Salmon Aquaculture Reduces Survival of Wild Salmonids

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Since the late 1980s, wild salmon catch and abundance have declined dramatically in the North Atlantic and in much of the Northwest Pacific, south of Alaska. In these areas, there has been a concomitant increase in the production of farmed salmon. The hypothesis that salmon aquaculture is an important contributor to the widespread decrease in wild salmon survival has been suggested, but not demonstrated. Experimental studies have shown the potential for negative impacts on wild salmonids, but their results have been difficult to translate into predictions of change in wild population survival and abundance. We compared marine survival of salmonids in areas with salmon farming to adjacent areas without farms, to estimate the effect of aquaculture on marine survival. Through a meta-analysis of existing data, we show a reduction in survival of 5 species of anadromous salmonids from 7 regions of the North Atlantic and Pacific, as a result of increased production of farmed salmon. In many cases, salmon farming reduced survival or abundance by more than 50%. This is the first demonstration that salmon farming reduces survival sufficiently to pose a significant threat to wild salmon and trout in many populations and countries.

1 INTRODUCTION

Salmon farming impacts wild salmonid populations through a number of mechanisms, including increasing parasite loads, hybridization with escaped farm salmon, and increasing predator densities near farm sites. A number of studies have predicted or evaluated the impacts of salmon farming through a single mechanism, in a given area. It is clear that some salmonids are infected by sea lice originating from salmon farms (Krkošek et al. 2005; Morton et al. 2003; Bjørn and Finstad 2002; Gargan et al. 2003), that other diseases have been spread to wild populations from salmonid farming activities (Johnsen and Jensen 1994; ICES 2001), and there is evidence that salmon parr are at lower density in areas of Scotland where there is aquaculture (Butler and Watt 2003). In addition, farmed salmon escape in all areas where salmonid aquaculture is practiced, and although their breeding success may be low on average, competition for mates and hybridization with wild salmon are likely to reduce survival of wild populations (McGinnity et al. 2003; Weir et al. 2004).

In this study, populations in which juvenile salmonids pass by salmon farms on their migrations were considered to be "exposed" to impacts of salmon farming. Therefore this study primarily measures impacts from disease or ecological change related to salmon farming, though many of our exposed populations may also have experienced genetic introgression from escaped farm salmon.

For each region analysed, we selected a control region that was not directly exposed to salmon farming, but which matched the exposed area as closely as possible, i.e. similar climate, acidification, and marine fisheries and migration (Table 1, details about the data used and the regions we compared are available in the Electronic Supplementary Material). Data from scientific surveys, e.g. counting fences, were used if possible; however, for Scottish salmon and Irish and Welsh sea trout, only catch data were available (Figure 2). Despite careful selection of exposed and control stocks, there is some possibility of spurious correlation between decline in a stock and the growth of salmon farming in that region. However, because we performed many comparisons, our meta-analytic means will be robust to such chance events, and are good indicators of the overall impact of salmon farming on wild stocks.

2 MATERIAL AND METHODS

2.1 Model

We modeled survival and, in a separate analysis, total returns to each stock, using a general linear mixed effects model for each region. To model survival, we used a Ricker model extended to include the production of farmed salmon in the area through which exposed juvenile salmon migrated, with random effects for each stock and year (Myers et al. 1999).

Let $S_{i,y}$ be an index of the number of fish that smolted, i.e. migrated to sea in the spring, in year y from stock i, let $R_{i,y}$ be the estimated number of those fish that would subsequently return to spawn in the absence of fishing, and let $P_{i,y}$ be the aquaculture production that those smolts were exposed to (in tonnes). The dynamics are assumed to be given by

$$\log(\frac{R_{i,y}}{S_{i,y}}) = \beta_0 + a_i + d_y + \beta_i S_{i,y} + \gamma(P_{i,y})^{\lambda} + e_{i,y}, \tag{1}$$

where β_0 is the fixed intercept for the average stock and year with no aquaculture production, a_i is the random deviation of the i^{th} stock intercept from β_0, d_y is the random deviation of the y^{th} year, β_i is the fixed slope of mortality (that is the density-dependence parameter) that will vary with each stock i, and γ is the coefficient of aquaculture mortality that is assumed to scale with a possibly nonlinear function of aquaculture production, $(P_{i,y})^{\lambda}$. The random error, $e_{i,y}$, is assumed to be first-order autocorrelated. We assume the a_i's and d_y's come from normal distributions with zero mean. The autocorrelation and the random year effect are included to account for established temporal and spatial correlations in environmental effects (Myers et al. 1997). The effects of aquaculture are summarized by the coefficient γ, for each region,

k. These coefficients were combined using meta-analysis to obtain an overall estimate of the change in wild salmonid survival related to aquaculture.

As the best functional form for aquaculture impact in the model, $(P_{i,t})^{\lambda}$, was not known, we investigated several functional forms: a linear increase in impacts with aquaculture, a square relationship, and a square root relationship. We chose the best model by AIC, and tested our results under alternative formulations.

We repeated the analysis with number of returning adults as the response variable, to test the robustness of the conclusions and because only returns data were available for some regions. This analysis used Equation 1 with $S_{i,t}$ and β_i dropped from the equation. The response variables for this analysis included rod catches, rod plus marine catches, counts of salmon returning to rivers, and estimates of returns to rivers in the absence of fishing (details in the Electronic Supplementary Material).

Outer Bay of Fundy salmon in New Brunswick, Canada, have been reduced to zero in one river and a handful in another. For this region, we used a generalized linear mixed effect model with negative binomial error instead of Equation 1.

2.2 Meta-Analysis

The effect of aquaculture is summarized by one parameter, γ, to which we now add a subscript to identify each region, k. For a fixed assumption about λ, the γ_k's are in the same units and can be directly compared using meta-analysis. In the general case, we model the effects of aquaculture as a mixed effects model,

$$\hat{\gamma}_k \sim N(\alpha_0, \sigma^2 + s_k^2), \tag{2}$$

where $\hat{\gamma}_k$ is the estimated value of γ_k, α_0 is the intercept, s_k^2 is the variance of the k'th estimate (which is taken from the analysis in Equation 1, and is held fixed), and σ^2 is the among-region variance. A fixed effect meta-analysis is obtained by constraining σ to be zero. We used maximum likelihood estimation and selected models by AIC.

For robustness, we considered 5 classes of models: different regions used as controls, different mixed model assumptions, different error assumptions, different functional forms for the aquaculture effect, and different autocorrelational structures, as well as performing a Bayesian meta-analysis. Overall, the results were very similar for all models. (See Electronic Supplementary Material for results of alternative models and details of the Bayesian analysis.)

We were unable to carry out analysis for Norway, because all parts of Norway are exposed to some extent (a map showing salmon farm locations is available from the Norwegian Directorate of Nature Management, at `http://english.dirnat.no/archive/images/01/12/salmo042.pdf`), because many rivers contained over 50% aquaculture escapees (Fiske et al. 2001), and due to confounding effects due to acidification and disease. For the West Coast of Vancouver Island it was not possible to obtain aquaculture production data by region over time, and Maine was not included because of a lack of suitable control rivers.

3 RESULTS

Survival of many stocks was reduced by more than 50% (Figure 3). All estimates of γ_k were negative, with the exception of survivals of Atlantic salmon (mainly from hatcheries) in Ireland (Figure 3). Both random-effects estimates of the mean γ were negative and highly significant, indicating a very large negative impact on survival. For example, the γ_k for Bay d'Espoir in Newfoundland was estimated to be -0.027. In 2003, the farmed salmon harvest from this area was 1450 tonnes, which under the dynamics of Equation 1, corresponds to a decrease in survival of 65% (95% CI: 44 to 80%), relative to no salmon farming.

Including autocorrelated errors reduced the Akaike Information Criteria (AIC) for most models, and AIC was lower when $\lambda = 0.5$ than when $\lambda = 1$ or 2 for the majority of regions, so this formed our base model for which results are given (see Electronic Supplementary Material). This value of λ indicates that relatively small amounts of aquaculture will depress wild survival, but the effect does not increase proportionally to aquaculture production.

4 DISCUSSION

We found higher impacts on populations in the Atlantic than those in British Columbia, possibly because Atlantic salmon populations are conspecific with farmed salmon, and therefore susceptible to genetic effects from interbreeding. These estimates may also be lower because we aggregated over large numbers of populations for pink, chum, and coho salmon, as estimates of fishing mortality were only available on a very coarse scale.

Populations that spend more time near salmon farms may experience higher impacts. Anadromous brown trout, which have coastal distributions, had one of the highest mortalities in our sample. Similarly, inner Bay of Fundy salmon may have a more localized marine distribution than other populations (Amiro et al. 2003). The largest correlation between declining returns and salmon farming was found in these populations. The aquaculture industry in the outer Bay of Fundy (New Brunswick, Canada) is extremely concentrated, and salmon from the St. Croix and Magaguadavic Rivers must pass by many salmon farms on their migrations. The wild salmon run in the St. Croix is extinct, and the returns to the Magaguadavic have declined from over 800 wild salmon to fewer than 10 in the last 15 years.

The time period over which we are estimating impacts of aquaculture includes the establishment of the industry in each region. Improvements in management as industries mature may explain our finding that impacts of salmon farming on wild salmon do not increase linearly with the volume of aquaculture. Better management should decrease the impact of salmon farming on a per tonne basis, though such improvements may not be able to keep pace with the growth of the salmon farming industry.

The increase in mortality related to salmon farming is in addition to mortality that is also acting on the control populations. In most cases, our controls are also experiencing decreases in marine (and sometimes freshwater) survival, for reasons that are only partially understood. At the same time, fishing has been reduced or eliminated in many areas, which has partially masked the decline in survival associated with aquaculture.

Both meta-analytic estimates (using survival and returns indices) provide strong evidence that salmon farms have had negative impacts on the populations studied. The reduction in survival of wild salmonids is large, and is expected to increase if aquaculture production increases. Most populations have been subject to only a few generations of aquaculture at high levels, at which very large reductions in survival are seen (Figure 3).

The supplementary Electronic Appendix is available at ...

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Table 1: Summary of stocks included

ID	species	country	exposed		control		type	ref
			region	*n*	region	*n*		
1	Sea trout	Ireland/UK	Ireland,* Western Region	16	Wales	32	C	(Russell et al. 1995; Sea Trout Review Group 2002) (Environment Agency 2005)
2	Atlantic salmon	Scotland	West Coast*	1	East Coast	1	C	(Fisheries Research Services 2005)
3			West Coast*	2	East Coast	10	T	(Thorley et al. 2005)
4		Ireland	Western Region**	4	Rest of Ireland	9	T,S	(ICES 2005)
5		Canada	Bay d'Espoir**	1	Rest of Newfoundland	4	T	(O'Connell et al. 2005)
			Bay d'Espoir*	1	Rest of Newfoundland	21	T,S	(O'Connell et al. 2005)
6			Fundy, Inner	2	Gulf of St Lawrence, Atlantic Coast	4	T,S	(DFO 2003; ICES 2005) (Gibson et al. 2003; Gibson and Amiro 2003)
7			St John River	2	Gulf of St Lawrence, Atlantic Coast	4	T,S	(DFO 2003; ICES 2005) (Jones et al. 2004; Chaput et al. 2001)
8			Fundy, Outer	2	Gulf of St Lawrence, Atlantic Coast	4	T,S	(DFO 2003; ICES 2005) (Jones et al. 2004; Chaput et al. 2001)
9	Coho salmon		Johnstone Strait	2	BC Central Coast	4	S	(DFO 2006)
10	Pink salmon		Johnstone Strait	2	BC Central Coast	4	S	(DFO 2006)
11	Chum salmon		Johnstone Strait	2	BC Central Coast	4	S	(Godbout et al. 2004)

* Used in Returns Analysis only

** Used in Survival Analysis only

Type "C" refers to catches, "T" refers to scientific traps, and "S" refers to other scientific surveys.

References

Amiro, P. G., Gibson, J., and Drinkwater, K. (2003) Identification and exploration of some methods for designation of critical habitat for survival and recovery of inner Bay of Fundy Atlantic salmon (*Salmo salar*). *DFO CSAS Res. Doc. 2003/120*.

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 J. Mar. Sci.* **59**, 131–139.

Butler, J. R. A., and Watt, J. (2003) Assessing and managing the impacts of marine salmon farms on wild Atlantic salmon in western Scotland: identifying priority rivers for conservation. In Mills, D. (Ed.), *Salmon at the Edge*. Oxford, UK: Blackwell Science Ltd. pp. 93–118.

Chaput, G., Moore, D., Hayward, J., Sheasgreen, J., and Dubee, B. (2001) Stock status of Atlantic salmon (*Salmo salar*) in the Miramichi River, 2000. *DFO CSAS Res. Doc. 2001/008*.

DFO (2003) Atlantic salmon Maritime Provinces overview for 2002. *DFO Science SSR 2003/026*.

DFO (2006) DFO Pacific Salmon Escapement Data System NuSEDS. P. VanWill, personal communication.

DFO Statistical Services (2006) Aquaculture production statistics for Canada. *http://www.dfo-mpo.gc.ca/communic/statistics/aqua/index_e.htm*.

Environment Agency (2005) Salmonid and freshwater fisheries statistics for England and Wales, 2004.

Fisheries Research Services (2005) J. MacLean, personal communication.

Fiske, P., Lund, R. A., Østborg, G. M., and Fløystad, L. (2001) Escapees of reared

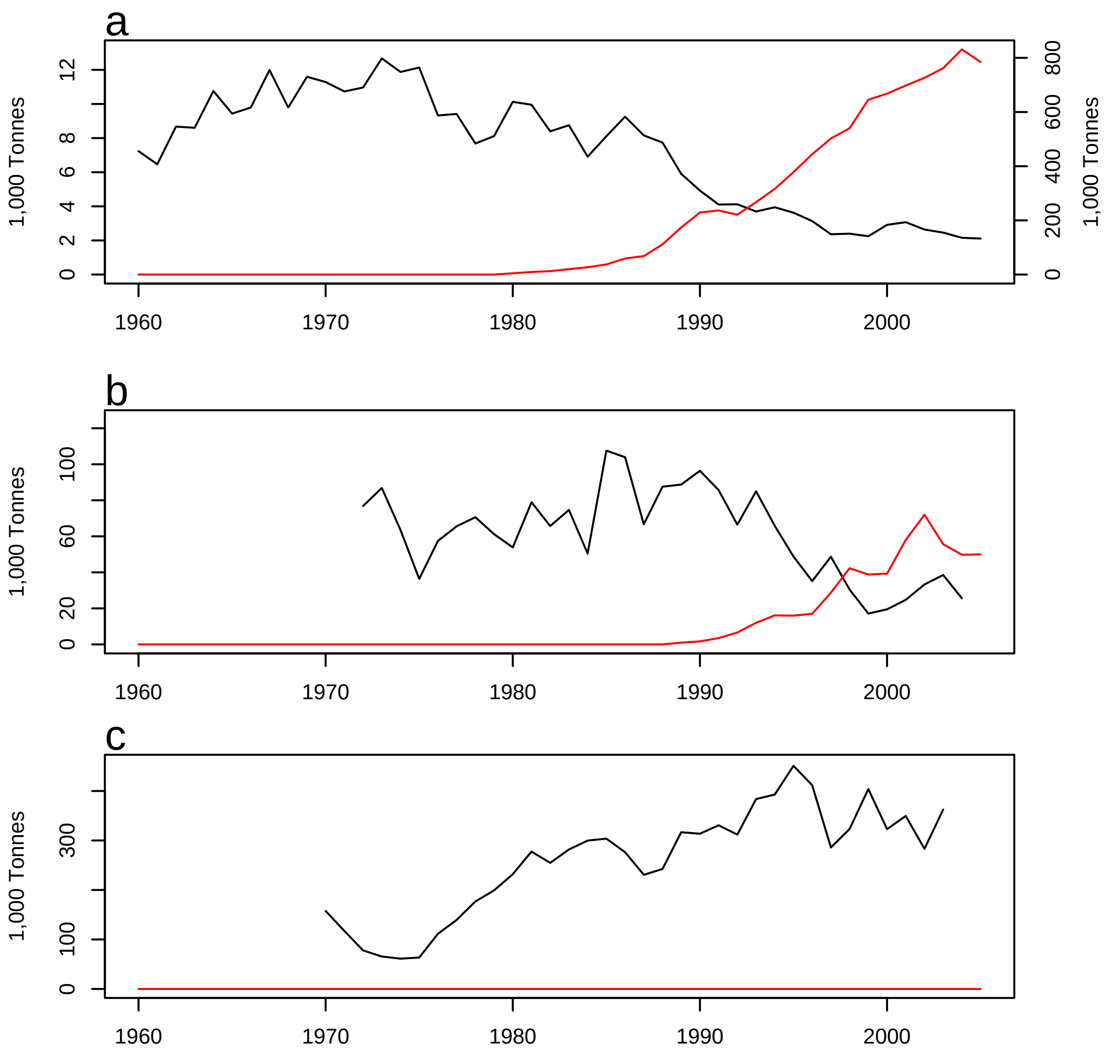

Figure 1: Total harvest of wild and farmed salmon. (a) Total catch of Atlantic salmon (black, left-hand axis) and production of farmed salmon (red, right-hand axis) in the North Atlantic (ICES 2005). (b) Total catch of salmon (all species, in black) and farmed salmon (all species, in red) in British Columbia, Canada (ICES 2005; DFO Statistical Services 2006). (c)Total catch of salmon (all species) in Alaska, USA, where no salmon farming occurs (State of Alaska 2006).

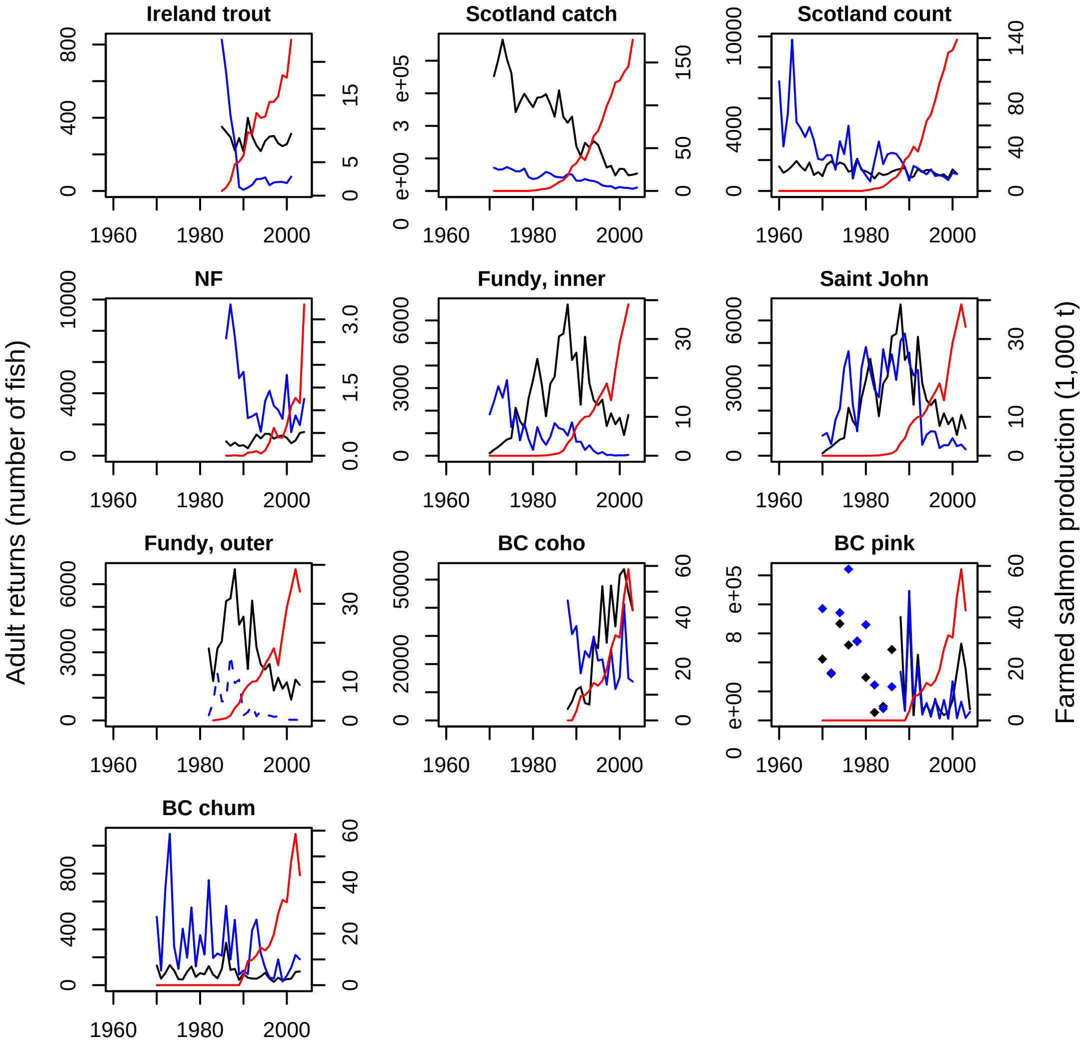

Figure 2: Adult returns of wild salmonids in control (black) and exposed (blue) stocks, along with aquaculture production(red). For plotting, the returns to controls and exposed stocks have been separately summarized by a multiplicative model ($\log(Returns_{i,y}) = a_i + d_y + e_{i,y}$); the mean returns across stocks for each year are shown. Returns to exposed regions in the inner Bay of Fundy have been multiplied by 10 for clarity (dashed line), and only even year values are available for pink salmon prior to 1989 (details in Supplementary Methods). Irish salmon are not included because only marine survivals (not returns) were available.

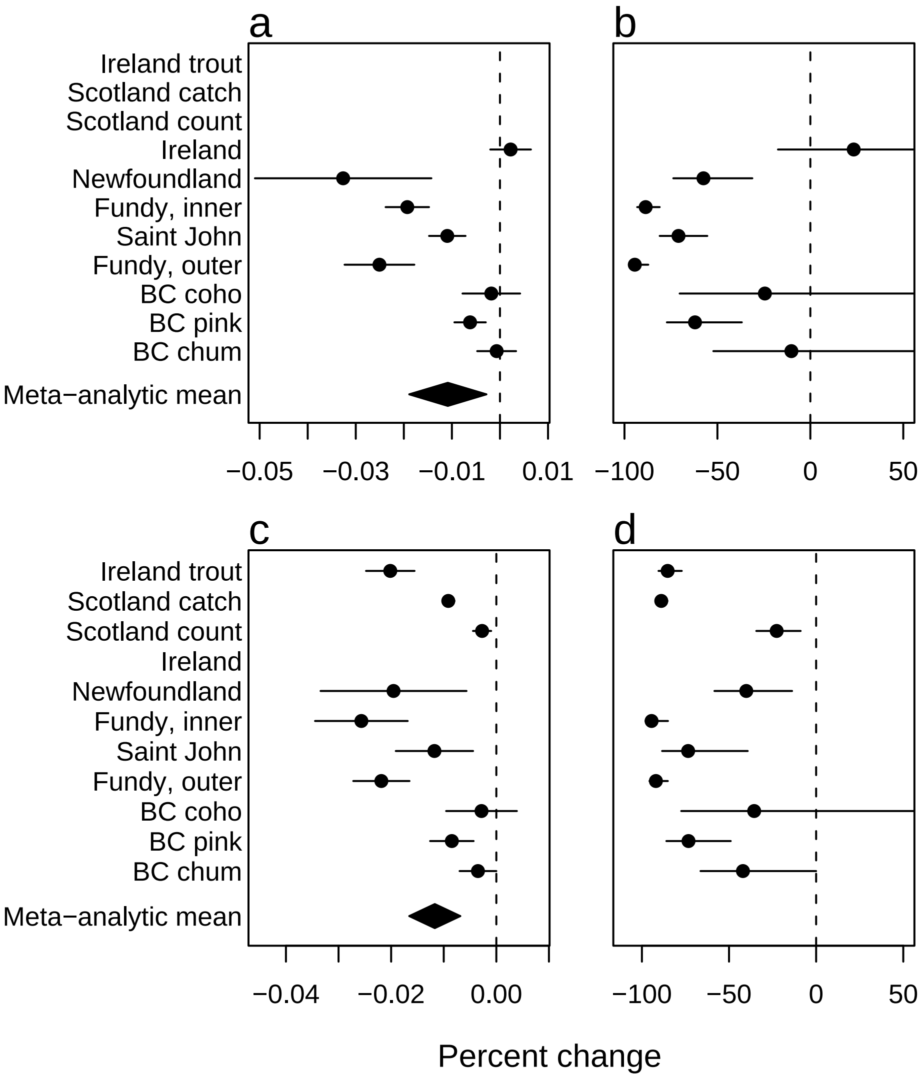

Figure 3: Impacts of salmon farming. All estimates are for Atlantic salmon unless otherwise specified. Percent change is $(1 - e^{\hat{\gamma}_k}) * 100$. (a) Estimated percent change in survival per generation per tonne of farmed salmon production. The diamond indicates the random-effects meta-analytic mean. (b) Estimated percent change in survival of wild salmonids due to salmon farming, per generation, at the mean tonnage of farmed salmon harvested in each region, during the study period. A meta-analytic mean is not given because of the large variation in aquaculture production values across regions. (c), (d), As for (a), (b), but representing the change in returns to each stock. Bars and width of diamonds are 95% confidence intervals.

salmon in coastal and riverine fisheries in the period 1989-2000. *NINA Oppdragsmelding* **704**, 1–26.

Gargan, P. G., Tully, O., and Poole, W. R. (2003) Relationship between sea lice infestation, sea lice production and sea trout survival in Ireland, 1992-2001. In Mills, D. (Ed.), *Salmon at the Edge*. Oxford, UK: Blackwell Science Ltd. pp. 119–135.

Gibson, A. J. F., and Amiro, P. G. (2003) Abundance of Atlantic salmon (*Salmo salar*) in the Stewiacke River, NS, from 1965 to 2002. *DFO CSAS Res. Doc. 2003/108*.

Gibson, A. J. F., Jones, R. A., Amiro, P. G., and Flanagan, J. J. (2003) Abundance of Atlantic salmon (*Salmo salar*) in the Big Salmon River, NB, from 1951 to 2002. *DFO CSAS Res. Doc. 2003/119*.

Godbout, L., Irvine, J. R., Bailey, D., Will, P. V., and McConnell, C. (2004) Stock status of wild chum salmon (*Oncorhynchus keta Walbaum*) returning to British Columbia's Central Coast and Johnstone and Georgia Straits (excluding the Fraser River). *DFO CSAS Res. Doc. 2004/007*.

ICES (2001) *Report of the Working Group on North Atlantic Salmon (WGNAS). ICES Headquarters Copenhagen, 3-13 April 2002,*.

ICES (2005) *Report of the Working Group on North Atlantic Salmon (WGNAS), 5-14 April 2005, Nuuk, Greenland.* ICES CM 2005/ACFM:17. 290 pp.

Johnsen, B. O., and Jensen, A. J. (1994) The spread of furunculosis among salmonids in Norweigan rivers. *J. Fish Biol.* **45**, 47–55.

Jones, R. A., Anderson, L., and Goff, T. (2004) Assessments of Atlantic salmon stocks in southwest New Brunswick, an update to 2003. *DFO CSAS Res. Doc. 2004/019*.

Krkošek, M., Lewis, M. A., and Volpe, J. P. (2005) Transmission dynamics of parasitic sea lice from farm to wild salmon. *Proc. R. Soc. Lond. B Biol. Sci.* **272**, 689–696.

McGinnity, P., Prodöhl, P., Ferguson, A., Hynes, R., Ó Maoiléidigh, N., Baker, N., Cotter, D., O'Hea, B., Cooke, D., Rogan, G., Taggart, J., and Cross, T. (2003) Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. *Proc. R. Soc. Lond. B Biol. Sci.* **270**, 2443–2450.

Morton, A., Routledge, R., Peet, C., and Ladwig, A. (2003) 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. *Can. J. Fish. Aquat. Sci.* **61**, 147–157.

Myers, R. A., Bowen, K. G., and Barrowman, N. J. (1999) Maximum reproductive rate of fish at low population sizes. *Can. J. Fish. Aquat. Sci* **56**, 2404–2419.

Myers, R. A., Mertz, G., and Bridson, J. (1997) Spatial scales of interannual recruitment variations of marine, anadramous, and freshwater fish. *Can. J. Fish. Aquat. Sci.* **54**, 1400–1407.

O'Connell, M. F., Dempson, J. B., Reddin, D. G., Bourgeois, C. E., Porter, T. R., Cochrane, N. M., and Caines, D. (2005) Status of Atlantic salmon (*Salmon salar* L.) stocks of insular Newfoundland (SFAs 3-14A), 2004. *DFO CSAS Res. Doc. 2005/064*.

Russell, I. C., Ives, M. J., Potter, E. C. E., Buckley, A. A., and Duckett, L. (1995) Salmon and migratory trout statistics for England and Wales 1951-1990. *Fish. Res. Data Report No. 38*, 252pp.

Sea Trout Review Group (2002) Report of the Sea Trout Review Group 2002. 32pp pp.

State of Alaska (2006). *www.cf.adfg.state.ak.us/geninfo/finfish/salmon*.

Thorley, J. L., Eatherley, D. M. R., Stephen, A. B., Simpson, I., MacLean, J. C., and Youngson, A. F. (2005) Congruence between automatic fish counter data and rod catches of Atlantic salmon *Salmo salar* in Scottish rivers. *ICES J. Mar. Sci.* **62**, 809–817.

Weir, L. K., Hutchings, J. A., Fleming, I. A., and Einum, S. (2004) Dominance relationships and behavioural correlates of individual spawning success in farmed and wild male Atlantic salmon, *Salmo salar*. *J. Anim. Ecol.* **73**, 1069–1079.