Supplementary Information for ***Large Scale Salmon Aquaculture Reduces Survival of Wild Salmonids***

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Data Sources and Treatment

Ireland trout We compared rod catches of sea trout in Ireland's Western Region, to rod plus in-river fixed engine catches in Wales, from 1985-2001. (There are no fixed engine fisheries directed at sea trout in Ireland.) Trout caught and released are included in both countries. Only catch estimates were available for most of these rivers, and because anadromous brown trout interbreed with freshwater resident trout, recruitment could not be derived, so this stock was only included in the returns modeling (not survival). Salmon farming is concentrated in the Western Region (Connemara area) of Ireland, but does occur in other parts of the country. Farmed salmon production for the entire country was used in modeling and in deriving the farmed:wild ratio for meta-regression [1].

Controls: 32 Welsh Rivers: Aeron, Afan, Arto, Cleddau, Clwyd, Conwy, Dee, Dwyfawr, Dwyryd, Dyfi, Dysynni, Glaslyn, Gwendreath, Gwyrfai, Llyfni, Lougher, Mawddach, Neath, Nevern, Ogmore, Ogwen, Rheidol, Rhymney, Seiont, Taf, Taff, Tawe, Teifi, Tywi, Usk, Wye, Ystwyth [2,3]

Exposed: 16 Rivers in Western Ireland: Athry, Bhinch (Lower), Bhinch (Middle), Bhinch (Upper), Burrishoole, Costello, Crumlin, Delphi, Erriff, Gowla, Inagh, Inverbeg, Invermore, Kylemore, Newport, Screebe [4]

The distribution of salmon farms in Ireland can be seen at www.saveourseatrout.com/map.html.

Scotland catch We compared marine plus rod catches from the East Coast of Scotland to catches from the West Coast (1971-2004), where salmon farming is widespread [1]. Rod catches included salmon caught and released. These data were only used in modeling returns.

Controls: East Coast marine [1] and rod catches (J. Maclean, personal communication)

Exposed: West Coast marine [1] and rod catches (J. Maclean, personal communication)

Salmon farms are widely distributed on the West Coast of Scotland, maps are available from Fish-

eries Research Services of Scotland:
www.marlab.ac.uk/Uploads/Documents/fishprodv9.pdf

Scotland counts We also used counts of salmon (all ages) returning to rivers from 1960-2001 in Scotland in the returns modeling. Fish counters are maintained by Fisheries Research Services or by Scottish and Southern Energy plc.

Controls: East Coast Rivers: Aigas, Beanna, Torr Achilty, Dundreggan, Invergarry, Logie, Westwater, Cluni, Erich, Pitlo [5]

Exposed: West Coast Rivers: Awe Barrage, Morar [5]

Ireland salmon Estimates of marine survival to 1SW for hatchery (and two wild) Atlantic salmon populations Ireland and Northern Ireland (1980-2004) are collected and reported by the ICES Working Group on North Atlantic Salmon [1]. As only survival estimates are provided, these data were only used in the survival analysis (Figure 1).

Controls: 4 Rivers: Shannon, Erne, Lee, Bush (wild and hatchery), Corrib (wild and hatchery) [1]

Exposed: 4 Rivers: Screebe, Burrishoole, Delphi, Bunowen [1]

Newfoundland (Canada) Two data sets from Newfoundland were used - marine survival estimates for 4 rivers from 1987 to 2004 were used in the survival analysis, and grilse returns to 21 rivers from 1986 to 2004 were used in the returns modeling. Salmon farming in Newfoundland is confined to the Bay d'Espoir on the South Coast [6]. Only the Conne River was considered exposed, the Little River (also in the Bay d'Espoir) was excluded because it is has been regularly stocked [7]. The Exploits and Rocky Rivers were also removed from the analysis because of stocking [8].

Controls: Three rivers with marine survivals: Campbellton River, Northeast Brook (Trepassey), and Western Arm Brook for returns analysis, returns to 18 Rivers: Campbellton, Crabbes, Fischells, Flat Bay Brook, Highlands, Humber, Lomond, Middle Brook, Middle Barachois , Northeast Brook (Trepassey), Northeast (Placentia), Northwest, Pinchgut Brook, Robinsons, Salmon, Terra Nova (upper and lower), Torrent, Western Arm Brook [7]

Exposed: Conne River [7]

Salmon farming in Newfoundland is practiced only in the Bay d'Espoir region of the South Coast. Salmon farm sites are available from www.aquagis.com/aquamap.asp.

Inner Bay of Fundy (New Brunswick, Canada) For all New Brunswick rivers, an estimate of egg deposition was used as an index of "spawners", to account for a significant increase the age of spawners in many rivers over the study period. The number of grilse and large spawners in each year was multiplied by a river-specific estimate of fecundity for a salmon of that size. Then "spawners" in a given year were derived by adding up all the eggs that could produce smolts in a year *y*, using river-specific age at smolting numbers from the literature. Returning hatchery-origin spawners are also added to the "spawners" but not to "returns". "Recruits" is the number of grilse that return to each river in year $y + 1$, so that R/S is the number of grilse returning per egg that would have smolted in year *y*. Estimates of returns to rivers from traps and other surveys were used in the returns analysis. No corrections were made to account for marine fisheries, but marine exploitation has quite limited since the late 1980's, when salmon farming became a substantial industry [6,9].

Controls: Restigouche River, Miramichi River, Catamaran Brook, LaHave River (Nova Scotia) [1,10–12]

Exposed: Stewiacke River, Big Salmon River [13,14]

Salmon farming in New Brunswick is highly concentrated in the Quoddy region of the outer Bay of Fundy, though some farms are also found along the Nova Scotia coast of the Bay of Fundy as well. Farm locations in New Brunswick are available from www.gnb.ca/0177/10/Fundy.pdf.

St John River (New Brunswick, Canada) Controls: Restigouche River, Miramichi River, Catamaran Brook, LaHave River (Nova Scotia) [1,10–12]

Exposed: St John River, Nashwaak River [15]

Outer Bay of Fundy (New Brunswick, Canada) Controls: Restigouche River, Miramichi River, Catamaran Brook, LaHave River (Nova Scotia) [1,10–12]

Exposed: St. Croix River, Magaguadavic River [15]

Outer Bay of Fundy salmon must pass by salmon farms early in their migrations [16], but the evidence that the Quoddy region (with salmon farms) is important habitat for other Bay of Fundy populations (Saint John River and inner Bay of Fundy) is mixed [17,18]. For this reason, we ran an alternative model with only outer Bay of Fundy populations considered exposed, and all other New Brunswick and Nova Scotia rivers as controls.

BC coho (Canada) Spawner estimates are based on DFO's escapement database (NuSEDS), which includes estimates of spawning salmon of all species for hundreds of rivers and streams on the British Columbia coast, since 1950. Coverage varies considerably in time and space, as does the quality of the estimates. We changed all indicators of unknown values (including "none observed" and "adults present") to a common missing value indicator. All rivers with fewer than 15 enumeration records since 1950, and all rivers known to be regularly stocked with hatchery salmon, or to have constructed spawning channels were also removed from exposed and control areas. In the exposed areas, only rivers on the East side of the Queen Charlotte and Johnstone Straits were used. To reduce effects of inconsistent monitoring procedures, only data since 1970 were included in the analysis. Estimates were combined for each Statistical Area (SA), the smallest areas for which catch rates are estimated. This was done by modeling returns in each SA and year, using a generalized linear model with negative binomial errors. The predicted returns for each SA were then used as spawner estimates.

After Simpson et al. (2004) [19], we applied exploitation rate estimates from Toboggan Creek (J Sawada, personal communication) to the controls, and the average of the exploitation rates for Quinsam Hatchery, Big Qualicum Hatchery and the Black Creek wild indicator population to the exposed stocks. After 1998, only the estimates from Black Creek were used for exposed stocks. Recruitment for coho was determined assuming a fixed three-year life cycle.

For pink, chum, and coho salmon, aquaculture production estimates include all salmon species farmed in SAs 12 and 13 (the Queen Charlotte and Johnstone Straits) from 1990 to 2003. In years where 2 or fewer companies were raising salmon in either area, estimates were not available (H Russell, personal communication).

Controls: BC Central Coast from Finlayson Channel to Smith Inlet (SAs 7 (34 rivers), 8 (20 rivers), 9 (10 rivers), 10 (6 rivers)) [19–21]

Exposed: East side of Queen Charlotte and Johnstone Straits, from Wakeman Sound to Bute Inlet (SAs 12 (27 rivers) and 13 (22 rivers)) [20,21]

Maps showing salmon farm tenures in British Columbia can be found at www.agf.gov.bc.ca/fisheries/images/marine_fishfarms.jpg.

BC pink (Canada) Pink salmon spawners were derived in the same way as coho salmon spawners. “Returns” are spawners plus catch for a given year, and these are lined up with spawners two years previous, to generate an index of recruitment. Wood et al. (1999) [22] consider the pink salmon catches in SAs 8, 9, and 10 to consist mainly of salmon returning to those areas, so catch from DFO online [21] was used in each of these SAs. Area 7 was excluded from the survival analysis because catches for SA 7 are difficult to estimate due to the adjacent regions being much larger [22]. For Queen Charlotte and Johnstone Straits, DFO does not estimate catches at the level of individual SAs. To get approximate returns to each exposed SA, we found the proportion the of total escapement to the Straits that was in our data set (i.e., non-enhanced, regularly enumerated rivers on the east side of the Straits) and assumed the same proportion of the total catch would be returning to those rivers (i.e., assumed equal catchability across stocks). For odd years, we used estimates from the Pacific Salmon Commission (2005) [23] of the catch of pinks in Johnstone and Georgia Straits that were not returning to the Fraser River. In even years, there is no pink salmon run on the Fraser River, so total returns to the Straits could be used.

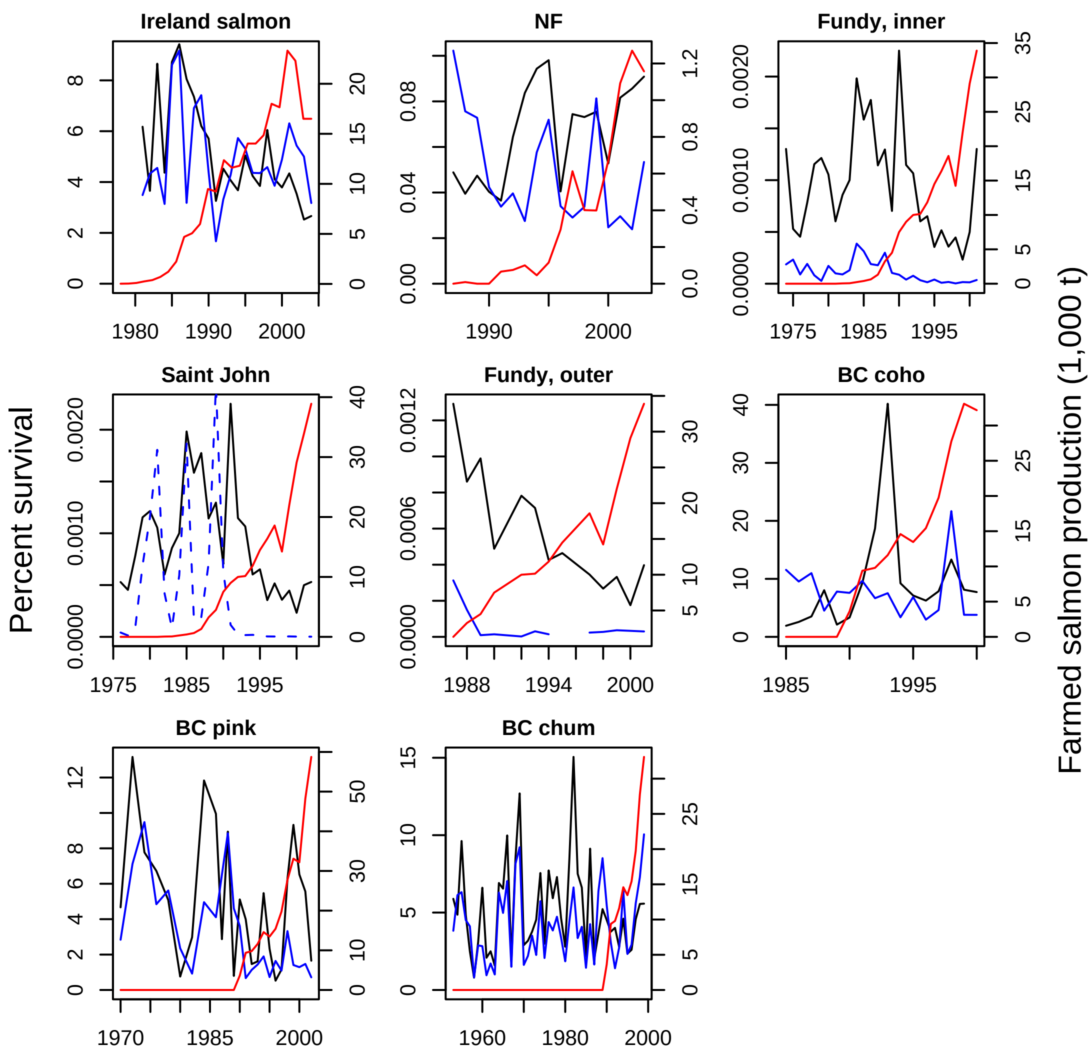
Controls: BC Central Coast from Burke Channel to Smith Inlet (SAs 8 (29 rivers), 9 (16 rivers), 10 (2 rivers)) [20,21]

Exposed: East side of Queen Charlotte and Johnstone Straits, from Wakeman Sound to Bute Inlet (SAs 12 (26 rivers) and 13 (10 rivers)) [20,21,23]

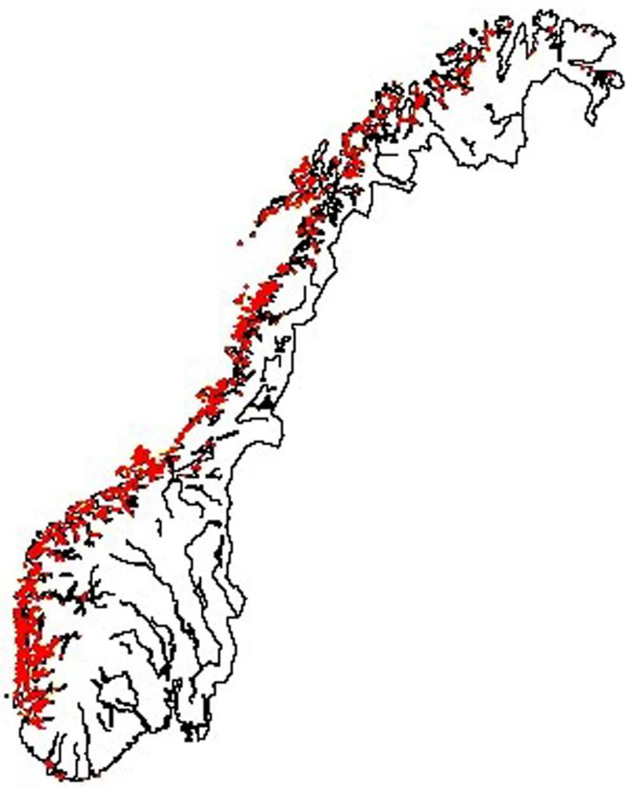
BC chum (Canada) For chum, we compared estimates of returns (before exploitation) and spawners for the Central Coast (controls) to the East side of Queen Charlotte and Johnstone Straits (exposed), from Godbout et al (2004). An index of recruits per spawner was generated by lining up returns with spawners according to age distributions given in Ryall et al. (1999) [24], to 1998, and then the average values from 1988-1998 for 1999-2003.

Controls: BC Central Coast, from Bute Channel to Seymour Inlet (SAs 8-11) [25]

Exposed: East Queen Charlotte and Johnstone Straits (SAs 12 and 13), from Wakeman Sound to Bute Inlet [25]



Supplementary Figure 1: Survivals of salmonids in control (black) and exposed (blue) stocks, along with aquaculture production (red). The returns for controls and exposed have been separately summarized by a multiplicative model ($\log(\frac{R_{i,y}}{S_{i,y}}) = a_i + d_y + e_{i,y}$); the mean survival across stocks for each year is plotted. Survivals for exposed Saint John River stocks have been multiplied by 10 for clarity (dashed line). Survival is estimated across different portions of the life cycle in different regions; from smolt to adult for Irish salmon and Newfoundland, from egg to adult for Bay of Fundy and Saint John River stocks, and from adult to adult in BC stocks.



Supplementary Figure 2: Locations of salmon farms in Norway.[26]

Alternative Models

Alternative Controls For the outer Bay of Fundy, our base model compared the St. Croix and Magaguadavic rivers (exposed) to control rivers on the Atlantic coast of Nova Scotia and the Gulf of St. Lawrence. If only these outer Bay of Fundy rivers are considered exposed to farming, and other Bay of Fundy rivers (inner Bay of Fundy and Saint John River) are included as controls along with the Nova Scotia and Gulf of St. Lawrence rivers, the γ estimate is still significant and negative in both versions of the analysis.

Alternative Model Formulations We repeated all analysis in R (MASS and lme packages) and SAS (Proc Mixed, Proc Genmod and Proc GLIMMIX). In all cases the difference in the results were very minor. We also considered a large number of alternative statistical models, six of which are described in Tables 1 and 2.

If we did not include autocorrelated error, the parameter estimates did not change substantially, but the standard errors were smaller because we effectively over-estimated the degrees of freedom. The AIC was generally higher for these models. In general, $\lambda = 0.5$ provided a better fit than $\lambda = 1$ or 2 (Tables 1 and 2). However, the effect was always of the same sign, and had similar levels of significance.

We also ran a fixed effects model with normal errors after log transformation and with gamma errors with a log link. These models are not directly comparable using the AIC, but always gave similar parameter estimates.

Bayesian Meta-Analysis

Let τ_k^2 be the true, unobserved estimation variance of γ_k. The relationship between the true variance, τ_k^2, and the estimated, s_k^2, is given by

$$\frac{\nu_k s_k^2}{\tau_k^2} \sim \chi^2_{\nu_k}, \tag{1}$$

where ν_k is the degrees of freedom [28]. Thus, our prior for τ_k^2 is given by

$$\tau_k^2 \sim \frac{\nu_k s_k^2}{\chi^2_{\nu_k}}. \tag{2}$$

We used the number of years of overlapping time series as an estimate of the degrees of freedom. To ensure that we were not overestimating the certainty of our estimated variance, we also estimated the model assuming half that number.

We assumed weakly informative priors for α_0 and α_1, i.e. normal distributions with zero mean and relatively large standard deviations. As suggested by Gelman (2004) [29] we used a uniform prior on the standard deviation of of the among study variation.

The Bayesian analysis was carried using Markov chain Monte Carlo (MCMC) using WinBUGS. One hundred thousand iterations were dismissed as burn-in and the following two hundred thousand iterations were used for parameter estimation. Convergence was assessed using the diagnostics in WinBUGS.

The Bayesian analysis gave 95% credible limits slightly larger than those estimated by maximum likelihood, but in no case were these increases large enough to affect the interpretation of the results.

Supplementary Table 1: Results of alternative models for the survival analysis.

Region		base model $\lambda = 0.5$ x10^3	no autocorrelation x10^3	$\lambda = 1$ x10^4	$\lambda = 2$ x10^8	fixed effects x10^3	all fixed, Gamma errors x10^3
Ireland salmon	γ	3.319	3.985	2.774	1.606	7.185	4.954
	s.e.	2.36	2.093	1.532	0.594	2.492	1.971
	AIC	593.266	599.885	592.123	596.4	NA	NA
Newfoundland	γ	-26.987	-28.129	-59.776	-379.359	-34.176	-32.489
	s.e.	8.335	7.75	24.325	203.047	8.369	7.917
	AIC	74.701	73.137	77.562	79.508	NA	NA
Fundy, inner	γ	-19.272	-18.678	-11.541	-2.375	-11.461	-12.705
	s.e.	2.374	1.844	1.63	0.677	2.484	2.202
	AIC	316.584	326.726	326.309	343.018	NA	NA
Saint John	γ	-10.956	-10.347	-5.475	-1.018	-6.679	-6.058
	s.e.	2.006	1.155	1.114	0.305	1.853	1.81
	AIC	166.743	177.11	168.578	173.431	NA	NA
Fundy, outer	γ	-25.07	-15.673	-10.2	-2.71	-18.01	-13.469
	s.e.	3.703	2.174	1.123	0.444	3.372	4.356
	AIC	117.381	161.582	167.682	128.536	NA	NA
BC coho	γ	-1.799	-3.259	-1.342	-0.464	-11.591	-10.911
	s.e.	3.22	2.786	2.044	0.67	4.326	3.422
	AIC	288.686	295.558	288.556	288.502	NA	NA
BC pink	γ	-6.215	-6.183	-3.015	-0.5	-5.305	-4.335
	s.e.	1.716	1.668	0.925	0.203	2.419	2.123
	AIC	368.747	366.908	371.078	375.277	NA	NA
BC chum	γ	-0.69	-0.62	0.438	0.544	-3.311	-3.597
	s.e.	2.112	1.393	1.39	0.475	1.84	1.786
	AIC	249.332	276.783	249.34	248.08	NA	NA

Supplementary Table 2: Results of alternative models for the returns analysis.

Region		base model $\lambda = 0.5$ x10^3	no autocorrelation x10^3	$\lambda = 1$ x10^4	$\lambda = 2$ x10^8	fixed effects x10^3	all fixed, Gamma errors x10^3
Ireland trout	γ	-20.162	-18.957	-9.188	-2.528	-21.543	-19.825
	s.e.	2.355	2.261	1.364	0.639	2.447	1.783
	AIC	2184.272	2335.682	2355.682	2383.515	NA	NA
Scotland catch	γ	-9.134	-0.309	-0.13	-0.011	-0.094	-0.095
	s.e.	0.476	0.257	0.067	0.004	0.257	0.256
	AIC	-9.348	81.524	79.251	76.227	NA	NA
Scotland count	γ	-2.71	-2.621	-0.74	-0.052	-2.067	-2.491
	s.e.	0.883	0.505	0.154	0.013	0.543	0.508
	AIC	577.49	739.618	742.743	748.774	NA	NA
Newfoundland	γ	-19.543	-24.093	-29.672	-49.9	-25.972	-27.75
	s.e.	7.1	6.214	12.277	39.287	6.243	6.371
	AIC	484.488	498.006	506.761	510.918	NA	NA
Fundy, inner	γ	-25.659	-24.004	-14.829	-4.183	-25.76	-21.586
	s.e.	4.519	2.275	1.394	0.486	2.624	1.575
	AIC	407.765	561.951	562.193	588.788	NA	NA
Saint John	γ	-11.77	-9.891	-5.203	-1.207	-11.302	-7.916
	s.e.	3.772	2.141	1.247	0.368	2.294	1.402
	AIC	299.922	484.079	486.951	492.893	NA	NA
Fundy, outer	γ	-21.86	-53.297	-36.8	-12.221	-14.54	-15.821
	s.e.	2.877	3.372	4.926	14.646	2.271	1.511
	AIC	536.682	558.996	738.046	1273.499	NA	NA
BC coho	γ	-2.819	-8.124	-3.009	-0.389	-13.84	-11.764
	s.e.	3.468	2.601	1.106	0.204	2.917	2.319
	AIC	280.239	320.049	321.187	323.6	NA	NA
BC pink	γ	-8.457	-7.998	-4.115	-0.769	-7.141	-6.373
	s.e.	2.127	1.89	0.908	0.182	2.012	1.626
	AIC	398.23	404.162	401.726	404.124	NA	NA
BC chum	γ	-3.495	-2.963	-1.333	-0.197	-2.428	-2.627
	s.e.	1.793	1.301	0.658	0.137	1.333	1.261
	AIC	351.754	368.446	369.486	371.482	NA	NA

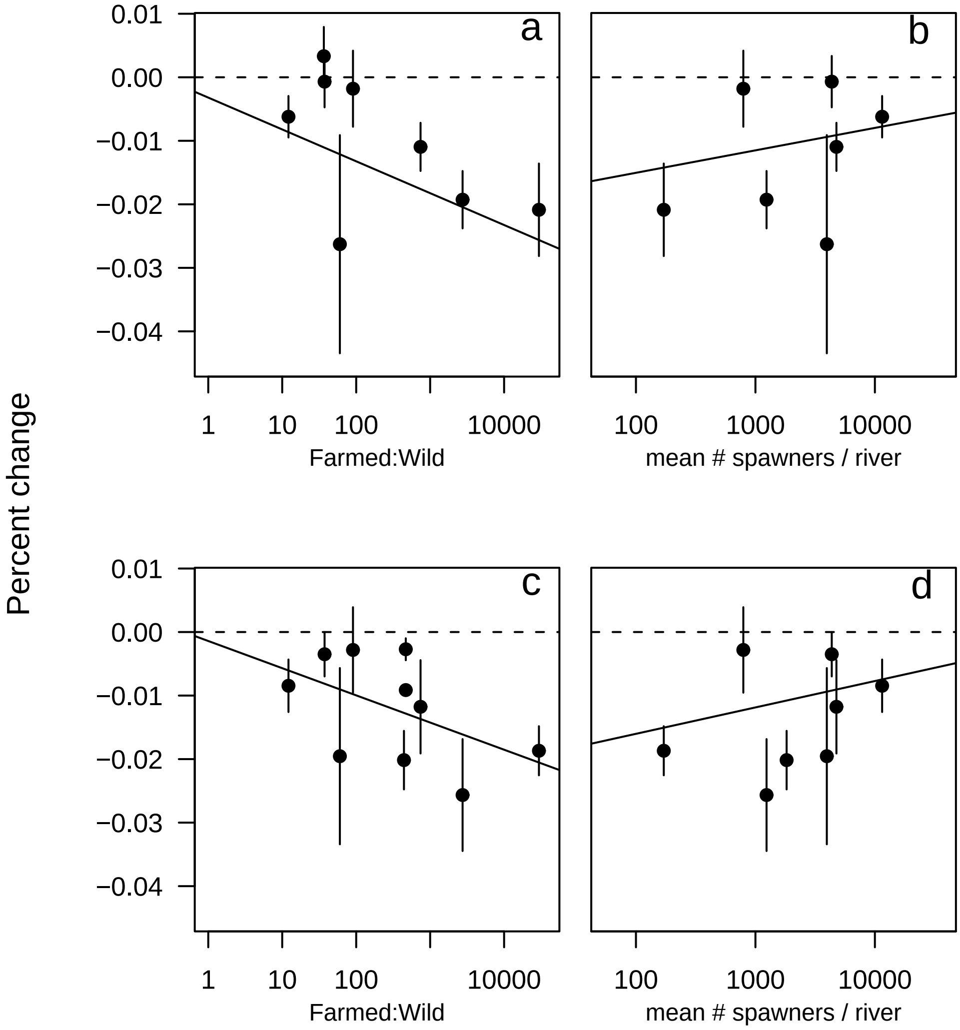
Meta-regression

Meta-regression was used to test whether impacts of salmon farming on wild stocks would increase as the ratio of farmed salmon to wild salmon in a region increased, or as the number of spawners in a stock decreased. The methods are based on van Houwelingen et al. (2002) [27], expanding the meta-analysis to include a slope:

$$\hat{\gamma_k} \sim N(\alpha_0 + \alpha_1 R_k, \sigma^2 + s_k^2), \tag{3}$$

where the α's are the intercept and slope, 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_k^2 is the among region variance.

The slopes of the relationship between γ and the logged ratio of farmed to wild production were negative for both the survival and returns analyses, but not significant (at the P=0.05 level, Figure 3). We also regressed γ against the mean size of the spawning stock (i.e., returns to each river after fishing) in each region, to see if the absolute size of the stocks would be a better predictor of susceptibility to impacts from aquaculture. This relationship was also not statistically significant at the P=0.05 level, but the slope is in a positive direction, indicating that larger stocks may be impacted less than small stocks. We do not detect a relationship between the farmed to wild ratio or the size of wild populations and the impact of salmon farming, but we have few data points, and each is averaging over a number of populations, so this study is not ideal for detecting such effects.



Supplementary Figure 3: Factors that may affect impact. a, Percent change in survival per generation with one tonne of salmon farming, versus the mean ratio of farmed to wild salmonids (of the species given) produced in a single year, in each region. b, Percent change in survival per generation with one tonne of salmon farming, related to the mean size of a spawning stock (returns to each river after fishing) over the study period. c, d, As for a, b but representing the change in returns to each stock. Bars represent 95% confidence intervals.

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