1 TODO

Add test of "resident fish", inner Bay of Fundy and Brown Trout.

2 Intro

As wild salmon has declined in the North Atlanic, and in some areas of the North Pacific, e.g. British Columbia, the production of pen reared aquaculture salmon has increased. However, in other areas, e.g. Alaska and the Baltic, with out large scale pen aquaculture, wild salmon production and catches have been relatively stable. Although there are are clearly many reasons for changes in the abundance of wild salmon stocks, the hypotheses that aquaculture is a major contributor to the decrease in salmon survival has not been demostrated. Here we show, in a meta-analyhsis that compares survival over time in regions with aquaculture, with nearby regions without, that there is an association with increased mortality of 5 species of anadromous salmonids from 7 regions of the North Atlantic and Pacific.

There are factors that are not easily contorled that are important forthe effect the on the survival of wild salmon. Some are as have much greater concdntration of salmonthatis not adequctely caputerd form hte models. For example, Aquaculture in Canad ais concentrated in two areas, Pasamaquody Bay (100,000?? tones in ? xq. kilometers) and Bay DeSpoir, Newfoundland. The conce ntration is There are several known mechanisms associated with pen aquaculture that can increased mortaltiy of wild salmonids. Aquacultur e serves as a reservoir for sea lice which can kill wild fish ( ). Several diseases have been known to be introduced by aquac ulture operations ( ). Salmon from aquaculture salmon serve to concentrate predators, e.g. seals, at least locally (). Escape d salmon may mate with wild salmon, and hybrid disgenesis may decrease the fitness of wild salmon ( ). It is possible to miti gate, but probably not eliminate, each of these effects.

These factors should opperate most strongly for regions where

Brown trout, which spend more

How can we put in about the declines in catches as the stocks decline,

3 Data Selection

For each region potentially affected by aquaculture, we selected a control region that matched the exposed as closely as possible, i.e. similar climate, acidification, and at at sea fisheries and migration, that was not directly exposed (Table 1). This allowed us to examine potential impacts of aquaculture when all rivers in a larger region were declining or increasing. Data from surveys, e.g. counting fences, were used if possible; however, for the Scotish salmon and the Irish and Welsh brown trout, only catch data was available.

4 Methods

We carried out alternative analyses using survival and total returns. For survival, we used an extended Ricker model in a linear mixed model framework (Myers et al (1999) and Meuter et al (2002)). We will describe out base model; 8 alternative models were used for robustness and are described in the supplement. Let $S_{i,y}$ be index of the number of fish that smolt, i.e. migrate to sea in the spring, in year y from stock i, let $R_{i,y}$ be the number of those fish that subsequently return spawn in the absence of fishing, and let $P_{i,y}$ be the aquaculture production that those smolts were exposed to. The dynamics is assumed to be given by

$$\log(\frac{R_{i,y}}{S_{i,y}}) = \beta_0 + a_i + d_t + \beta_i S_{i,y} + \gamma F(P_{i,y}) + e_{i,y}, \quad (1)$$

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_i is the random deviation of the y^{th} year intercept from β_0, β_i is the fixed slope of mortality (that is the density dependent 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, $F(P_{i,y})$. The random error, $e_{i,y}$, is assumed to be first order autocorrelated, i.e.

$$e_{i,y} = \rho e_{i,y-1} + \delta_{i,y}, \quad (2)$$

where ρ is the autocorrelation and $\delta_{i,y} \sim N(0, \sigma^2)$. We also assume the a_i's and d_i's come from normal distributions with zero mean.

The best functional form for aquaculture in the model $(F(P_{i,t}))$ was not known, we thus investigated several functional forms for each model assuming a power relationship, i.e. P^λ a linear increase in impacts with aquaculture, and a square relationship, and a square root relationship. We have chosen the best fit by comparing the AICs for these alternative models, and tested our results under alternative formulations.

Because only return data was availabe for some rivers, and we wished to carry out alternative analyses, the above analysis was repeated using the above model with $S_{i,t}$ and β_i dropped from the equation.

4.1 Meta-Analysis

The effects of aquaculture is summarized by one parameter, γ_k, to which we now add a subscript to identify each region, k. For a fixed assumption about λ, the γ 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 function of the log ratio of wild to aquaculture production R_k, as a mixed effect model, i.e.

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

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 Eq. ?, and is held fixed), and σ_k^2 is the among region variance. A fixed effect meta-analysis is obtained by constraining σ_k and α_1 to be zero, a random effects meta-analysis is obtained by constraining α_1 to be zero; model section is by AIC.

We used restricted maximum likelihood estimation of a random effects meta-analysis [?].

4.2 Alternative Models

For robustness, we considered 5 classes of models: different regions used as controls, different mixed model assumptions, different error assumptions, different functional for the aquaculture effect, and different autocorrelational structures.

4.3 Data

Table 1 and Figures 1 and 2 are summarize the data. We ran equations 1 and 2 (on survival and returns data, respectively), without an aquaculture production term, and with Years as fixed effects. The plots show the overall Year effects for the exposed and control regions, plus the time series of Aquaculture production estimates used in each Region. Different scales (left-hand axis) on the survival plots (Figure 1) reflect different parts of the life-cycle being modeled. For example, the Newfoundland estimates represent smolt-adult survivals, New Brunswick estimates are for egg to adult survivals, and BC estimates are from spawners to returning adults. "Returns" in figure 2 refer to the number of returning adults per stock.

5 Results

There is significant heterogeneity for aquaculture mortality.

5.1 Model Selection

AIC was lowest when the $\lambda = 0.5$ in the majority of regions, and including autocorrelated errors also reduced AIC for most models, so this formed our base model for which results are given. Overall the results were very similar for the 5 alternative models we considered.

5.2 Estimated Impacts

All estimates of γ_k were negative, with the exception of hatchery survivals of Atlantic salmon in Ireland (Figure 3). Not all γ_k's were significantly different from zero (at the P=0.05 level); Ireland salmon, BC coho and BC chum were non-significant in the survival analysis, and the St John River, BC coho and BC chum were non-significant in the returns analysis. However, both random-effects estimates of the mean γ (i.e., α_0 when α_1 is equal to zero) were negative and highly significant, with $\gamma = -0.010130 \pm 0.00319$ (1 s.e.) for the survival analysis and $\gamma = -0.01100 \pm 0.002527$ (1 s.e.) for the returns.

These estimates translate to a very large impact on survival of wild salmonids. For example, the estimated change in log survival per tonne of salmon farming (ie, the γ) for the Conne River in Newfoundland is -0.027 (95% CI: -0.016 to -0.043). In 2003, the farmed salmon harvest from the area was 1450 tonnes, so under the dynamics of equation 1, the change in survival related to aquaculture is $e^{-0.027(1450)^{\frac{1}{2}}}$, which is a decrease in survival of 65% (95% CI: 44 to 80%).

5.3 Metaregression

The slopes, α_1s (the relationship between γ and the logged ratio of farmed to wild production), were -0.00126 ± 0.00117 (1 s.e.) for the survival analysis and -0.00149 ± 0.00104 (1 s.e.) for the returns analysis (Figure 3 c and d?).

5.4 Alternative control rivers

Choosing the best controls and exposed rivers was difficult in New Brunswick. If only outer Bay of Fundy rivers are considered exposed to farming, and other Bay of Fundy rivers are taken as controls along with the other control rivers listed, the γ estimate is still significant and negative, -0.01544 +/- 0.00425.

6 for discussion?

- The scale thing, why this is tricky, are there basic assumptions that would change the results in this section?

- The estimated impacts relative to fishing mortality and non-response to fisheries closures.

7 Concludion

Other studies, BC stuff, and lower parr dnsity where there is

We conclude that, on average, survival of wild salmonids decreases with salmon production. This decrease in survival is often disguied by the restrictions on the harvest of wild salmon.

The effects of aquaculture should be viewed as additional mortality that occurs after the main period of density-dependent mortality has occured. It is thus similar to fishing mortality mortality with one crucial exception; it is possible, at least in theory, to reduce fishing mortality when enviromental conditions are good. It will be difficulty todo this with aquaculture production.

The results were expressed as two alternative

We then compared the effects on survival w and carried out an analysis where the changes

8 Figures

Fig. 1 changes in catch, and aquaculture in different regions,

Fig. 2. 4 panel plot

IS THIS ALL WE NEED???

9 Reviewers

Volte

Alberta guys

Chairman of the ICES group.

Terry Quinn

Jessica Gurvich - author of meta-analysis in ecology.

10 Supplement

More info on the data: - more detail on each comparison, what data, where, sources, omissions. - why we excluded Norway, Maine, Vancouver Island - BC and NB, where the numbers come from.

Alternative models: - alternative controls in NB and BC - what other models we tried and their results - separate table - Bayesian meta-analysis

10.1 Bayesian Meta-Analysis

SHOULD DIC BE USED?

We tested the robustness of our likelihood meta-analysis using a Bayesian meta-analyais. In particular, we were concerned that the traditional meta-analytic methods may not adequately represent the uncertainty in the estimates because it is assumed that the s_k^2's are known without error. 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

$$\frac{\nu_k s_k^2}{\tau_k^2} \sim \chi^2_{\nu_k}, \tag{4}$$

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

$$\tau_k^2 \sim \frac{\nu_k s_k^2}{\chi^2_{\nu_k}}. \tag{5}$$

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

[?] 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 []. Example model code is listed in Appendix A. 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.

DuMouchel W., Bayesian meta-analysis in: Berry D.A. (Ed.), Statistical Methodology in the Pharmaceutical Industry, Dekker, New York, 1990, pp. 509529.

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11 JUNK??????????

In each area where salmon farming is practiced, some groups have believed that the practice has been detrimental to wild salmon populations in their area. The difficulty in evaluating these claims is that other factors have been influencing marine survival over the same time period. Our solution to this problem is to control for many changes, particularly climatic effects, by using rivers in the same regions as controls. By comparing nearby populations, we can sometimes control for changes in fisheries as well.

Any two rivers will always be different, so it is matter of judgment to determine whether or not they differ systematic ways that would make comparing them misleading. To make these judgments, we looked for co-variation in time series, talked to local salmon biologists, and consulted the published literature. Because we are modeling indices of survival, the stocks we are comparing do not need to be similar in size or productivity because we can account for these differences. Also, we can look for impacts of aquaculture when all rivers are declining or increasing, by measuring the difference in rates of change, and the timing with respect to salmon farm development.

The chances of one spurious decline in an exposed population (relative to the controls) are fairly high, but the chances of a coincidental decline in many exposed populations, around the world, are much lower. Meta-analytic techniques are used to quantify how likely it is this result is due to chance.

Choosing regions We wanted to perform as many comparisons as possible, so an area with substantial salmon farming and wild salmonids was only excluded if we couldnt perform a comparison, either because there was no suitable control, because data on salmon populations was not available in sufficient detail, or because available information on the salmon farming industry was not sufficient. And then Ill detail what Im referring to in the data section Norway, West Van, and Maine.

Comparison with other Johnstone Strait regions, chum