Density-dependent Marine Survival of Hatchery-origin Chinook Salmon may be Mediated by Pink Salmon

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Density-dependent effects between pink salmon (Oncorhynchus gorbuscha) and other species, including other species of Pacific salmon, have been documented by a number of studies. Density-dependent interactions between pink and Chinook salmon (O. tshawytscha) have also been previously hypothesized in the Salish Sea (Claiborne et al. in press; Ruggerone and Goetz 2004; Ruggerone et al. 2019), a rich and diverse but highly-impacted inland sea in Washington State and British Columbia. In the central and southern parts of the Salish Sea, almost all pink salmon spawn in odd-numbered years and juveniles emigrate in even-numbered years. Juvenile Chinook and pink salmon are both found there between April through July of even years (Duffy et al. 2005; B. Berejikian, NOAA Fisheries, unpublished data).

Increasing the abundance of adult Chinook salmon in the Salish Sea is currently an ecosystem management priority (Riddell et al. 2013). Chinook salmon have been produced by hatcheries for over 100 years (Beamish et al. 1997), and increased production has been proposed (WDFW 2019). Our objectives are to examine historical patterns of Chinook salmon survival and identify the potential need for future work examining the mechanisms behind our observations. We seek to answer the question: in the past, when more hatchery Chinook salmon have been released into the central and southern Salish Sea in years when juvenile pink salmon are and are not also emigrating (pink years vs. non-pink years, respectively), has there been an associated increase in the number of hatchery Chinook salmon that have survived during their migration in the ocean and returned as adults?

We first used data from 33 Pacific Salmon Commission’s Chinook Technical Committee CWT stocks with release numbers and marine survival rates over ocean entry years (OEY) 1983–2012. These data included the total number of tagged Chinook salmon juveniles released from a given hatchery and estimates of the numbers of tagged fish recovered in the North Pacific Ocean at age 2 years (for those released as sub-yearlings) or age 3 years (for those released as yearlings) (Joint Chinook Technical Committee (CTC) 2018). These stocks were grouped into eight regions (Fig. 1).

To evaluate factors associated with marine survival of hatchery Chinook salmon, we fit multiple hierarchical regression models to survival rates from CWT data. Specifically, we modeled instantaneous mortality rate from...
release to age 2 for each stock $i$ in region $r$ in year $t$ ($M_{i,r,t}$) as a function of multiple covariates. We explored model formulations that included covariates including juvenile Chinook life history (sub-yearling vs. yearling release; $\text{LifeHist}_t$), release region, the standardized number of hatchery releases per region ($\text{Hatch}_{r,t}$), presence of pink salmon in the Salish Sea ($\text{Pink}_t$), and release year. Based on model selection criteria that considered model fit and complexity, the best-performing model was:

$$M_{i,r,t} = \beta_0 + \text{LifeHist}_t + \text{Region}_r + \beta_1 \text{Hatch}_{r,t} + \text{Pink}_t + \beta_2 (\text{Pink}_t \times \text{Hatch}_{r,t}) + \varepsilon_i.$$  

This model explained 44% of the variation in the observed mortality rates from release to age 2.

Regional effects appeared to be important in explaining marine survival to age 2 or 3 of hatchery Chinook salmon, specifically JUAN, MPS, NPS, and FRA (Fig. 1 and Table 1). The interaction between the presence of juvenile pink salmon in the Salish Sea and juvenile hatchery Chinook release numbers was also found to have “significant” explanatory power in the best-performing model (Table 1). The coefficient value suggested a significant negative interaction between juvenile pink salmon and hatchery release number. Therefore, in even-numbered years, greater hatchery Chinook salmon releases were associated with decreased marine survival. Predicted mean marine survival rates in these pink years were lower than those in non-pink years.

**Table 1.** Summary of posterior distributions for regression coefficients in the best-performing model. Included are the estimates for the posterior mean, standard deviation, and 95% credible intervals (CIs). Parameter estimates and credible intervals shown in bold do not overlap with zero.

| Parameter                                                | Mean | SD  | 2.5% CI | 97.5% CI |
|----------------------------------------------------------|------|-----|---------|----------|
| Intercept (Region 1 [JUAN])                              | 5.46 | 0.36| 4.72    | 6.18     |
| Region 2 (HOOD)                                          | -0.81| 0.73| -2.20   | 0.67     |
| Region 3 (SPS)                                           | -0.81| 0.49| -1.76   | 0.17     |
| Region 4 (MPS)                                           | -1.19| 0.47| -2.09   | -0.27    |
| Region 5 (NPS)                                           | -1.07| 0.43| -1.91   | -0.22    |
| Region 6 (NOWA)                                          | -0.80| 0.53| -1.87   | 0.25     |
| Region 7 (VAN)                                           | -0.79| 0.45| -1.66   | 0.13     |
| Region 8 (FRA)                                           | -1.99| 0.49| -2.95   | -0.99    |
| Life history                                             | -0.07| 0.31| -0.68   | 0.56     |
| Juvenile hatchery Chinook salmon abundance               | -0.12| 0.10| -0.31   | 0.07     |
| Juvenile pink salmon presence                            | 0.12 | 0.07| -0.01   | 0.25     |
| Juvenile pink salmon presence x juvenile hatchery Chinook salmon abundance | **0.54** | **0.13** | **0.28** | **0.80** |

We simulated the numbers of sub-yearling Chinook salmon that had survived over the range of observed releases of juvenile hatchery fish; the predicted numbers were termed “recruits.” We simulated survival rates for stocks in each geographical region in pink and non-pink years. The relationship between the numbers of recruits and the numbers of juveniles released was different for juveniles released in pink and non-pink years. Across regions, in non-pink emigration years, increases in hatchery Chinook production are associated with generally linear increases in age-2 recruits (Fig. 2). However, in pink years, increases in Chinook hatchery production were associated with a leveling off or even a diminishing number of recruits, which suggests the presence of density-dependent mortality. This suggests that the presence of emigrating juvenile pink salmon may somehow alter the relationship between the abundance of juvenile Chinook hatchery released and their marine survival. Therefore, hatchery Chinook salmon may have experienced density dependent survival in years when there are higher total numbers of salmon in the Salish Sea. Greater understanding of potential density-dependent interactions in the Salish Sea in the past may help inform Chinook salmon hatchery production and encourage future work evaluating potential mechanisms behind the findings.
Fig. 2. Projected sub-yearling Chinook salmon recruits (age 2) in the ocean (y-axis) vs. the total number of juveniles released in each region (x-axis). Grey lines show projected values in non-pink years while red lines show values in pink years. Dashed lines depict 95% posterior predictive intervals. Vertical dashed lines show average annual number of releases for the most recent 5 years in each region.

In our second analysis we used a dataset that included all sub-yearling Chinook salmon released into the central and southern parts of the Salish Sea along with estimates of the numbers of adult hatchery Chinook salmon returning to Puget Sound (i.e., total run size; before any fish were caught in Puget Sound) between 1980 and 2015. We examined the relationship between the numbers of juvenile hatchery Chinook salmon released in pink years vs. non-pink years in the six Puget Sound regions and the associated total run-reconstructed index numbers of adult Chinook salmon that returned to Puget Sound. We plotted these cohort-specific values for each region and used simple linear regression to estimate trends between pink- and non-pink-year emigration cohorts for each region. For pink year emigrants, this relationship was negative in 5 of the 6 regions (Fig. 3), statistically significantly at the 0.05 level for two regions (SPS and MPS). This relationship was significantly positive for NOWA. For non-pink-year emigrants, the slope of the regression line was positive for three regions (MPS, NPS, and NOWA) and negative for the three others. In five regions, the linear trend in pink years was more negative than it was in non-pink years. Notably, there was only one region (NOWA) where the relationship between hatchery releases and returns was significantly positive in either pink or non-pink years (Fig. 3).

Fig. 3. Run reconstruction of the total numbers of adult hatchery Chinook salmon from each region returning to Puget Sound (y-axis) vs. the number of juveniles released that produced those adults (x-axis). Grey line is the regression trend line of data from non-pink years while red line is the best-performing regression line of pink-year data. Dashed lines depict 95% credible intervals for each series. Red and grey numbers are the probability of each slope being > zero.
Recovery of Chinook salmon in the Salish Sea will be a complicated and difficult process (Marshall et al. 2016) that will need to address the range of the 4-Hs of human impacts on salmon (Ruckelshaus et al. 2002). The story of density-dependent mortality of hatchery Chinook in the Salish Sea is by no means complete, though we have found signs of such mortality when many juvenile hatchery Chinook and pink salmon are present in the system. The findings of this paper cannot and should not simply be extrapolated to inform future hatchery releases; environmental conditions faced by hatchery Chinook in past years will not be the same as those faced in the future. However, by considering potential density-dependent interactions of hatchery Chinook salmon with pink salmon in the Salish Sea and exploring the mechanisms behind these findings, hatchery management practices and research can be further informed to benefit Chinook salmon conservation.

REFERENCES

Beamish, R.J., C. Mahnken, and C.M. Neville. 1997. Hatchery and wild production of Pacific salmon in relation to large-scale, natural shifts in the productivity of the marine environment. ICES J. Mar. Sci. 54: 1200–1215.
Claiborne, A.M., L. Campbell, B. Stevick, T. Sandell, J.P. Losee, M. Litz, and J. Anderson. In press.
Correspondence between scale growth, feeding conditions, and survival of adult Chinook salmon returning to the southern Salish Sea: implications for forecasting. Prog. Oceanogr.
Duffy, E.J., D.A. Beauchamp, and R.M. Buckley. 2005. Early marine life history of juvenile Pacific salmon in two regions of Puget Sound. Estuar. Coast. Shelf S. 64(1): 94–107.
Joint Chinook Technical Committee (CTC). 2018. Annual report of the exploitation rate analysis and model calibration. Pacific Salmon Commission Joint Chinook Technical Committee Report TCCHINOOK (18)-1 V1, Vancouver, BC.
Marshall, K.N., A.C. Stier, J.F. Samhouri, R.P. Kelly, and E.J. Ward. 2016. Conservation challenges of predator recovery. Conserv. Lett. 9(1): 70–78.
Riddell, B., M. Bradford, R. Carmichael, D. Hankin, R. Peterman, and A. Wertheimer. 2013. Assessment of status and factors for decline of Southern B.C. Chinook Salmon: independent panel’s report. Prepared with the assistance of D.R. Marmorek and A.W. Hall, Vancouver, B.C. for Fisheries and Oceans Canada (Vancouver, B.C.) and Fraser River Aboriginal Fisheries Secretariat (Merritt, B.C.).
Ruckelshaus, M.H., P. Levin, J.B. Johnson, and P.M. Kareiva. 2002. The Pacific salmon wars: what science brings to the challenge of recovering species. Annu. Rev. Ecol. Syst. 33: 665–706.
Ruggerone, G.T., and F.A. Goetz. 2004. Survival of Puget Sound Chinook salmon (Oncorhynchus tshawytscha) in response to climate-induced competition with pink salmon (Oncorhynchus gorbuscha). Can. J. Fish. Aquat. Sci. 61: 1756–1770.
Ruggerone, G.T., A.M. Springer, L.D. Shaul, and van G.B. Vliet. 2019. Unprecedented biennial pattern of birth and mortality in an endangered apex predator, the southern resident killer whale, in the eastern North Pacific Ocean. Mar. Ecol. Prog. Ser. 608: 291–296.
Washington Department of Fish and Wildlife (WDFW). 2019. Proposal to increase hatchery production to benefit Southern Resident Killer Whales. Washington Department of Fish and Wildlife, Olympia, WA.