial genome of *L. salmonis* (the origin of the test subjects is not stated) has a novel gene order. The closest crustacean relative appears to be the copepod *Tigriopus japonicus*. There was no genetic variation between samples of *L. salmonis* collected from Norway, Scotland and Russia, and very weak variation between *L. salmonis* from the North Atlantic and from Atlantic Canada. Pacific samples, however, clearly belonged to a separate population.
Importance to Broughton: Baseline genetic characterization of sea lice is needed for genetic studies of its population structure, which may in turn provide options for forensic identification of the origin of lice on wild salmonids.
See also: Tjensvoll et al. (2006).

Todd, C.D., Stevenson, R.J., Reinardy, H., and Ritchie, M.G. 2005. **Polyandry in the ectoparasitic copepod *Lepeophtheirus salmonis* despite complex precopulatory and postcopulatory mate-guarding.** Marine Ecology Progress Series 303: 225-234.
Geographic area: Scotland
Sea lice topic: Natural history, specifically mating behaviour
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): Scottish Association for Marine Science
Rating: Can Read (useful background)
Question: Are *L. salmonis* females monogamous?
Main message: Based on microscopic examination and microsatellite DNA typing on female *L.salmonis* from farmed Atlantic salmon, multiple mating appears to be common. This finding

may have importance for developing integrated pest management strategies that do not rely entirely on chemical control.
Importance to Broughton: Provides natural history information potentially useful to the aquaculture industry in sea lice control, while increasing our understanding of the louse life cycle.

Genna, R.L., Mordue, W., Pike, A.W., and Mordue (Luntz), A.J. 2005. **Light intensity, salinity, and host velocity influence pre-settlement intensity and distribution on hosts by copepodids of sea lice, *Lepeophtheirus salmonis*.** Canadian Journal of Fisheries and Aquatic Sciences 62(12): 2675-2682.
Geographic area: Atlantic
Sea lice topic: infection dynamics
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): Natural Environment Research Council (Scotland)
Rating: Must Read (critical to the debate)
Question: How do various combinations of lighting, salinity and host swimming speed affect the way copepodids settle on Atlantic salmon smolts?
Main message: Light, salinity and swimming speed affect the boundary layer around a host fish and determine where sea lice will settle. Host speed has the greatest effect on settlement intensity. Copepodids probably seek out areas where the optimal physical conditions exist: medium to high salinity, low to medium light, and slow host speed. Such conditions are found in estuaries at night, close to the surface. Salmon farms should be sited to avoid such conditions.
Importance to Broughton: The findings can be used not only to aid in farm siting (for minimal infection) but also help us understand the areas where juvenile wild salmon may be most susceptible.
See also: Other experimental infection studies, for example Webster et al. (2007).

Morton, A., Routledge, R.D., and Williams, R. 2005. **Temporal patterns of sea louse infestation on wild Pacific salmon in relation to the fallowing of Atlantic salmon farms.** North American Journal of Fisheries Management 25: 811-821.
Geographic area: Broughton Archipelago
Sea lice topic: effect of fallowing
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Tides Canada Foundation; NSERC; Jane Marcher Foundation
Rating: Must Read (critical to debate)
Question: Does fallowing affect the numbers of sea lice on juvenile salmon collected near farm sites?
Main message: Wild juvenile pink and chum salmon were sampled by dip net and beach seine within 1 km of three Atlantic salmon farm sites over a three year period (2002-2004), and at another site during its first two years' operation. Most of the conclusions in the paper are drawn from the first three farms, which were fallowed in 2003. Although interpretation of the data was complicated by lack of knowledge of lice infestation on the farms, lack of knowledge about

chemical treatment on the farms, a different sampling method in year three and the continued operation of other farms within passive transport range of infectious copepodids, an iterative statistical modeling process demonstrated significant year-to-year fluctuations in copepodid abundance on wild salmon juveniles. Infestation during the fallowing year, when 36% of the fish were still infected, may represent transmission from more distant farm sites. Sea louse abundance on juvenile salmon also appeared to be correlated with temperature (2003 was colder than the other years), but statistical modeling indicated temperature could not account for the lower abundance in 2003. Fallowing may be a successful mitigation measure, but it is hard to say how important fallowing is in relation to chemical treatment, a general reduction in Atlantic salmon at farms in the Broughton as a result of other diseases, and temperature. The level of infestation recorded (up to 4.5 copepodids/fish and 2 adults/fish) may have had sublethal or lethal impacts, but this was not assessed.
Importance to Broughton: Despite limitations in data, demonstrates correlation between fallowing and a decline in numbers of copepodids on wild pink/chum juveniles within 1 km of farms and is thus an argument for further studies of fallowing as a mitigation method.
See also: Relevant to all subsequent research on the source of sea lice on juvenile salmon in the Broughton; see McVicar (2004) for a theoretical discussion of the difference between correlation and causation that is relevant to this and other studies.

Brooks, K.M. 2005. **The effects of water temperature, salinity and currents on the survival and distribution of the infective copepodid stage of sea lice (*Lepeophitheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia.** Reviews in Fisheries Science 13:177-204.
Geographic area: Broughton and Europe
Sea lice topic: dispersion of sea louse larval stages in Broughton Archipelago
Kind of research: desk study
Kind of document: critical review of published literature
Funder(s): not stated
Rating: Must Read (critical to debate)
Question: What do published studies on the effects of water temperature, salinity and currents on sea louse dynamics tell us about the source of sea lice on juvenile wild salmon in the Broughton?
Main message: The source of sea lice observed on out-migrating pink and chum salmon juveniles in the Broughton Archipelago may be farmed or wild adult salmon, or a number of alternate hosts including stickleback, depending on the combined effects of prevailing oceanographic conditions. These conditions, which include temperature, salinity and net currents and are rainfall and snowmelt-dependent, vary with locality and distance from the shore. Hence, explaining epizootics in the open and nearshore marine environments is a very complex challenge. Concluding that salmon juveniles are infected "in the vicinity of" salmon farms is not consistent with published studies on net currents that transport larval sea lice out of the farm area before they can become infective. Models of larval transport based on net currents within the archipelago do, however, show that infection is quite possible further downstream from a given farm (e.g. the Glacier Falls farm). Louse salinity tolerances probably determine their availability to infect wild salmon and imply a natural control mechanism based on annual rainfall, but more research is needed to draw a definitive salinity threshold, as well as to clarify other life history

traits (such as vertical migration) that can affect interception of salmon. Ratios of *L. salmonis* to *C. clemensi* are important, as the two species have different alternate hosts that may be implicated in transmission to wild salmon, especially in the nearshore area where net currents may be complicated by local features (e.g. eelgrass beds, rock formations) and are not a good predictor of louse transport. The presence or absence of adult Atlantic salmon at each farmed site is critical to any conclusions about its implication as a louse source (fallowed farms don't contribute). Zones of infection by farm-released lice are highly site-specific, as net currents vary significantly for all farms in the archipelago. Hydrodynamic models can help in predicting zones of infection, although nearshore effects are not well handled by the models. Migratory routes for wild salmon must also be known in order to comment on the likelihood of infection; in many areas, these routes are still a mystery. Higher current vectors in the open waters of the Broughton's main channels suggest that interaction of lice and salmon is more likely in poorly circulated areas.
Importance to Broughton: This long and detailed review challenges some conclusions of the first reports of infection of pink and chum salmon juveniles by lice emanating from salmon farms. Its author concludes there is also an important role for wild salmon and non-salmonid hosts, and that the proportion of lice contributed by salmon farms is unknown and presently unpredictable.
See also: Morton et al. (2004) and Krkošek et al. (2005a) are the two key papers challenged. Re: relevance of sticklebacks, note the work of Jones et al. 2006a (109) who show that *L. salmonis* does not complete its life cycle on stickleback. Gillibrand et al. (2007) argue for even greater complexity of dispersion models. Krkošek et al. (2006b) rebuts the paper, and is in turn responded to by Brooks and Stucci (2006).

Krkošek, M., Lewis, M.A., and Volpe, J.P. 2005a. **Transmission dynamics of parasitic sea lice from farm to wild salmon.** Proceedings of The Royal Society of London, Series B. 272: 689-696.
Geographic area: Broughton Archipelago
Sea lice topic: transmission dynamics
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): David Suzuki Foundation; Raincoast Conservation Society; Raincoast Research Society; NSERC.
Rating: Must Read (critical to debate)
Question: How does a single, isolated salmon farm change the natural transmission dynamics of sea lice to pink and chum juvenile salmon?
Main message: Analysis of field data on infection rates in juvenile salmon using a mathematical model shows that lice from farmed salmon infect wild juvenile salmon, who in turn serve as a significant secondary source of infection. Despite abundant and unaccounted-for statistical noise, calculations suggest that the farm studied raised infection levels by four orders of magnitude. The model predicts that lice are close to their farm source. No general conclusion on transmission dynamics is drawn from this one study.
Importance to Broughton: A mathematical model suggests lice infect juvenile salmon close to salmon farms; beginning of the "debate of the models."

See also: Krkošek et al. (2006a) connects these transmission data with mortality data to draw more general conclusions about the role of salmon farms and wild hosts in sea lice transmission; Brooks (2005) draws different conclusions using a different model.

Stien, A., Bjørn, P.A., Heuch, P.A., and Elston, D.A. 2005. **Population dynamics of salmon lice *Lepeophtheirus salmonis* on Atlantic salmon and sea trout**. Marine Ecology, Progress Series 290: 263-275.
Geographic area: North Atlantic
Sea lice topic: development of population dynamics models
Kind of research: desk study
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: How do you describe the progress of sea louse developmental stages using a mathematical model?
Main message: Published literature (mainly laboratory studies) on development and stage-specific mortality rates of *L. salmonis* was examined for data that could be used to build a mathematical model that focused on the effect of temperature on stage duration. With modification, including consideration of parameters other than temperature, the model will be useful for describing the population dynamics of *L. salmonis* on wild and farmed hosts in field situations,
Importance to Broughton: Background for one species of louse important locally (*L. salmonis)*; the population dynamics model is useful in understanding transmission dynamics.
See also: Krkošek et al. (2005) for a transmission dynamics model.

Morton, A., and Routledge, R. 2005. **Mortality rates for juvenile pink *Oncorhynchus gorbuscha* and chum *O. keta* salmon infested with sea lice *Lepeophtheirus salmonis* in the Broughton Archipelago.** Alaska Fishery Research Bulletin 11(2): 146-152.
Geographic area: Broughton Archipelago
Sea lice topic: Mortality of infected juvenile salmon
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Tides Canada Foundation; NSERC
Rating: Must Read (critical to debate)
Question: How many sea lice can juvenile chum and pink salmon tolerate?
Main message: Juvenile pink and chum salmon captured by beach seine in Tribune Channel were held in mesh-ended barrels tethered to a floating dock for up to 47 days. They were grouped according to initial infestation level and fed a commercial diet while remaining exposed to natural food and further lice infestation. Salmon initially infested with sea lice died at a higher rate than uninfected fish in all trials. Many sea lice disappeared during the trials; the reason for this low retention is unclear, and cannot be compared to retention rates in the wild. Development of lice may also have been reduced during the experiment, although the reason is not known.
Importance to Broughton: Provides the first evidence of a link between infestation level and mortality of juvenile salmon.

See also: Any controlled infestation report, for example Webster et al. (2007) or Sivertsgård et al. (2007).

Heuch, P.A., Bjorn, P.A., Finstad, B., Holst, J.C., Asplin, L., and Nilsen, F. 2005. **A review of the Norwegian National Action Plan Against Salmon Lice on Salmonids: the effect on wild salmonids**. Aquaculture 246: 79-92.
Geographic area: Norway
Sea lice topic: Effects of lice from farmed Atlantic salmon on wild salmonids
Kind of research: desk study
Kind of document: critical scientific review
Funder(s): Animal Health Authority of Norway
Rating: Should Read (part of the puzzle)
Question: What has been the effect of actions taken to reduce lice loads on farmed Norwegian salmon between 1998 and 2002? What can the scientific literature (to 2004) tell us?
Main message: A review of current knowledge on interactions between lice on farmed and wild salmon in Norway, coupled with the performance of the Norwegian National Action Plan Against Sea Lice on Salmonids, shows there is a very high likelihood of a cause and effect relationship between salmon farming and sea louse epizootics on the Norwegian South West coast, where there are few wild salmon. However, infection dynamics seem different in North Norway, where, as in B.C., there are many wild salmon; here, infection seems to depend as much on smolt timing and migratory behaviour as it does on the presence or absence of salmon farms (lice have not been found on smolts in the heavily farmed Altafjord system). The lethal infection rate for Atlantic salmon smolts is around 0.75 lice/gram fish weight. However, there is high annual variation in louse prevalence and intensity on wild smolts. Effects of infestations on actual population sizes of wild salmonids have not been clearly shown, so we don't know how much infestation the wild populations can tolerate over time. Mandatory electronic reporting by salmon farms is recommended to produce the high quality data needed to understand the relationship between farmed salmon and epizootics, and will help explain why some wild populations seem unaffected by salmon farms, while others are strongly compromised.
Importance to Broughton: Different species, wild salmon abundance and ocean conditions notwithstanding, this detailed review touches on many of the issues encountered in the Broughton.
See also: Boxaspen (2006) is a good companion review.

Krkošek, M., Morton, A., and Volpe, J.P. 2005b. **Nonlethal assessment of juvenile pink and chum salmon for parasitic sea lice infection and fish health**. Transactions of the American Fisheries Society 134: 711-716.
Geographic area: Broughton Archipelago
Sea lice topic: sampling and identifying lice
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): David Suzuki Foundation; Raincoast Conservation Society; Raincoast Research Society; NSERC; Walter H. Johns Graduate Fellowship
Rating: Must Read (critical to debate)

Question: Is it possible to count and identify sea lice on juvenile pink and chum salmon without killing the fish?
Main message: A simple and inexpensive method wherein beach-seined juvenile salmon are examined in a Ziplock bag does not compromise survival and yields results comparable to a lethal method. *L.salmonis* and *C.clemensi* were not distinguishable except for gravid females, and were thus lumped together. The nonlethal method probably underestimates the true abundance of lice. It is much cheaper than lethal methods that require transport of samples off site, and is amenable to community participation.
Importance to Broughton: Provides a simple and easily learned method for counting sea lice on nearshore juvenile salmon.
See also: Brooks (2005); Brooks and Stucchi (2006) and Krkošek et al. (2006b) for criticism of the method and rebuttal.

Revie, C.W., Gettinby, G., Treasurer, J.W., and Wallace, C., 2005a. **Evaluating the effect of clustering when monitoring the abundance of sea lice populations on farmed Atlantic salmon.** Journal of Fish Biology 66: 773-783.
Geographic area: Scotland
Sea lice topic: farm sampling protocols
Kind of research: field and desk study
Kind of document: peer reviewed journal article
Funder(s): U.K. Department of the Environment, Fisheries and Rural Affairs
Rating: Must Read (critical to debate)
Question: Should the fact that farmed salmon are clustered in cages affect the design of routine sampling for sea lice?
Main message: In health studies, sampling individuals in clusters (such as salmon in cages) may not be random, because the animals are not independent. Sample size (how many fish taken from each cage) and location (which cage) are critical when testing for sea lice abundance, prevalence and response to treatment. Sampling protocols for farmed Atlantic salmon have to take into account the Intra-Class Correlation (ICC), which can be worked out from existing data or through a planned study. In the Scottish farms tested in this study, ICC was larger for mobiles than for chalimus stages. The ICC value determines the number of fish and cages that should be sampled; if ICC and cluster effects are ignored, under-sampling will result. A simple rule is that sampling a small number of fish from a large number of cages is better than sampling many fish from fewer cages.
Importance to Broughton: Data from industry sampling are becoming more integrated into independent research, so the rationale for their collection and representation of the true situation are critical.
See also: Saksida et al. (2007) reviews sea lice abundance levels based on sampling on B.C. farms between 2003 and 2005.

Kolstad, K., Heuch, P.A., Gjerde, B., Gjedrem, T., and Salte, R. 2005. **Genetic variation in resistance of Atlantic salmon (*Salmo salar*) to the salmon louse *Lepeophtheirus salmonis*.** Aquaculture 247 (1/4): 145-151.
Geographic area: Norway

Sea lice topic: reducing susceptibility to infection
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Research Council of Norway
Rating: Should Read (part of the puzzle)
Question: Can Atlantic salmon be bred to reduce susceptibility to *L. salmonis*?
Main message: The work confirms and refines earlier reports of genetic variation in resistance to sea lice by Atlantic salmon by measuring the magnitude of resistance and finding the best way to record and use the trait. When different commercially bred families of Atlantic salmon were exposed to *L. salmonis* in "natural" (sea cage) and "controlled challenge" (tank) conditions, different families showed clear and substantial variation in their susceptibility. When fish were exposed more than once, differences in susceptibility were reduced, suggesting that immunity may have obscured any family differences. Controlled challenge infection was more reproducible than natural infection. Selective breeding of farmed Atlantic salmon for higher resistance to sea lice can be an eco-friendly way of improving lice control on farms. The best selection criterion will be the number of sessile (non-motile) stages on the fish.
Importance to Broughton: Farming of Atlantic salmon in the Broughton could benefit from selective breeding research carried out in B.C. and elsewhere. Increased resistance on the part of farmed fish would presumably reduce the amplification of sea louse numbers in farms, and could be an adjunct to, or replacement for, chemical treatment that may cause environmental effects.

Willis, K.J. Gillibrand, P.A., Cromey, C.J., and Black, K.D. 2005. **Sea lice treatments on salmon farms have no adverse effects on zooplankton communities: a case study**. Marine Pollution Bulletin 50(8): 806-816.
Geographic area: Scotland
Sea lice topic: environmental effects of control chemicals
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Department for Environment, Food and Rural Affairs; Veterinary Medicines Directorate and Chemicals and Genetic Modification Policy Directorate; Scottish Executive Environmental and Rural Affairs Department; Scottish Natural Heritage; Scotland and Northern Ireland Forum for Environmental Research; Scottish Quality Salmon.
Rating: Should Read (part of the puzzle)
Question: What are the effects of two chemical sea lice treatments on zooplankton communities near Scottish salmon farms?
Main message: To monitor long term ecosystem effects of the synthetic pyrethroid Excis and emamectin benzoate (Slice) near salmon farms in Scotland, zooplankton samples were collected both near (within 100m) and farther away (1,000m) from a single farm. Dispersion and concentrations of the two chemicals were predicted using mathematical models. Trends in zooplankton abundance and composition were similar in the 100m and 1,000m sampling stations, and any changes were natural and unrelated to treatment with Excis or Slice. Emamectin benzoate entering the marine environment will be part of fish feed and feces and will settle in sediments, but will also exist in soluble form after leaching out of uneaten food. Mathematical models predicted environmental concentrations of emamectin benzoate below those known to cause toxicity to planktonic copepods in laboratory studies.

Importance to Broughton: While local currents, temperatures and farmed salmon treatment regimes may be different from Scotland, the study suggests that the protocols used in Scotland may not cause long term zooplankton effects.
See also: Pacific Salmon Forum is funding ongoing studies on the effects of Slice on prawns in sentinel cages near salmon farms in the Broughton Archipelago.

Revie, C.W., Robbins, C., Gettinby, G., Kelly, L., and Treasurer, J.W. 2005b. **A mathematical model of the growth of sea lice, *Lepeophtheirus salmonis*, populations on farmed Atlantic salmon, *Salmo salar* L., in Scotland and its use in the assessment of treatment strategies.** Journal of Fish Diseases 28(10): 603-613.
Geographic area: Scotland
Sea lice topic: dynamics of response to chemical treatment
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: How can a mathematical model help predict the response of sea lice to treatment?
Main message: The mathematical model described here generally agreed with observed trends but required different parameters for sites using hydrogen peroxide and cypermethrin (Excis) for control of sea lice. Increasing the amount of cypermethrin during a production cycle gave better control, but timing of treatments was critical. (Read in Abstract only).
Importance to Broughton: A farm tool useful only for hydrogen peroxide and cypermethrin control programs.

2004

Glover, K.A., Aasmundstad, T., Nilsen, F., Storset A., and Skaala, Ø. 2004a. **Variation of Atlantic salmon families (*Salmo salar* L.) in susceptibility to the sea lice *Lepeophtheirus salmonis* and *Caligus elongatus*.** Aquaculture 245(1–4): 19-30.
Geographic area: North Atlantic
Sea lice topic: susceptibility of different strains of farmed salmon
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Norwegian Research Council
Rating: Can Read (useful background)
Question: Do different cultured strains of Atlantic salmon have different susceptibilities to sea lice? If so, can farming be improved by using these strains?
Main message: Although affected by an IPN infection at the test site, 30 different families of farmed Atlantic salmon showed a small but significant difference in their susceptibility to *L. salmonis*. However, the difference in susceptibility does not appear to be strongly heritable, suggesting an environmental component in susceptibility. For this reason, selecting Atlantic salmon for genetic resistance to sea lice, while potentially useful to farmers, may be difficult.

Importance to Broughton: Some interest for studies on genetic basis of susceptibility of different pacific salmon hosts (e.g. pink *vs* chum *vs* chinook)
See also: Bjørn et al. (2006); Kolstad et al. (2005).

Wagner, G.N., Mckinley, R.S., Bjørn, P.A., and Finstad, B. 2004. **Short-term freshwater exposure benefits sea lice-infected Atlantic salmon.** Journal of Fish Biology 64(6): 1593-1604.
Geographic area: Norway
Sea lice topic: swimming performance after infection and freshwater entry
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): AquaNet; NSERC; NINA Research Station, Norway
Rating: Can Read (useful background)
Question: Is the physiological performance of sub-lethally infected Atlantic salmon improved or compromised after short term transfer to fresh water?
Main message: Sixty Atlantic salmon post-smolts (average weight 650g) were infected with *L. salmonis* and then transferred to freshwater. Swimming speed in seawater declined with infection but improved with transfer to fresh water, despite physiological evidence of stress based on real-time cardiac performance and blood values. There is thus evidence for a link between the physiological effects of sea lice and the early return of salmonids to freshwater as noted for sea trout. Atlantic salmon seem to suffer no major physiological penalties in moving from seawater to freshwater, while benefiting from increased swimming performance and sea lice removal.
Importance to Broughton: Findings on the physiological effects of infection are of some importance for both farmed Atlantic and wild Pacific salmon; premature return to freshwater is not a major issue in the Broughton but the removal of lice in freshwater has some interest.
See also: Sivertsgård et al. (2007) for effects of infection on swimming performance of migrating Atlantic salmon in the wild, not in the laboratory; Webster et al. (2007) for salinity preferences of infected pink and chum salmon.

Morton, A., Routledge, R., Peet, C., and Ladwig, A. 2004. **Sea lice (*Lepeophtheirus salmonis)* infection rates on juvenile pink (*Oncorhynchus gorbuscha)* and chum (*Oncorhynchus keta*) salmon in the nearshore marine environment of British Columbia, Canada.** Canadian Journal of Fisheries and Aquatic Sciences 61: 147-157.
Geographic area: Broughton Archipelago, Central B.C. coast
Sea lice topic: abundance on pink and chum salmon juveniles in areas close to and remote from salmon farms
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Tides Canada Foundation – Wild Salmon Fund; NSERC
Rating: Must Read (critical to debate)
Question: Is there a relationship between sea louse incidence on juvenile pink and chum salmon and the nearness of salmon farms?
Main message: Pink and/or chum salmon post-smolts were sampled and their lice identified by a variety of crews using several different techniques (including dip nets and towed seines) in five geographic areas on the B.C. coast, including the Broughton Archipelago. Samples were taken

from areas near salmon farms (250 m away in Broughton; unstated in Bella Bella) and in areas without farms (parts of Broughton; Rivers Inlet, Smith Inlet and Prince Rupert). The fact that data were contributed from a variety of independent sampling studies conducted outside the Broughton Archipelago at different times meant there were different collection methods and required sophisticated statistical analysis. *L. salmonis* was rare outside the Broughton, where its abundance was highest on fish sampled within 250 m of farm sites with second-year Atlantic salmon. *C. clemensi* was highest near farm sites in the Broughton and Bella Bella. Overall, estimated sea lice abundances were eight times higher at sampling sites close to farms than in control sites with no farms. Also, sustained dominance of juvenile louse stages suggests that infection was continuous and local. Because there were not believed to be large wild salmonid populations in the Broughton at the time of sampling, the possibility of a causal link between salmon farms and infection of juvenile salmonids indicates using a precautionary approach
Importance to Broughton: A key paper frequently referred to in subsequent research. Has stimulated spirited discussion and experimentation in many areas, including sampling methodology and timing, statistical analysis, mathematical modeling of water movements and spread of infection, and life history strategies for both salmon lice and their wild hosts.
See also: Morton and Routledge (2005) for associated mortality rates.

Johnson, S.C. and Fast, M.D. 2004. **Interactions between sea lice and their hosts.** In: Flik, G., Wiegertjes, G. and Wendellar-Bonga, S. [eds.] Host Pathogen Interactions. SEB Symposium Series 55: 131-160.
Geographic area: global
Sea lice topic: interactions between sea lice and salmonids
Kind of research: desk study
Kind of document: book chapter
Funder(s): not stated
Rating: Can Read (useful background)
Question: What is the current scientific understanding of the effects of sea lice on their hosts?
Main message: *L. salmonis* and *C. elongatus* are the most-studied parasitic copepods due to their economic impact on aquaculture. Life cycle, morphology, attachment and feeding and associated physiological and pathological effects are summarized, including variations in susceptibility between salmonid species and the likelihood that lice cause a generalized stress response and depress the host's immune system enough to permit coexistence. Further advances are expected to come from genetic techniques that measure host gene expression and how it is modulated by lice. Infection trials are summarized, as are typical louse intensities on wild fish (mostly from European studies).
Importance to Broughton: This book chapter is a valuable reference work. While it does not cover results from Broughton fish, the physiological and pathological principles will be the same, and are fundamental to making judgements about overall effects of infection.

Todd, C.D., Walker, A.M., Ritchie, M.G., Graves, J.A., and Walker, A.F. 2004. **Population genetic differentiation of sea lice (*Lepeophtheirus salmonis*) parasitic on Atlantic and Pacific salmon.** Canadian Journal of Fisheries and Aquatic Sciences 61(7): 1176-1190
Geographic area: North Atlantic and North Pacific

Sea lice topic: genetic separation between sea lice populations
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): Natural Environment Research Council, UK
Rating: Should Read (part of the puzzle)
Question: How great is the genetic distance between sea lice from wild and farmed Atlantic salmon from various locations in the North Atlantic and North Pacific?
Main message: Based on microsatellite DNA analysis of adult *L. salmonis* collected from wild and farmed Atlantic salmon from different locations (most of them on the Scottish coast, but including one salmon farm in New Brunswick and one in B.C.), only the Pacific and the North Atlantic comparison showed significant genetic differentiation. Scottish salmon, whether farmed, wild, one-sea-winter or two-sea-winter, all bore lice belonging to the same population; the finding is easily explained by migratory behaviour. Since there is no genetic substructure in the lice infesting wild and farmed Atlantic salmon, forensic identification of the origin of lice on wild salmon does not appear feasible using genetic markers.
Importance to Broughton: If Atlantic *L. salmonis* is genetically different from Pacific *L. salmonis*, how much of the predominantly European literature on sea lice physiology and behaviour is relevant in B.C.? The finding that farmed and wild fish are infested by a single population, however, likely applies in B.C.
See also: Tjensvoll et al. (2005) for similar findings; Koop (2007 (Unpublished Research, below) provides evidence that the Atlantic and Pacific populations are different species.

Butterworth, K.G., Li, W., and McKinley, R.S. 2004. **Carbon and nitrogen stable isotopes: a tool to differentiate between *Lepeophtheirus salmonis* and different salmonid host species?** Aquaculture 241: 529-538.
Geographic area: Broughton, Hecate Strait, Bay of Fundy
Sea lice topic: distinguishing between lice on farmed and wild salmon
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): AquaNet
Rating: Should Read (part of the puzzle)
Question: Can the ratios of isotopic carbon and nitrogen be used to distinguish between sea lice on farmed and wild salmon?
Main message: The amounts of isotopic forms of carbon (C) and nitrogen (N) are called "signatures" and reflect the organism's diet. Based on analysis of the carbon and nitrogen signatures of farmed Atlantic salmon (from Broughton and Bay of Fundy) and wild coho salmon (from Hecate Strait, an area with no salmon farms), the nitrogen signatures of *L. salmonis* differ significantly. It is thus possible to differentiate lice from wild salmon from those on farmed salmon based on their nitrogen signature.
Importance to Broughton: Because isotope signatures reflect diet, the technique reported here essentially tells you that lice from farmed and wild salmon are eating different foods. It does not tell you where the lice originated and is not a forensic tool.
See also: Recent developments in genetic characterization of *L. salmonis* (e.g. Koop (2007) "Unpublished", below).

Nagasawa, K. 2004. **Sea lice, *Lepeophtheirus salmonis* and *Caligus orientalis* (Copepoda: Caligidae), of wild and farmed fish in sea and brackish waters of Japan and adjacent regions: A review.** Zoological Studies 43(2): 173-178.
Geographic area: coastal Japan
Sea lice topic: occurrence of sea lice on wild and farmed fish
Kind of research: desk study
Kind of document: critical review
Funder(s): not noted
Rating: Can Read (useful background)
Question: What are the characteristics of sea louse infection in wild and farmed fish species in Japan?
Main message: Although *L. salmonis* are brought into the area of coho salmon net cages in northern Honshu by returning chum salmon, transmission occurs only for a restricted period in the fall, and the parasite is not a serious problem for coho culture. However, *L. salmonis* has also been recorded from the non-salmonid host Japanese dace (*Tribolodon hakonensis*), a euryhaline minnow that inhabits fresh, brackish and coastal waters. Hatchery-produced chum salmon juveniles have also been observed carrying *L. salmonis* in coastal areas.
Importance to Broughton: The presence of sea lice on the resident Japanese dace suggests similarities to its recent discovery on stickleback in the Broughton.
See also: Nagasawa et al. (1994).

Rikardsen, A.H. 2004. **Seasonal occurrence of sea lice *Lepeophtheirus salmonis* on sea trout in two north Norwegian fjords.** Journal of Fish Biology 65(3): 711-722.
Geographic area: northern Norway
Sea lice topic: Louse load on wild sea trout
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Norwegian Institute for Nature Research; Governor of the Counties of Troms and Nordland
Rating: Must Read (critical to debate)
Question: How many sea lice are there on wild sea trout (*Salmo trutta*) in a fjord with no salmon farms?
Main message: Seasonal louse loads on sea trout in northern Norwegian fjords where there are no salmon farms provide some idea of background infestation because there are few wild Atlantic salmon in the areas sampled. Based on sampling of 333 wild sea trout using floating gill nets from March to December, infestation peaked in summer and autumn, although somewhat later than in more southerly fjords examined in other studies. Lice were not identified to species. Infestation was never high, and the percentage of chalimus stages was higher than in southern fjords studied earlier (again, probably due to lower water temperatures further north). Presence of lice on sea trout sampled during the winter suggests these fish help maintain a local population of lice in the fjord. However, the winter behaviour of sea trout is still poorly known, and their propensity for returning to fresh water either to spawn or as immature fish is a complicating factor; spent fish caught in the sampling nets, for example, were usually louse-free. Much

remains to be learned about the complicated and flexible life histories of sea trout, especially in harsh northern winter conditions.
Importance to Broughton: Provides some idea of "background" sea louse infestation, but more importantly shows how hard it is to draw conclusions when the actual behaviour and life history of the target species are poorly known. Note too that the study area has few wild salmon, not at all comparable to the Broughton.
See also: Krkošek et al. (2007a) for a study of background sea louse infestations on wild Pacific salmon in an area with no salmon farms.

Ho, J.S. 2004. **Invasiveness of sea lice (Copepoda, Caligidae) in marine aquaculture**. Journal of the Fisheries Society of Taiwan 31(2): 85-99.
Geographic area: mainly Asia
Sea lice topic: state of our knowledge of parasitic copepods on cultured marine fishes in Asia
Kind of research: desk study
Kind of document: peer reviewed journal article
Funder(s): Paramitas Foundation
Rating: Can Read (useful background)
Question: Do we know enough about sea lice and cage culture of marine fishes?
Main message: Nearly half the known species of marine parasitic copepods are reported from Asian waters. The effects of some of them on cage culture of a variety of marine species (both warmwater and coldwater) are well known in Japan and Taiwan, and starting to become known in other countries including China and Korea. Some species of parasitic lice may have been transported on juvenile seedstock from countries as far away as Australia, where several well known epizpootics have occurred. Given the very large extent of cage farming in Asia and its potential for growth, the lack of parasitologists working on copepods is worrying, and there is an urgent need to find better ways to exchange the limited information we have.
Importance to Broughton: Another reminder that Atlantic salmon are by no means the only farmed species susceptible to sea lice infestation; gives the perspective of another part of the world where cage culture is economically very important.
See also: Johnson et al. (2004) is a good companion review of the same issue.

Thorstad, E.B., Økland, F., Finstad, B., Sivertsgård, R., Bjørn, P.A., and McKinley, R.S. 2004. **Migration speeds and orientation of Atlantic salmon and sea trout post-smolts in a Norwegian fjord system.** Environmental Biology of Fishes 71(3): 305-311.
Geographic area: Norway
Sea lice topic: vulnerability of juvenile salmon
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): AquaNet Canada; European Commission; Norwegian Institute for Nature Research; Statkraft
Rating: Must Read (critical to debate)
Question: What are the migratory routes, geographic distribution and swimming speeds of Atlantic salmon and sea trout post-smolts departing a river mouth in a Norwegian fjord?

Main message: Tagged hatchery Atlantic salmon and wild sea trout post-smolts were released from a river mouth and tracked by GPS for up to 14 hours as they migrated into the inner part of Romsdalsfjord. After correcting for the effect of current using a drogue to simultaneously record current speed and direction, sea trout swimming speed was lower than that of Atlantic salmon and the sea trout's movements less directed, as would be expected for a species known to spend time in nearshore areas rather than exiting fjords directly. For both species, observed direction depended on which way the fish was swimming, not on current direction. This means that water currents were not used as an orientation cue by either species and may not be a good predictor of migration pathways, at least in the inner fjord studied here. The higher swimming speeds of Atlantic salmon mean that they may pass fish farms faster than sea trout as long as the net current movement takes them that way. Subsequent, longer-term studies using wild Atlantic salmon will clarify the picture.
Importance to Broughton: Emphasizes how little is known about orientation, navigational cues, swimming speed and response to current for out-migrating salmonids – and both species studied here are much larger and easier to monitor than juvenile pink and chum salmon.
See also: The more recent paper by the same authors (Sivertsgard et al. 2007) where tagged hatchery fish were infected, released and followed for a longer period (five weeks).

Penston, M.J., McKibben, M.A., Hay, D.W., and Gillibrand, P.A. 2004. **Observations on open-water densities of sea lice larvae in Loch Shieldaig, Western Scotland.** Aquaculture Research 35(8): 793-805.
Geographic area: Scotland
Sea lice topic: louse dispersion in an area with salmon farms
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Should Read (part of the puzzle)
Question: What is the relationship between lice on a local farm and those collected by plankton tows at various locations in the area?
Main message: Based on plankton tows at six locations within six km of two salmon farms in Loch Shieldaig, some preliminary conclusions can be drawn about the origin of sea lice larvae in the loch. While complicated by not identifying sea lice to species and despite high variability in the data, there is some evidence that a local fish farm was one source of larvae concentrated in the estuary, suggesting that transport away from the open sea can occur due to wind-forced surface currents, flooding tide and low outflow of fresh water. Larvae diluted by large volumes of open water may become concentrated in nearshore areas. Explanation of pulses of larvae in the loch are complicated by sea louse treatments on the farm.
Importance to Broughton: Provides some early evidence, based on field sampling, of landward transport of sea lice larvae towards estuarine areas.
See also: Foreman et al. (2006) describe the performance of mathematical models that provide another way of explaining larval transport (in contrast to strictly field observations such as these); Gillibrand and Willis (2007) propose a mathematical model to further examine landward forcing of currents.

Costello, M.J., Burridge, L., Chang, B., and Robichaud, L. 2004. **Sea Lice 2003. Proceedings of the Sixth International Conference on Sea Lice Biology and Control.** Aquaculture Research 35(8): 711-712.
Geographic area: global
Sea lice topic: Overview of international conference
Kind of research: desk study
Kind of document: editorial in peer reviewed journal
Funder(s): not stated
Rating: Can Read (useful background)
Question: What progress has been made in understanding sea lice biology and its control?
Main message: The sixth international conference on sea lice biology and control was held in St. Andrews, NB, in 2003, and involved 60 experts from six countries. Larval distribution was a major topic, with new evidence that *L. salmonis* copepodids can congregate in estuaries.
Importance to Broughton: Evidence of the amount of European research that had already occurred by 2003, including on larval dispersal.

McKibben, M.A., and Hay, D.W. 2004. **Distributions of planktonic sea lice larvae *Lepeophtheirus salmonis* in the inter-tidal zone in Loch Torridon, Western Scotland in relation to salmon farm production cycles.** Aquaculture Research 35(8): 742-750.
Geographic area: Scotland (Loch Shieldaig)
Sea lice topic: distribution of *L. salmonis* larvae
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Must Read (critical to debate)
Question: How are sea lice larvae distributed near the river mouth, and how do abundances there relate to louse abundance on nearby farms?
Main message: In an attempt to clarify the confusing picture of sea trout infection soon after sea entry, spring and summer plankton samples were taken for 2001 and 2003 in the estuarine and nearshore regions of Loch Shieldaig. Two Atlantic salmon farms 4-6 km seaward of the estuary provided data on louse numbers. Copepodids at the shoreline sampling sites (no other stages were seen) were most abundant near the river mouths in early spring and were only found when gravid female sea lice were present on the farms. This suggests that the copepodids were of farm origin and that sea lice can be dispersed at least 4.6 km away from the open ocean. Sea lice in the estuaries could not have come from naturally returning salmon or sea trout, as no salmon entered the fish trap at the river mouth during the study period.
Importance to Broughton: Strong circumstantial evidence of farm origin of sea lice in an estuarine area, suggesting that, in sea trout at least, infection happens on the way out of the river.
See also: Papers on sticklebacks as alternate hosts and therefore alternate sources of infection in nearshore areas (e.g. Jones et al. 2006b,c); papers by Brooks and Krkošek on dispersal modeling that attempt to explain how larvae can travel within fjords.

Westcott, J.D., Hammell, K.L., and Burka, J.F. 2004. **Sea lice treatments, management practices and sea lice sampling methods on Atlantic salmon farms in the Bay of Fundy, New Brunswick, Canada.** Aquaculture Research 35(8): 784-792.
Geographic area: Bay of Fundy, New Brunswick
Sea lice topic: monitoring on farms
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): AquaNet; Schering-Plough Animal Health
Rating: Can Read (useful background)
Question: How do Bay of Fundy salmon farmers monitor sea lice?
Main message: While there are no regulations for monitoring and reporting sea lice infestations on Atlantic salmon farms in New Brunswick, a survey of 83 cage sites in 2002 using interviews and questionnaires showed that most farms follow methods used in Europe, and some are more stringent. Most count lice weekly during periods of high louse burden, using 5-10 fish from a variable number of strategically selected cages. Most use Slice as a control agent, and the decision to apply it is made by local management.
Importance to Broughton: Gives some idea of the kind of data that result if there are no standards for counting, reporting and applying chemical control.

Schram, T.A., 2004. **Practical identification of pelagic sea lice larvae.** Journal of the Marine Biological Association of the United Kingdom 84: 103-110.
Geographic area: Sweden
Sea lice topic: identification of larvae
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: How do you distinguish between the pelagic larvae of four common species of *Lepeophtheirus* and one *Caligus*?
Main message: Larvae of parasitic copepods are hard to tell apart. Body measurements, pigmentation and other features of nauplius and copepodid stages of *L. salmonis, L. pollachius, L. pectoralis* and *C. elongatus* help make the distinction. Colour and its distribution are key factors, but are lost if larvae are preserved at sea in formalin. Immediate examination of live samples is best, although preserving a small extra sample in alcohol and examining it as soon after collection as possible can also help in identifying colour distribution.
Importance to Broughton: An important technical resource for any field study of larval sea lice, with detailed drawings and hints about preservation and timing of examination.

Glover, K.A., Hamre, L.A., Skaala, Ø., and Nilsen, F., 2004b. **A comparison of sea louse (*Lepeophtheirus salmonis*) infection levels in farmed and wild Atlantic salmon (*Salmo salar* L.) stocks.** Aquaculture 232: 41-52.
Geographic area: Norway
Sea lice topic: inherited susceptibility to sea lice
Kind of research: laboratory

Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: Do farmed and wild stocks of Atlantic salmon have different susceptibility to *L. salmonis* in laboratory challenge experiments?
Main message: Salmon farmers could take advantage of the observed species and population differences in susceptibility to sea lice to develop breeds that are more resistant to sea lice and therefore require less chemical treatment. Atlantic salmon smolts from three wild and two farmed strains were challenged with *L. salmonis* in replicate mixed-stock tanks. The lowest density of *L. salmonis* was found in one of the wild strains (Dale). The greatest difference in infection level between any two strains was 29%, suggesting that the pool of variation for louse resistance is large enough to justify breeding for the trait. Furthermore, the greatest difference was between two neighbouring wild stocks, and the one with highest resistance (Dale) also has a higher ocean survival.
Importance to Broughton: While aimed at selective breeding of farmed fish (to reduce susceptibility), observations of innate genetic differences between species and populations of salmonids are relevant.
See also: Glover et al. (2004).

Asplin, L., Boxaspen, K., and Sandvik, A.D. 2004. **Modelled distribution of salmon lice in a Norwegian fjord.** ICES CM 2004/P:1-11.
Geographic area: Western Norway (Sognefjord)
Sea lice topic: modeling the spread of salmon lice
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: What can a mathematical model tell us about sea lice distribution in the Sognefjord?
Main message: Based on laboratory results for *L. salmonis* growth rate and ability to infect over time, and a mathematical model for ocean circulation fed with data on currents, weather (winds), temperature and river runoff, various scenarios for louse dispersal and potential encounters with wild salmonid post-smolts in the Sognefjord were examined. Varying the louse release date and location dramatically affected the range of louse movement, from almost no movement to 100 km. Simulated encounters with salmon post-smolts suggested different infection rates depending on the source of the lice, and that bends and narrows in the fjord were areas of convergence. Dependence of modeling results on a large number of poorly known variables is still a problem.
Importance to Broughton: A good example of the pros and cons of ocean circulation models; results cannot however be imported to the Broughton.
See also: Foreman et al. (2006) and Brooks and Stucchi (2006) for description of another ocean circulation model, this one for the Broughton; Gillibrand and Willis (2007) present a more complex model.

McKenzie, E., Gettinby, G., McCart, K., and 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(8): 764-772.
Geographic area: Scotland
Sea lice topic: dynamics of infections on farms
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): DEFRA; Scottish Quality Salmon
Rating: Can Read (useful background)
Question: Are there cycles in *C. elongatus* infestation in four farms in western Scotland?
Main message: Formal time-series analysis is a statistical technique that can uncover patterns in data collected over time. Weekly (although not regular) counts of *C. elongatus* in four farms in western Scotland were statistically analyzed to show that infestation is strongly seasonal, and lower for fish in their second year of culture, when *L. salmonis* may compete with *C. elongatus*.
Importance to Broughton: Concentration on *C. elongatus* limits applicability, and the effects of chemical treatment are not clear.

Johnson, S.C., Treasurer, J.W., Bravo, S., Nagasawa, K., and Kabata, Z. 2004. **A review of the impact of parasitic copepods on marine aquaculture.** Zoological Studies 43(2): 229-243.
Geographic area: global
Sea lice topic: impact on marine aquaculture
Kind of research: desk study
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Should Read (part of the puzzle)
Question: How do parasitic copepods affect marine fish cultured around the world?
Main message: This review summarizes the known effects of marine parasitic copepods, including but not limited to *L. salmonis* and *C. elongatus*, on a very wide variety of marine finfish grown in coldwater and warmwater operations. Environmental impacts (transfer to wild fish) are only briefly considered. For northern waters, treatment trigger levels on Atlantic salmon in various countries are summarized as of 2004. Although salmon farming in Japan is extensive, sea lice are not a major problem because the main species farmed (coho) is resistant to infection, and fish are reared for a single year. The same superiority of coho salmon is noted for Chile, where Atlantic salmon are susceptible to several *Caligus* species that also have numerous wild hosts. A long list of cultured warmwater, non-salmonid species are parasitized by a variety of sea lice species in many countries, although the economic impacts aren't well known. Copepod abundance on farms, and the seriousness of infestations, are driven by many physical and biological factors that can be modified by engineering and husbandry practices; in other words, good farm management can dramatically affect the amplification of sea lice on a farm. Species like *Caligus* that have broad host ranges and many wild hosts seem to be the hardest to control.
Importance to Broughton: Gives a good global perspective of the sweep of marine aquaculture and how it is affected by parasitic copepods; the resistance of coho salmon is noteworthy, even ironic, considering that coho and chinook were the first salmon species farmed in B.C.

Pietrak, M., and Opitz, H.M. 2004. **An evaluation of three potential methods for preventing the spread of larval *Lepeophtheirus salmonis* (Krøyer, 1837)**. Aquaculture Research 35: 759 - 763.
Geographic area: Maine
Sea lice topic: resistance to disinfection
Kind of research: laboratory
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Can Read (useful background)
Question: How well do routine farm disinfection procedures work on *L. salmonis* egg strings?
Main message: On salmon farms, sea lice infection could potentially spread between sites if equipment is not disinfected. Standard disinfection methods using Povidone-iodine or sodium hypochlorite, which work for bacteria and viruses, did not work for *L. salmonis eggs*. Desiccation (4-24h) was the only method that worked. (Read in Abstract only).
Importance to Broughton: Husbandry-related, and gives an idea of the resilience of sea louse eggs.

Sepúlveda, F., Marín, S.L., and Carvajal, J. 2004. **Metazoan parasites in wild fish and farmed salmon from aquaculture sites in southern Chile.** Aquaculture 235: 89-100.
Geographic area: southern Chile
Sea lice topic: parasites on farmed salmon and native species
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): University of Los Lagos, Chile.
Rating: Can Read (useful background)
Question: What parasites are found on farmed Atlantic salmon and the native non-salmonid fish species that live near net pens in southern Chile?
Main message: 144 native fish from seven non-salmonid species were caught by hook and line next to Atlantic salmon pens in southern Chile. Their ectoparasites (external parasites) and endoparasites (internal parasites) were compared with those found in farmed Atlantic salmon netted from the adjacent pens. Numbers and species of parasite on the wild fish varied with fish species and habitat, and transmission to or from farmed fish was not studied. Most of the wild fish species were shown to have eaten pelleted feed. Three species of *Caligus* sea lice and one of *Lepeophtheirus* were found on wild fish; only one of these (*C. rogercresseyi*) was also found on farmed salmon. The direction of transmission of *C. rogercresseyi* (whether from farmed to wild or wild to farmed) is still not clear.
Importance to Broughton: Provides more evidence for a connection between sea lice found on farmed Atlantic salmon and an adjacent wild fish species, but the circumstances of sampling (angling next to salmon pens), the different wild species (all non-salmonid), the number of species involved and their different habitats, plus the lack of any investigation of transmission dynamics, make any further parallels tenuous.

McVicar, A.H. 2004. **Management actions in relation to the controversy about salmon lice infections in fish farms as a hazard to wild salmonid populations.** Aquaculture Research 35(8): 751-758.
Geographic area: Europe and Canada
Sea lice topic: correlation between salmon farms and decline in wild stocks
Kind of research: desk study
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Must Read (critical to debate)
Question: What is the scientific justification for management actions to reduce the numbers of sea lice on farmed Atlantic salmon?
Main message: This review, based largely on findings in Europe and particularly Scotland, takes a formal risk analysis approach to two linked questions: "Are salmon lice from fish farms a hazard to the size of wild salmon populations?" and "Will control of lice levels on farms improve wild salmon returns?" There are no data confirming a cause and effect relationship between lice on farmed and wild salmon population size; we still lack knowledge about the many factors that affect the size of wild salmon populations; population declines of wild Atlantic salmon and sea trout often predate farming; and pathogenic effects of sea lice on wild salmon, including actual mortality rates, are not well known in the wild. Given these and other uncertainties and despite concerted research effort, management actions to reduce sea lice on farmed salmon are still a field experiment on a grand scale. The Scottish system differs from that in Norway and Ireland in using a risk analysis approach based on Area Management Agreements between local stakeholders with a common interest in reducing lice levels on farmed salmon.
Importance to Broughton: While based on European research to 2003, this is still a valid summary of the logic behind questioning the risk to wild salmon populations from sea lice originating on salmon farms, which is the "big picture" question in the Broughton. Formal risk analysis takes account of uncertainties such as those in our understanding of louse transmission, louse effects and fluctuations in wild salmon populations.
See also: An earlier paper by McVicar (1997) provides discussion not only on sea lice but also other diseases. Beamish et al. (2006) is a recent example of a field study concluding that wild salmon populations in the Broughton Archipelago can fluctuate independently of sea louse infection. On the other hand, Krkošek et al. 2007b argue that wild salmon populations in the Broughton have in fact been depressed by sea lice originating in salmon farms.

Before 2004

Bjørn, P.A., and Finstad, B. 2002. **Salmon lice, *Lepeophtheirus salmonis* (Krøyer) infestation in sympatric populations of Arctic char, *Salvelinus alpinus* (L.) and sea trout, *Salmo trutta* (L.) in areas near and distant from salmon farms.** ICES Journal of Marine Science 59: 131-139.
Geographic area: Norway
Sea lice topic: comparison of louse loads on wild salmonids in areas with and without farms
Kind of research: field

Kind of document: peer reviewed journal article
Funder(s): Norwegian Directorate for Nature Management; Norwegian Institute for Nature Research
Rating: Should Read (part of the puzzle)
Question: What are the levels of *L. salmonis* on sea trout and arctic char in Norwegian fjords with and without salmon farms?
Main message: Louse levels on sea trout and char were similar. Based on two years' study (1992 and 1993) in two areas in northern Norway, differences between infestation in exposed and unexposed areas varied with the year. The unexposed areas had more lice in 1992 than they did in 1993. In 1992, prevalence and mean numbers of lice on fish in exposed and unexposed areas were similar. In 1993, prevalence rose in both groups, but the mean number of lice on fish was significantly higher in the exposed group of fish. Comparisons are complicated by differences in the pattern of infestation for each year (timing and louse stages) that may reflect local meteorological conditions; for example, 1993 was a late spring.
Importance to Broughton: A frequently cited paper arguing for infestation of wild salmon populations by lice from salmon farms. Unfortunately, the tabular presentation of the data makes conclusions hard to draw. Important for showing annual variation in infestations and their monthly timing.

Jacobsen, J.A., and Gaard, E. 1997. **Open-ocean infestation by salmon lice (*Lepeophitheirus salmonis)*: comparison of wild and escaped farmed Atlantic salmon (*Salmo salar* L.).** Journal of Marine Science 54: 1113-1119.
Geographic area: Faroe Islands
Sea lice topic: transfer of lice from escaped farmed Atlantic salmon to wild Atlantic salmon
Kind of research: field
Kind of document: peer reviewed journal article
Funder(s): Nordic Council of Ministers; Norwegian Directorate for Nature Management; Faroese Home Government
Rating: Can Read (useful background)
Question: Do escaped farmed Atlantic salmon feeding in the Faroe Islands transfer lice to wild salmon?
Main message: One-sea-winter farmed salmon caught in feeding grounds off the Faroe Islands had more lice (*L. salmonis*) than their wild counterparts, although the difference disappeared after two years. Parasite load may thus be higher on farmed escapees when they enter the Faroe area. Adult female sea lice appear to survive over the winter at sea. Lack of any historic infestation data for wild fish at sea makes it impossible to draw any conclusions about transmission between farmed and wild fish.
Importance to Broughton: Not really comparable (because this paper deals with transmission from escapees), but interesting as another potential route for transfer of sea lice from farmed to wild salmon (that is, on the oceanic feeding grounds).

Tully, O., Daly, P., Lysaght, S., Deady, S., and Varian, S.J.A. 1996. **Use of cleaner-wrasse (*Centrolabrus exoletus* (L.) and *Ctenolabrus rupestris* (L.)) to control infestations of *Caligus elongatus* Nordmann on farmed Atlantic salmon.** Aquaculture 142: 11-24.

Geographic area: Ireland
Sea lice topic: biological control of sea lice
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): Commission of the European Communities Fisheries and Aquaculture Research Programme
Rating: Can Read (useful background)
Question: How well do wrasse control louse infestation on Atlantic salmon in different conditions?
Main message: Two species of cleaner-wrasse (*Ctenolabrus* spp.) were variously effective in removing *Caligus elongatus* from Atlantic salmon smolts in tanks and commercial-scale cages of different sizes. As in previous reports from Scotland and Norway, wrasse showed promise as a control agent, but better experiments have to be done to separate the effects of louse species, wrasse density and behaviour, and cage shape and size, including degree of net fouling. Factors that affect the number of encounters between wrasse and infected salmon (for example, cage shape, relative numbers, and schooling behaviour) have to be better understood and controlled if cleaner fish such as wrasse are to used effectively.
Importance to Broughton: A good summary of the pros and cons of biological control of sea lice on farmed salmon, which has not been seriously followed up for farms in the Broughton region because there are so far no known appropriate species.

Bruno, D.W., and Stone, J. 1990. **The role of saithe, *Pollachius virens* L., as a host for the sea lice, *Lepeophtheirus salmonis* (Kroyer) and *Caligus elongatus* (Nordmann).** Aquaculture 89: 201-207.
Geographic area: Scotland
Sea lice topic: alternate, non-salmonid host for *L. salmonis*
Kind of research: field and laboratory
Kind of document: peer reviewed journal article
Funder(s): not stated
Rating: Should Read (part of the puzzle)
Question: Are saithe a host for *L. salmonis*, and can they transfer the louse to Atlantic salmon?
Main message: Saithe (*Pollachius virens*) caught near Atlantic salmon farms were infested with adult *C. elongatus* and pre-adult (but not adult) *L. salmonis*. The presence of saithe in and around sea cages could be a louse reservoir, and the finding of pre-adult *L. salmonis* on saithe represents a new, non-salmonid host. Based on tank experiments, both species of louse transferred from saithe to Atlantic salmon. *L. salmonis* did not appear to mature on saithe.
Importance to Broughton: While it's most likely the saithe acquired *L. salmonis* from farmed salmon, their role as an alternate host is unclear, especially as the lice do not appear to mature on saithe. The situation has some interesting parallels to stickleback in the Broughton, on which non-maturing *L. salmonis* are also found. However, the source of the lice on saithe and sticklebacks may be different.

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Appendix: Unpublished or In Progress

The following selections give a flavour of some recent research approaches; some presentations were omitted if they were too sketchy or presented no data. The selection is definitely not representative and readers of these summaries must bear in mind that they were intended for a quick presentation only. The Interim Research Results from the Paciic Salmon Forum are described in more detail in the Proceedings of that workshop.

BC PACIFIC SALMON FORUM: Interim Research Results Information Meeting

November 8/9, 2007
Vancouver

Juvenile pink salmon health survey 2007. Sonja Saksida, Gary Marty, Simon Jones, Sophie St.Hilaire and Howie Manchester.
Geographic area: Broughton
Sea lice topic: levels of lice, and their health effects
Kind of research: field
Kind of document: PowerPoint
Main message: The aims of the study were to assess the health of out-migrating wild pink salmon in the Broughton Archipelago in 2007 (Glendale population), determine whether sea lice infestations have any effects on health, and determine whether other lesions/pathogens may have effects on health. We sampled over three time periods, noting weights, lengths, sea lice species and stage, environmental data, virology, bacteriology and histology. There was low sea lice infestation intensity in the region in 2007 (of 302 fish examined, only 41 fish had motile sea lice), and no evidence of health issues associated with observed sea lice levels. Other pathogens/infections were observed, some appearing to have more substantial health effects on the juvenile fish than did sea lice.

Plankton sampling in the Broughton. Dave Mackas and Moira Galbraith.
Geographic area: Broughton
Sea lice topic: number and location of larvae
Kind of research: field
Kind of document: PowerPoint
Main message: Aims of the study are to develop methods for sampling planktonic sea lice; determine the level of effort needed to discriminate between ‘‘low’’and ‘‘zero or near zero’ abundance; map the distributions of planktonic-stage sea lice along Knight Inlet and Tribune Channel before and during the spring season out-migration of wild pink and chum salmon; and compare observed distributions to surface water properties and proximity to active fish farms. After shoreline horizontal plankton tows in the surface layer, each sample jar contains several thousand ‘‘other zooplankton’’ similar in size and shape to larval sea lice, so we needed to search all of every sample. We found *Lepeophtheirus salmonis* nauplii, *L. salmonis* copepodites,

and *Caligus clemensi* copepodites. Abundances per sample were low, ranging from zero (the most common) to nine. There was no clear time trend for *L. salmonis* nauplii or copepodites, but *Caligus* copepodites disappeared in late March. *L. salmonis* larvae were relatively rare, but their occurrence rates and abundances were higher near active fish farms. *L. salmonis* presence/abundance were also positively correlated with surface salinity in Knight/Tribune, but this association was weaker. *Caligus* was most abundant in side inlets. We will repeat the observations in 2008, compare 2007 patterns to patterns under enhanced fallowing/treatment, and estimate cumulative encounter rates with salmon fry.

Migration routes of juvenile sockeye in the Skeena estuary and the potential for transfer of IHNV between wild salmon and penned Atlantics. Allen S. Gottesfeld, Bart Proctor, Dave Rolston and Charmaine Carr-Harris.
Geographic area: B.C. North Coast
Sea lice topic: siting of salmon farms
Kind of research: field
Kind of document: PowerPoint
Main message: While not specifically targeting sea louse transmission, this study of salmon smolt migration routes in one area of the North Coast included data for sockeye, pink and chinook salmon, and showed that one can define travel corridors in the inshore coastal zone. There are places of persistent and consistent high densities of sockeye, and these are places to avoid siting salmon farms if we are concerned about reducing the likelihood of disease transmission.

Outgroup analyses of sea lice infections: studies from the Central Coast. Michael Price and John Reynolds.
Geographic area: Central Coast
Sea lice topic: louse levels on juvenile salmonids
Kind of research: field
Kind of document: PowerPoint
Main message: The purpose of the study was to examine lice infection levels on juveniles in the Central Coast, and relate to subsequent returns of spawners. Average louse prevalence was 4.2% over 3 months' sampling for four salmonid species, with roughly equal numbers of *L. salmonis* and *C. clemensi*. Comparison with escapement levels for pink salmon in the Central Coast is under way.

Effects of sea lice on the physiology and health of pink salmon. Brauner, CJ, Farrell, AP and Saksida, S.
Geographic area: Broughton
Sea lice topic: sea lice effects
Kind of research: laboratory and field
Kind of document: PowerPoint
Main message: This work aims to characterize the sub-lethal disturbances associated with different levels of sea lice density in pink salmon in the lab, and to use these data to develop a model for wild pink salmon populations. The underlying assumption is that sea lice impair iono-regulatory homeostasis and whole animal performance. Researchers include Amelia Grant (Technician), Laura Nendick (MSc student), Michael Sackville (MSc student) and Manuela Gardner (Postdoctoral Fellow). The experimental goals are to determine "normal" physiological and behavioural parameters for juvenile pink salmon as a function of age/stage; investigate the relationship between sea lice density and fitness of juvenile pink salmon in the laboratory; "ground truth" the laboratory experiments with field experiments relating lice density and fitness; calibrate fish health/survival monitoring efforts with predictors of fitness; and assess health of naturally migrating fish at different lice densities. To date, we have obtained novel baseline data for ~1 g pink salmon growth, swimming performance and iono-regulatory status, and developed novel methodologies to measure swimming performance (U_{max}) and drinking rate in ~1 g pink salmon. We can already conclude that natural lice infections up to 1 louse/fish have no effect on U_{max}; and that natural lice infections don't persist in the lab. We have developed a new method for controlled infection of fish in the lab with copepodids.

Improvements in ocean circulation modeling. Dario Stucchi & Mike Foreman.
Geographic area: Broughton
Sea lice topic: oceanography and circulation modelling
Kind of research: field
Kind of document: PowerPoint
Main message: River discharge (measured in Wakeman, Kingcome, Klinaklini Rivers and McAlister Creek) and wind forcing (based on 6 to 9 Davis Station sites installed since April 2007) are being used to improve the current circulation model. Wind is the main thing forcing surface circulation in parts of the Broughton, and important to our understanding of transport of lice larvae because these are found in the surface layer. Long term current meters (measuring from surface down to 165 m) and GPS surface drifters provide additional data. GPS surface drifter deployments at the end of March 2007 show considerable movement up Knight Inlet driven by prevailing winds. Wind forcing is a critical factor driving surface circulation in Knight Inlet. Circulation modeling now uses new code, the FVCOM (Finite Volume Coastal Ocean Model) developed at the University of Massachusetts, because the previous model (ELCIRC) had too much inherent damping. FVCOM is more sensitive to grid triangles, bathymetry, and boundary forcing and requires explicit river channels. Preliminary results for 5 rivers show lots of small-scale eddies. 3D animations with VisIT software make it easy to show flows along a cross-section and could be adapted for particles such as planktonic louse stages.

Marine monitoring of juvenile pink and chum salmon and sea lice in 2007 (second year). B. Hargreaves, S. Jones, A. Morton.
Geographic area: Broughton
Sea lice topic: annual monitoring
Kind of research: field
Kind of document: PowerPoint
Main message: A marine monitoring program to assess sea lice infections on wild juvenile pink and chum salmon, stickleback and other fish species in the Broughton has the following components: joint field sampling program (DFO and A. Morton); increased sampling in Tribune Channel and Knight Inlet; comparison of DFO species I.D. methods and sea lice results with those of M. Krkošek; and analysis of juvenile coho and chinook collected in previous years. In 2005, prevalence of *L. salmonis* on juvenile pink and chum salmon peaked in April-May at around 30%. Results for 2007 indicate lower prevalence; 80% of pink and chum salmon were lice-free, very similar to 2006. Average weight was also lower than in other years. The much higher abundance for 2004 may reflect higher surface water temperatures that year.

Genomics in lice and salmon. Ben Koop, Simon Jones, Willie Davison and Grant Murray.
Geographic area: Pacific Ocean
Sea lice topic: population genetics, including DNA fingerprinting
Kind of research: laboratory
Kind of document: PowerPoint
Main message: New DNA microarray (Gene Chip) technology allows us to see a graphic representation of gene activity during various life processes and responses to the environment. Identifying all the genes in *L. salmonis* and *C. elongatus* will allow building their Gene Chips (microarrays). These microarrays and those for salmonids will allow us to measure the response of different salmon species to lice; identify louse response to the environment and treatments; and develop genetic markers (DNA fingerprints) that could help distinguish different louse populations and their origins. Gene sequencing of Atlantic and Pacific forms of *L. salmonis* already shows around 10% difference in genetic makeup, indicating the two forms are likely different species; many potential genetic markers have now been identified.

WORLD AQUACULTURE SOCIETY. AQUACULTURE 2007: Sea Lice Session

March 1, 2007
San Antonio

Insights into the control of host-parasite interactions: Immune-gene regulation in salmonids following *Lepeophtheirus salmonis* challenge. M.D. Fast, S.C. Johnson, D.B. Groman, S.R.M. Jones.
Geographic area: various
Sea lice topic: effects of *L. salmonis* on juvenile pink and chum salmon
Kind of research: laboratory
Kind of document: PowerPoint
Funder(s): not stated
Main message: Using a standardized laboratory assay wherein hatchery pink and chum salmon are exposed to copepodids in 33L tanks, effects of *L salmonis* on the growth, physiological responses and survival of pink and chum salmon were studied. In pink salmon, infection level reduces quickly (<7 d) and there is an early increased expression of inflammatory genes. In chum and Atlantic salmon, infection is maintained at higher levels, with later expression of inflammatory genes (≥14 d), as well as increased cortisol and other stress parameters. Future questions include: Why is there a difference between laboratory and field observations on mortality of pink salmon? Do *L. salmonis* transfer from non-salmonid hosts as preadults? What impact do preadults have on the health and physiological status of pink and chum salmon? What is the relationship between host physical and physiological development and susceptibility to infection (scales, seawater adaptation, stress response)?

Monitoring the infective pressure of *Lepeophtheirus salmonis* (Krøyer 1837) on wild salmonid populations in Loch Torridon, Scotland. Ian R. Bricknell, Campbell C. Pert, Paul Cook, Rachel Kilburn, Alistair McBeath and Sonia McBeath.
Geographic area: Scotland
Sea lice topic: sentinel cages to study infection in wild salmonids
Kind of research: field
Kind of document: PowerPoint
Funder(s): not stated
Main message: Sentinel cages were used to help answer several questions about natural sea louse dynamics. Sentinel cages containing 150 Atlantic salmon are equipped to record flow, temperature, conductivity and light. After one week, fish are examined for lice, and their identification confirmed genetically. Sentinel cages show pre-adults establishing pioneer populations; however, we do not know what species are the source of the pre-adults. Copepodids are the most abundant stage in the warmer summer and early autumn months. *L. salmonis* copepodids are rare members of the plankton community. There is a peak of lice in late winter. Findings of sea lice in estuaries may be explained by: copepodids and nauplii incorrectly identified; water movement from the farming area in to the river mouths (field tests of a model suggest this distance can be travelled in one tidal cycle); transfer from wild fish in the area. Other questions: Do sea lice infect smolts shortly after sea transfer? Are wild salmonids the

source of these infections? Can peripatetic hosts (such as saithe and stickleback) act as *L. salmonis* reservoirs in the absence of salmonid hosts?

The prevalence, intensity and effect of *L. salmonis* infestations on wild juvenile pink salmon from the Central Coast of British Columbia, Canada. F. Cubitt, K. Butterworth and R.S. McKinley.
Geographic area: Central Coast
Sea lice topic: louse prevalence in relation to salmon farms
Kind of research: field
Kind of document: PowerPoint
Funder(s): not stated
Main message: Based on three areas (inland of farms, amongst farms and seaward of farms), the study found low numbers of sea lice and no relationship between salmon farms and sea lice prevalence. There was a stronger correlation between location and fish condition.

Salmon lice distribution in fjords: Numerical models and observations. Lars Asplin, Karin K. Boxaspen and Anne D. Sandvik.
Geographic area: Norway
Sea lice topic: louse dispersal within fjords
Kind of research: field and laboratory
Kind of document: PowerPoint
Funder(s): Institute of Marine Research; Bjerknes Climate Centre
Main message: Currently there are three models for estimating salmon louse distribution in Norwegian fjords: the wind model; fjord model and salmon lice growth and advection model. Based on data from 16 sentinel cages in 2004 to 2006, three model examples show that sea lice can disperse quickly (~2 km/h); they can be transferred within a fjord as a batch; and there can be large movement of water both in and out the fjord system.

Modelling the dispersal of salmon lice (*Lepeophtheirus salmonis*) from proposed salmon farm sites in Lough Swilly, County Donegal, Ireland. Neil R Bass and Naomi R Shannon.
Geographic area: Ireland
Sea lice topic: dispersion from salmon farms - models
Kind of research: desk
Kind of document: PowerPoint
Funder(s): Marine Harvest Ireland; BIM
Main message: To support applications for two new salmon farm licences in Lough Swilly, Marine Harvest Ireland commissioned an investigation into the likely dispersion of *Lepeophtheirus* larvae from the proposed sites. A calibrated tidal model and a dispersion model were developed. Lough Swilly is north- facing, out of the prevailing wind. Thus currents are primarily tidally driven. Three louse treatment trigger levels were used, and the dispersion model was adapted to enable the comparison of dispersal with and without a tidal geotaxis. Nauplii were excluded from some of the larval dispersions simulated (naupliar filter). Within the larval hatch range tested, the simulations show that farm-origin *Lepeophtheirus* copepodids are

unlikely to penetrate Lough Swilly river estuaries to reach their hosts. This appears to be a result of Lough Swilly's highly dispersive hydrography but is also likely to be related to the positions of the proposed farm sites relative to rivers. Mean lice densities drop by at least two orders of magnitude within 1000m of the site. Treatment trigger levels between 0.3 and 1.0 ovigerous lice per farmed fish serve little or no practical purpose with respect to risk of infestation of wild fish. The infestation pressure of a dispersing larval plume may be better expressed if nauplii are filtered out of the simulations.