Are B.C. Chinook and coho salmon run sizes positively linked to B.C. herring abundance?

Murdoch McAllister

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Abstract

I tested for linkages between estimates of annual BC herring (*Clupea pallasii*) stock abundance and Chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) run size using available stock assessment results for BC herring stocks and available data for run size reconstruction of B.C. Chinook salmon and coho salmon stocks. I used time series of data that extended back to the 1950s and 1960s and covered the period of major herring stock collapses in B.C. in the mid- to late-1960s. This could provide an indication of whether Chinook and coho salmon run sizes decreased in response to the herring stock collapses based on the hypothesis that chinook and coho salmon stock productivity are positively linked to herring stock abundance. To evaluate whether there could be bycatch effects of high herring fishery harvest rates on B.C. Chinook and coho salmon stocks, I also investigated associations between BC herring fishery harvest rates and Strait of Georgia chinook salmon run sizes. For the Strait of Georgia (SOG) there were only negative associations between SOG herring stock size and chinook and coho salmon run size, i.e., rather than dropping in abundance when B.C. herring stocks collapsed, SOG Chinook and coho run sizes within the period 1951-2018 were instead at all-time historical highs following the collapse of SOG herring in the mid-1960s to mid-1970s. For other B.C. coho salmon stocks there remained no consistent association between coho salmon run size and B.C. herring stock abundance. These findings refute the notion that Chinook and coho salmon population abundance are positively associated with B.C. herring stock abundance, e.g., that when herring stock size is lowest salmon stock size is also low and vice versa. In the Strait of Georgia low herring abundance was associated with high coho and Chinook salmon run sizes indicating that any benefits as prey species to chinook and coho salmon may have been overwhelmed by negative competitive effects between herring and coho and Chinook salmon in their first or second years of ocean life. I found however that extremely high SOG herring fishery harvest rates (e.g., harvest rates > 60%) in the 1960s had a negative association with SOG Chinook salmon run sizes, such that when the extraordinarily high herring fishery harvest rates decreased to near zero in the late 1960s, Chinook salmon run sizes increased by about nearly double. This suggests that extremely high herring fishery harvest rates could potentially negatively impact Chinook salmon run sizes. However, the potential positive effect on salmon runs size that may result from bycatch relaxation remains confounded with the potential positive effect of relaxation in Pacific herring-juvenile salmon competition that may have both simultaneously occurred with the Pacific herring stock collapse in the 1960s.

Executive Summary

1. For the Strait of Georgia (SOG) available records of catch and escapement data for coho salmon and Chinook salmon stocks were compiled with time series from the early 1951 to 2018.

2. For SOG, the time trends in catch plus escapement of aggregate data for coho salmon and chinook salmon show that both coho salmon and Chinook salmon undergo progressive declines in abundance after the 1970s. Strait of Georgia Chinook salmon run sizes peaked in the 1960s and early 1970s.

3. Fisheries and Oceans Canada stock assessment estimates of Age 2 herring abundance from about 1953-2017 in each of the five main Pacific herring management units (HMU) were previously made available by Jaclyn Cleary at the Department of Fisheries and Oceans Canada (DFO) Pelagic Stock Assessment Unit at the Pacific Biological Station.

4. Reconstructions of total herring stock biomass and harvest rate by HMU were obtained from Professor Emeritus Carl Walters who used a Virtual Population Analysis (VPA) methodology with DFO's fishery catch-at-age and spawn surveys. Estimated harvest rates on Pacific herring stocks in B.C.'s HMUs were at their highest in the early 1960s at up to about 90% and with the collapses of herring stocks in the HMUs in the 1960s and moratoriums on herring fishing in the late 1960s, the harvest rates approached zero. But with the rebuilding of the stocks in the 1970s and emergence of the herring roe fisheries in the late 1970s, the harvest rates in all HMUs increased but held at values on average no more than about 30% subsequently. A 2018 DFO stock assessment of Pacific herring stocks provided time series plots of herring stock abundance in the five herring management units also showed that there were collapses in the late 1960s, recoveries and then subsequent collapses after 2000 for some of the stocks.

5. For the SOG, during and shortly after herring stock collapses in the late 1960s, run sizes of Chinook salmon remained high; since 1950 the lowest abundances of age 2 herring and lows in total herring stock biomass are not associated with low run sizes of Chinook salmon.

6. For the SOG, during and shortly after herring stock collapses in the late 1960s until the mid-1970s, run sizes of coho salmon remained relatively high; since the early 1950s, the lowest abundances of age 2 herring and lows in total herring stock biomass are not associated with low run sizes of coho salmon.

7. Evaluations of associations between the abundance of aggregated Chinook salmon catch plus escapement (let's call this run size) and both age 2 herring abundance and total herring biomass in the Strait of Georgia show that there are negative associations, i.e., at low herring abundance Chinook salmon run size tends to be largest and at high herring abundance Chinook salmon run size tends to be lowest. This negative association was statistically significant at the alpha = 0.05 level.

8. Evaluations of associations between the abundance of aggregated coho salmon run sizes and age 2 herring abundance in the Strait of Georgia show that there is a negative association, i.e., at low herring abundance coho salmon run size tends to be largest and at high herring abundance coho salmon run size tends to be lowest. This negative association is statistically significant at the alpha = 0.05 level. This finding is slightly different than the findings of Beamish et al. (2001) where there was no significant association between the run size of Strait of Georgia coho salmon stocks and SOG herring abundance.

9. Several other long time series of B.C. coho run reconstructions back to the 1950s were investigated. For these fourteen additional coho salmon stocks, there was no consistent pattern of association between coho salmon stock run size and herring stock sizes.

10. Extremely high SOG herring fishery harvest rates (e.g., harvest rates > 60%) in the 1960s had a negative association with SOG Chinook salmon run sizes, such that when the extraordinarily high herring fishery harvest rates decreased to near zero in the late 1960s, Chinook salmon run sizes increased by about nearly double. This suggests that extremely high herring fishery harvest rates could potentially negatively impact Chinook salmon run sizes.

Introduction

This document reports on a precursory evaluation of potential linkages between the historic abundances of B.C. salmon species known to prey on Pacific herring (*Clupea harengus pallasi*) and herring abundance, i.e., Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*). Diet studies on Chinook salmon have found that juvenile, sub-adult and adult Chinook salmon prey upon herring, but also sand lance, juvenile chum salmon, pilchards/ sardines, anchovy, sticklebacks, rockfishes, pelagic amphipods, squids, shrimp, euphausiids, squid and crab larvae and that fish dominate the diet of adult Chinook salmon (Healy 1980; Healy 1981; Scott and Crossman 1973; Hertz et al. 12016; Reid 1961; Prakash 1962; Pritchard and Tester 1991). Sub-adult and adult coho salmon feed on herring, sand lance, anchovies, sardines, euphasiids, crab larvae, squid, juveniles of other salmon species and jellyfish; bait fishes also tend to dominate the diets of maturing coho salmon (Reid 1961; Hart 1973; Pritchard and Tester 1944).

Given that herring is a known diet item of Pacific salmon species such as Chinook and coho salmon, it may appear to be reasonable to assume that low herring stock abundance may lead to lowered productivity and salmon stock abundance for these salmon species. And it may also appear to be reasonable to presume that relatively high abundances of herring could be expected to support higher productivity and abundances of salmon stocks known to eat herring. It may thus appear to be beneficial to salmon stocks to develop herring fishery management policies that promote relatively high abundances of herring. These presuppositions while apparently reasonable however may not necessarily be empirically defensible or correct. And if they are incorrect, and fisheries management decisions are taken to reduce current levels of harvest of herring under the presumption that this would be beneficial to salmon stocks when it is not, this decision could be without any significant ecological benefits and end up being unnecessarily harmful to fishers and associated industry infrastructure and communities that harvest herring at non-negligible rates for economic revenues, income and food security.

The aim of the following analyses is to evaluate the consistency of the historical record with the above presumptions about there being a positive association between herring stock abundance and salmon stock abundance. It is well known that in B.C. herring fisheries up and down the coast collapsed in the late 1960s. DFO stock assessments of available fishery and fishery independent indices of abundance going back to the 1950s reveal severe depletions of B.C. herring stocks in the late 1960s and subsequent rebuilding of abundance in most B.C. herring stocks in the mid-and late-1970s (e.g., DFO 2018). I have also obtained estimates of B.C. herring stock abundance from Professor Emeritus Carl Walters who applied an alternative stock assessment methodology to DFO's. These estimates of time trends in B.C. herring stock abundance are similar to those provided by DFO's stock assessment and also show the B.C. herring stock collapses of the 1960s.

Trends in Pacific Herring abundance in the five B.C. herring fishery management areas

I obtained in 2019 a data file from the Jaclyn Cleary of the Pelagics section in the Pacific Biological Station on estimates of age 2 Pacific herring abundance in the five main B.C. herring management areas, i.e., Strait of Georgia (SOG), West Coast Vancouver Island (WCVI), Central Coast (CC), Haida Gwaii (HG) and Prince Rupert District (PRD). Collapses in herring stock abundance can be seen for all five stocks in the 1960s where in all five areas, herring stock biomass and spawning stock biomass reached extreme low levels for all five of these stocks (Figs. 1-5). By the 1980s, recoveries in stock size can also been in all five stocks. Due to there being fairly strong density dependence in survival rates in juvenile herring, the time series of abundances of juvenile, e.g., age 2, Pacific herring do not show nearly as strong a decline in abundance during the stock collapses in the 1960s (Figs. 1-5). Density dependence in survival rates of juvenile herring thus would indicate that despite sharp declines in total herring biomass and spawning stock biomass, the abundance of juvenile herring has been less prone to severe depletion even during periods of stock collapse. The dampened declines in juvenile herring due to density dependence in juvenile herring survival rates could thus dampen the effects of stock collapses on the food supply for species that may prey upon juvenile stages of Pacific herring, such as coho and Chinook salmon.

Figure 1. Estimates of a) relative abundance, b) rate of natural mortality, c) age 2 recruits, and d) spawning biomass for Pacific herring in the Haida Gwai (HG) fishery management unit. Bars in panel d represent catch biomass. Figure taken from DFO (2018).

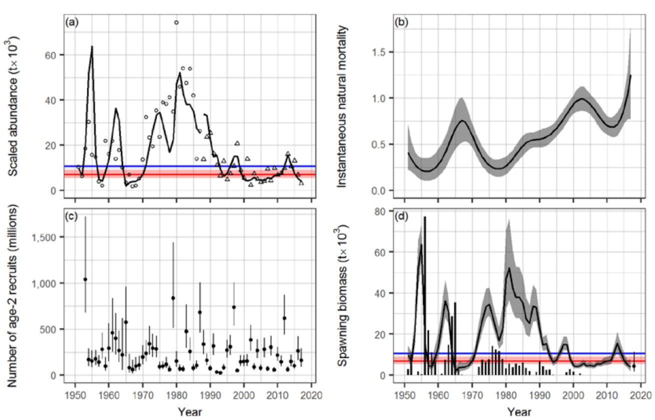


Figure 2. Estimates of a) relative abundance, b) rate of natural mortality, c) age 2 recruits, and d) spawning biomass for Pacific herring in the Prince Rupert District (PRD) fishery management unit. Bars in panel d represent catch biomass. Figure taken from DFO (2018).

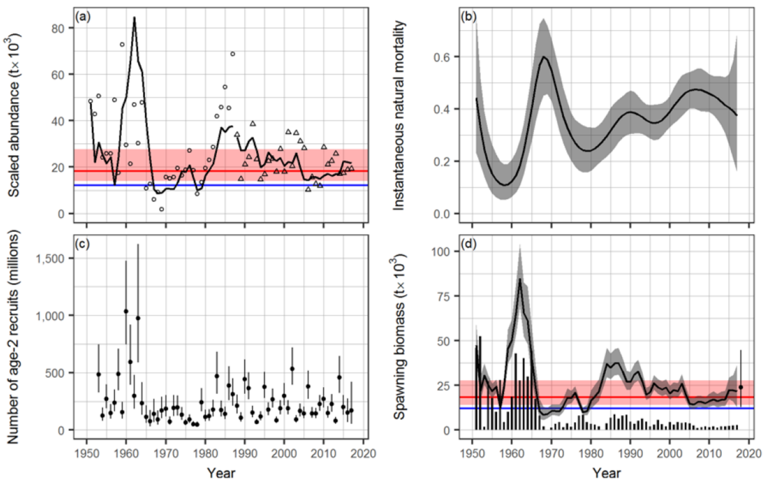


Figure 3. Estimates of a) relative abundance, b) rate of natural mortality, c) age 2 recruits, and d) spawning biomass for Pacific herring in the Central Coast (CC) fishery management unit. Bars in panel d represent catch biomass. Figure taken from DFO (2018).

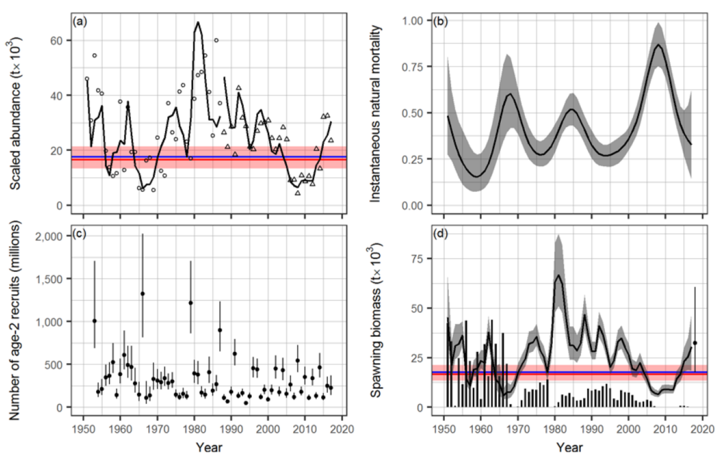


Figure 4. Estimates of a) relative abundance, b) rate of natural mortality, c) age 2 recruits, and d) spawning biomass for Pacific herring in the Strait of Georgia (SOG) fishery management unit. Bars in panel d represent catch biomass. Figure taken from DFO (2018).

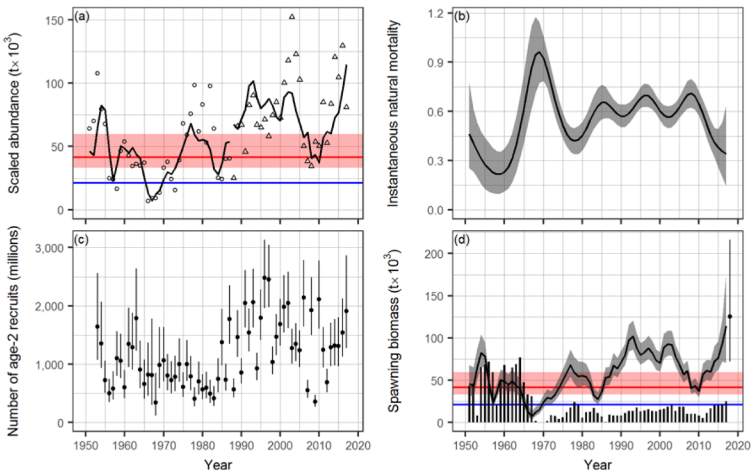
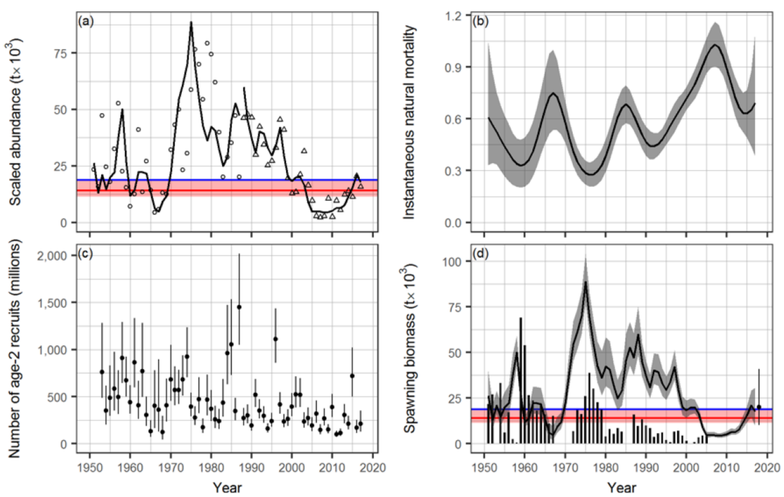


Figure 5. Estimates of a) relative abundance, b) rate of natural mortality, c) age 2 recruits, and d) spawning biomass for Pacific herring in the West Coast Vancouver Island (WCVI) fishery management unit. Bars in panel d represent catch biomass. Figure taken from DFO (2018).



Catch biomass approached or exceeded the reconstructed spawner biomass during the 1960s in all five management units and therefore, in the 1960s, the harvest rates on herring in the five management units were very high and these high harvest rates led to the stock collapses (Fig. 6). I investigate below whether chinook salmon and coho salmon run sizes responded negatively to the stock collapses and very high harvest rates on Pacific herring, available data permitting.

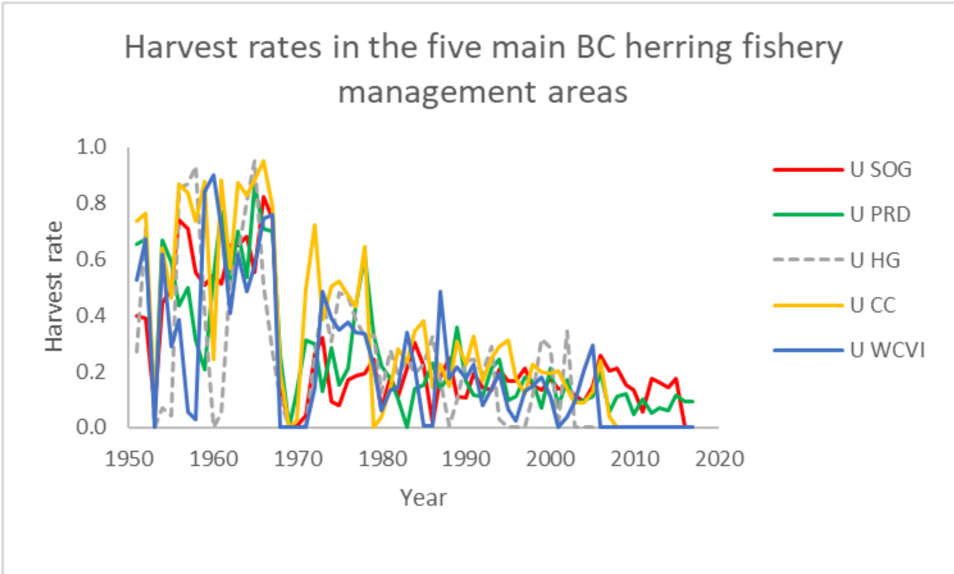
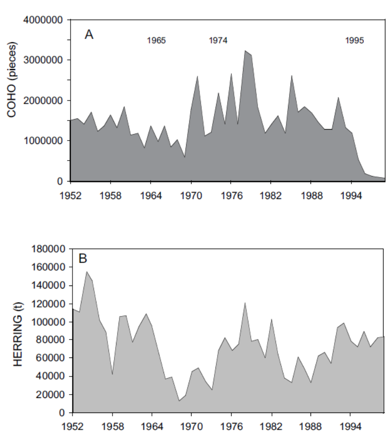


Figure 6. Estimated harvest rates (U) in the five main B.C. herring fishery management areas (source: CJ Walters).

Time series of Age 2 herring and Coho and Chinook salmon run sizes in the Strait of Georgia B.C.

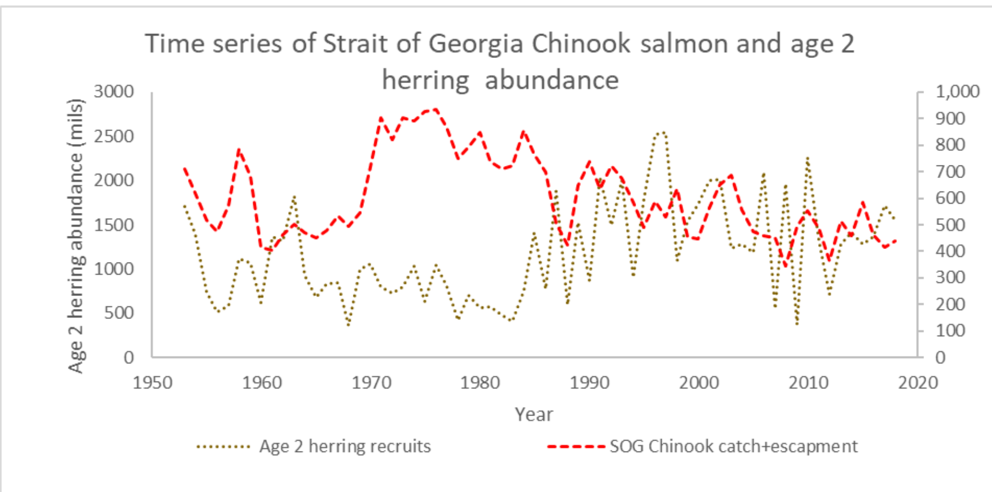
I recently searched the internet for papers that have investigated associations between Pacific herring stock abundance and Pacific salmon stock abundance and could find only one paper by Beamish et al. (2001) on this topic. Beamish et al. (2001) reviewed reconstructions of Pacific herring stock abundance and coho salmon run size in the Strait of Georgia from 1952-1999. They found that there was no statistically significant association between Pacific herring abundance and coho salmon run size between 1952 and 1999. When herring collapsed, in the 1960s, coho salmon remained relatively abundant. When coho salmon run size collapsed in the 1990s, herring stock abundance remained relatively high (Fig. 7).

Figure 7. A. Time series of Strait of Georgia coho salmon abundance (estimated assuming a 75% harvest rate). B. Time series of Strait of Georgia herring stock biomass. Copied from Beamish et al. (2001).



With the help of DFO biologist Greig Oldford who is also a PhD student with Professor Villy Christensen, I was able to obtain reconstructions of Strait of Georgia Chinook salmon catches and escapement and also Strait of Georgia coho salmon catches and escapement (with the summations of catches and escapement being approximations of total combined run sizes for stocks with natal rivers flowing into the Strait of Georgia). The run reconstructions show progressive declines in the total run sizes of SOG coho salmon and Chinook salmon after the mid-1970s (Figs. 8 and 9). The time trends for both SOG chinook salmon and coho salmon however do not track or align with the time trends for SOG Age 2 Pacific herring or herring stock biomass (Figs. 8 and 9). When the herring stock collapsed in the mid-1960s, SOG chinook salmon returns reached their highest levels in the 1970s. In the mid-1980s SOG herring abundance trended upwards whereas SOG chinook salmon and coho salmon abundance trend downwards (Figs. 8 and 9).

Figure 8. Strait of Georgia Chinook salmon run sizes (G. Oldford), and A. Age 2 Pacific herring abundance (J. Cleary), and B. SOG total herring stock biomass, total B.C. herring stock biomass, and %harvest rate on SOG herring (CJ Walters).



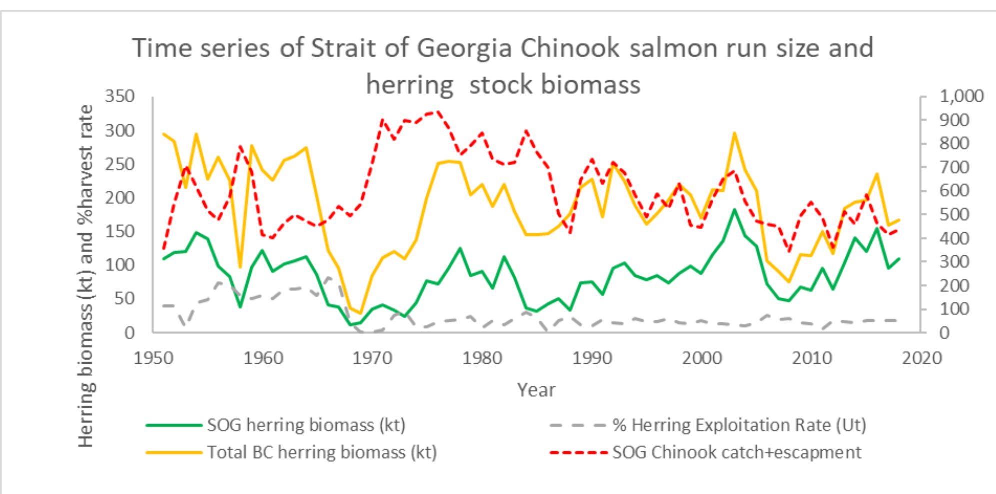
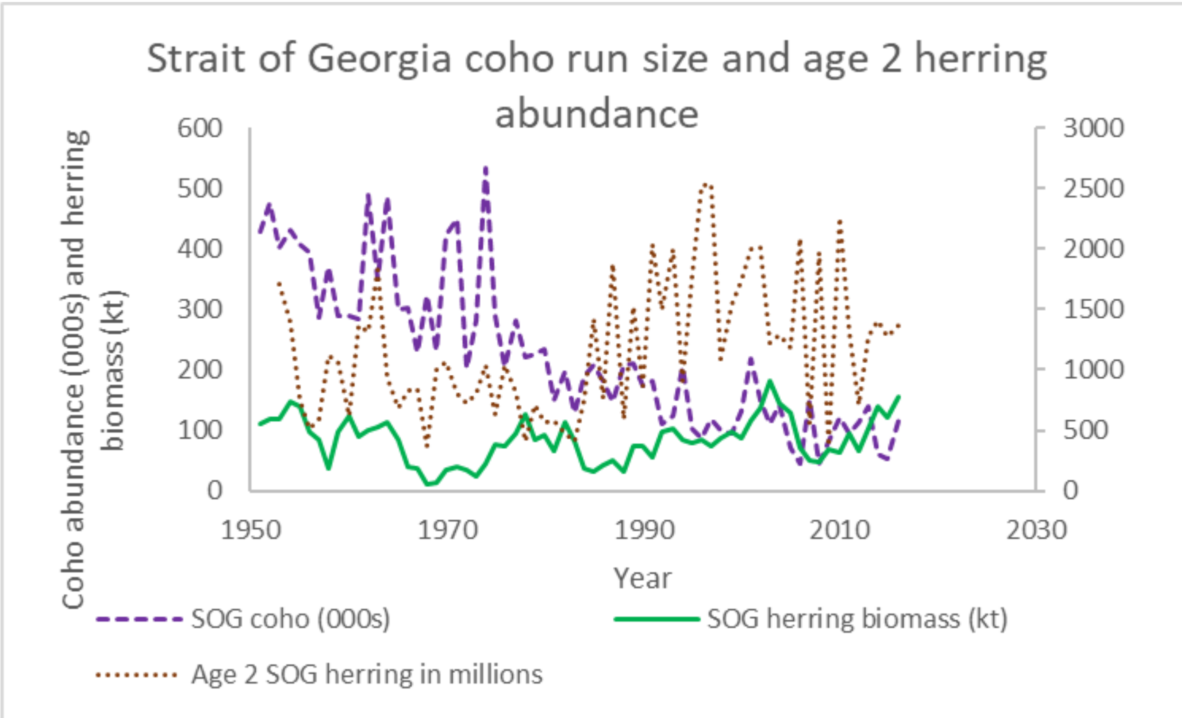


Figure 9. Strait of Georgia coho salmon run sizes (C. Walters, G. Oldford, S. Argue), age 2 Pacific herring abundance (J. Cleary) and herring stock biomass (C.J. Walters).



Plots of SOG Chinook salmon run size versus age 2 SOG herring abundance and SOG Chinook salmon run size and SOG herring stock biomass both show statistically significant negative associations between herring abundance and salmon run size (Fig. 10). A negative association between Chinook salmon run size and herring abundance indicates that when herring abundance is high, chinook salmon abundance tends to be low and vice versa. This negative association between herring abundance and Chinook salmon abundance in the Strait of Georgia refutes the hypothesis that Chinook salmon abundance is positively associated with herring stock abundance and the notion that low herring stock abundance will be associated with low Chinook salmon stock productivity and run size.

If herring competed with juvenile Chinook salmon upon ocean entry or soon after, a negative association could be expected between a strong herring cohort and Chinook salmon run size three years later. If we were to use age 2 herring abundance as a cohort strength indicator and juvenile chinook at ocean entry competed with young of year herring, then Chinook run size three years later would negatively covary with age 2 herring lagged by one year. If juvenile chinook competed with age 1 herring, then Chinook run size would negatively covary with age 2 herring lagged by two years. If juvenile chinook competed with age 2 herring, then Chinook run size would negatively covary with age 2 herring lagged by 3 years. If juvenile chinook were impacted by competition with the entire herring population as indexed by annual herring stock biomass, then Chinook run size would covary with herring stock biomass three years later. I therefore tested for a negative association between SOG Chinook salmon run size lagged by one, two and three years and age 2 herring abundance. I tested also for a negative association between and SOG Chinook salmon run size lagged by three years and herring stock biomass. SOG Chinook salmon run size at lag 1, 2 and 3 years was negatively correlated with age 2 herring abundance with R-squared values of 7%, 17% and 15% (Fig. 10a-c); these negative relationships were statistically significant at the alpha = 0.05 level (i.e., the P-value for the slope of the relationship for Chinook salmon was 0.03, 0.0008, and 0.0015, respectively). R-squared values indicate the percentage of variation in salmon run size that could be explained by variation in herring abundance. SOG Chinook salmon run size lagged three years was negatively correlated with herring stock biomass with an R-squared of 18% (Fig. 10d). This negative relationship was significant with a p-value of 0.0004. These results indicate that the larger the abundance of herring stock biomass or juvenile herring the year of ocean entry for SOG chinook salmon, the lower the subsequent run size when the chinook salmon return to spawn. While correlation and statistical significance in association does not imply causation, these results retain credibility for the hypothesis that competition between herring and juvenile chinook salmon negatively impacts chinook salmon in their first year of ocean life.

SOG Chinook salmon run size increased from moderately high levels in the 1950s and 1960s to an all time high during the collapse of the SOG herring stock in the 1970s. The marked increase in SOG run size in the late 1960s and early 1970s as mentioned above could have been associated with reduced competition with the collapsed herring stock. However, it could also have been assisted by potentially reduced bycatch in BC herring fisheries, including the SOG herring fishery when BC herring fisheries collapsed in the late 1960s. To evaluate whether there could be a negative association between SOG chinook stock run size and SOG herring fishery harvesting, I tested for a negative correlation between SOG herring fishery and SOG run size. Due to significant changes in herring fishery operations before and after the 1970s, tested associates between SOG Chinook run size and herring fishery harvest rates for a) the full time series, b) the early time series until 1987, and c) the time series after 1987. Significant negative correlations were found in all three instances with stronger negative correlations found when correlations were tested separately before and after 1987 (Fig. 10 e-g). These negative associations between Chinook salmon run size and herring fishery harvest rates are consistent with the hypothesis that high herring fishery harvest rates, e.g., > 60%, may negatively impact SOG chinook salmon run sizes. High herring fishery harvest rates occurred primarily before the 1970s (Fig. 6) and SOG chinook salmon run sizes nearly doubled with the herring fishery shut down after its 1960s collapse.

I tested also for negative associations between SOG coho salmon run sizes and age 2 herring stock abundance and SOG coho salmon run sizes and herring stock biomass. I tested for associations with either no lag or a lag of 1 year to account for potential impacts of herring stock abundance on coho salmon abundance in their first and second ocean years. Due to high variability in coho run sizes, I used the natural logarithm of coho run sizes for these tests. There was a negative association between the natural logarithm of coho salmon run size and age 2 herring stock abundance (R^2=0.15, p-value = 0.002) and but no significant association between the natural logarithm of coho salmon abundance and herring stock abundance with or without lags in the salmon response variable (Fig. 11).

The empirical time series show that when SOG herring abundance was at its lowest levels during the late 1960s and early to early-1980s, both chinook and coho salmon run sizes in the SOG were at their highest levels. The negative statistical associations between coho salmon run size and herring abundance refute the notions that the 1960s herring stock collapse and associated low herring abundances have negatively impacted SOG Chinook salmon and coho salmon run sizes.

Figure 10. Plots of a. SOG chinook salmon run lagged 1 year size versus Age 2 SOG herring abundance 1953-2018, b. SOG chinook salmon run size lagged 2 years versus Age 2 SOG herring abundance 1953-2018, c. SOG chinook salmon run size lagged 3 years versus Age 2 SOG herring abundance 1953-2018, d. SOG chinook salmon run size lagged 3 years versus SOG total herring stock biomass 1951-2018, e. SOG chinook salmon run size versus SOG herring fishery harvest rate 1951-2015, f. SOG chinook salmon run size versus SOG herring fishery harvest rate 1951-1987, g. SOG chinook salmon run size versus SOG herring fishery harvest rate 1988-2015.

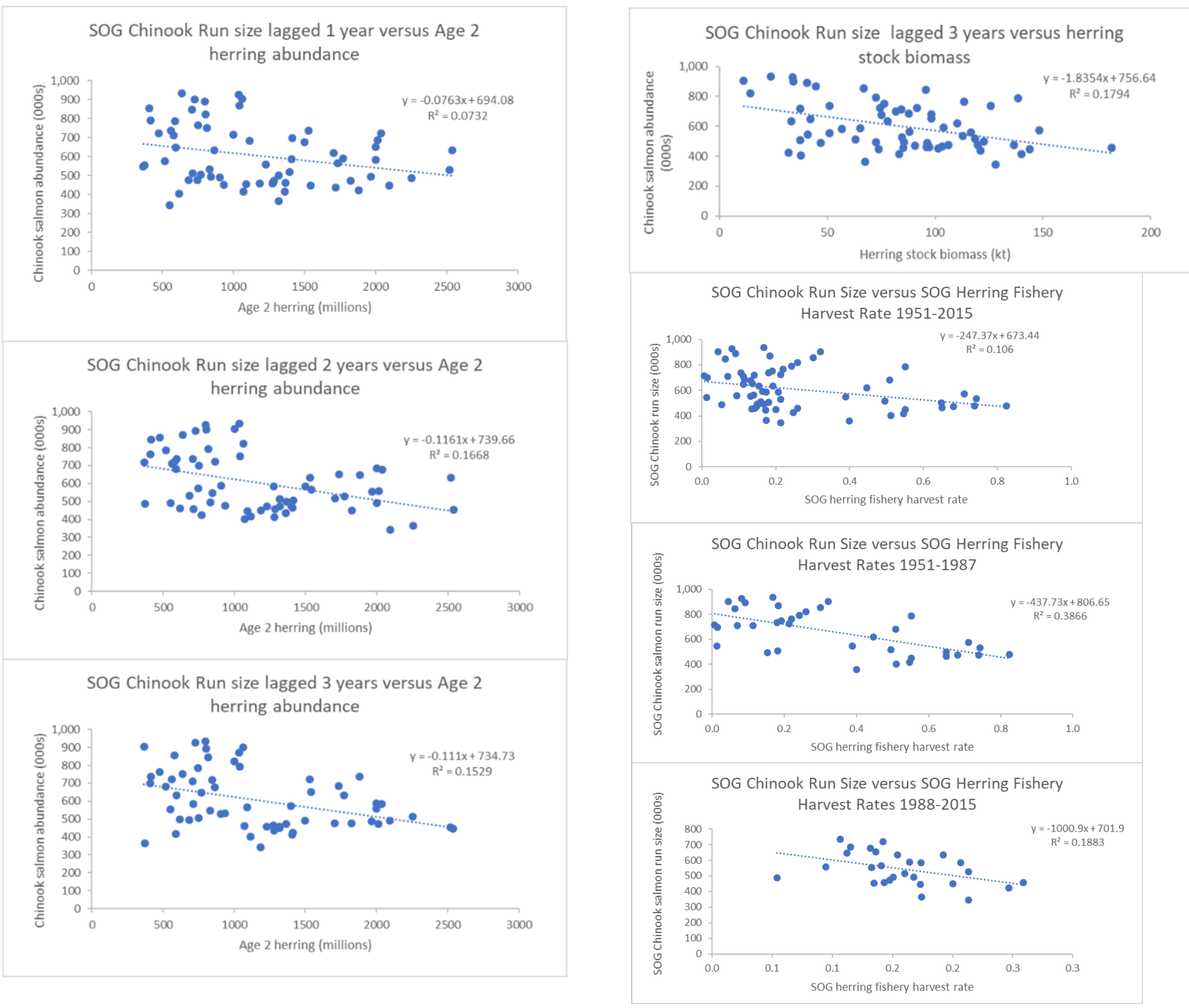
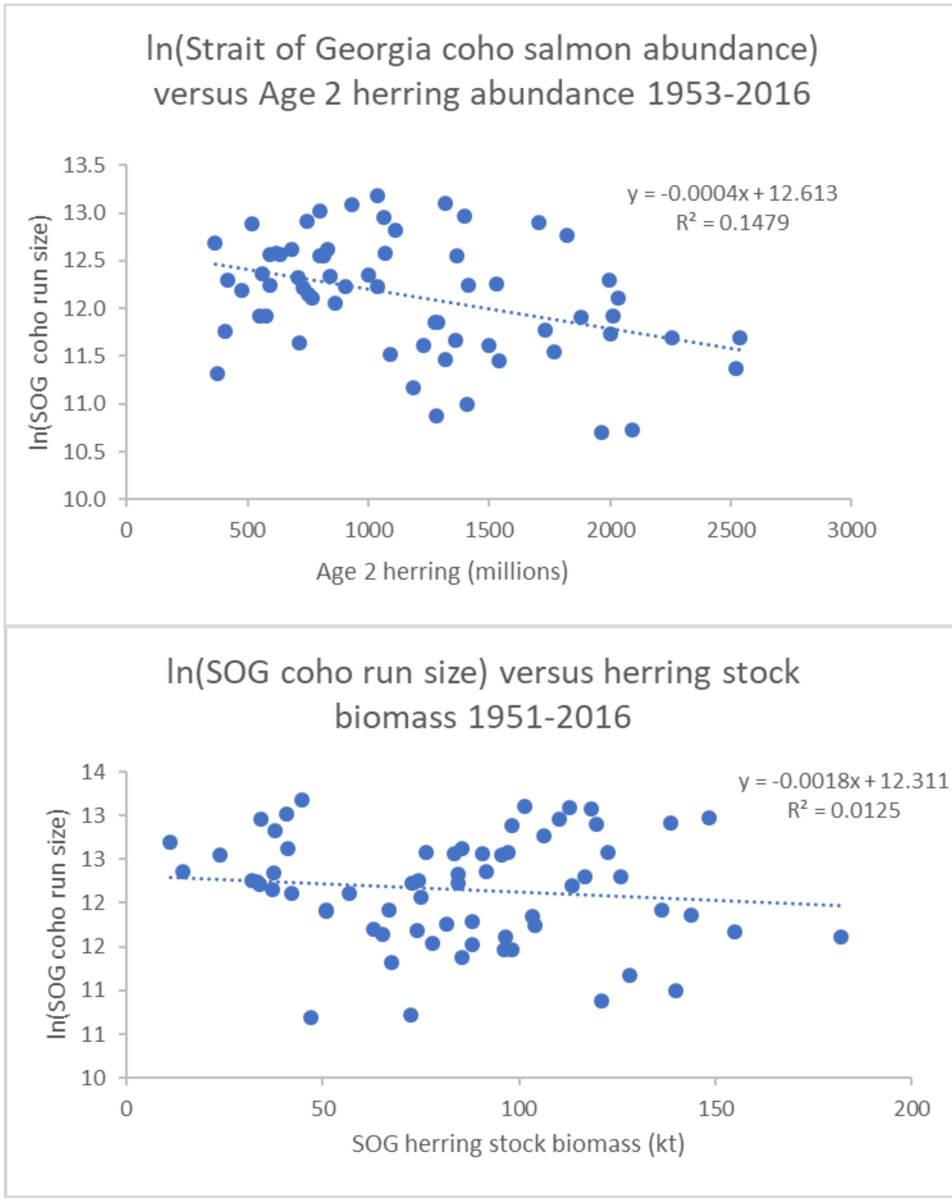


Figure 11. Plot of natural logarithm of SOG coho salmon run size versus a) age 2 SOG herring abundance 1953-2016 and b) SOG herring stock biomass 1953-2016. Source for SOG coho: C. Walters, G. Oldfield, S. Argue Report.



Time series of Age 2 herring and Coho salmon abundance in Northern B.C.

G. Oldford of DFO helped me to locate from the NUSEDS online data base several long time series of coho salmon run reconstruction for Skeena and other Northern B.C. runs of coho salmon. The time series of coho salmon run sizes from the early 1950s to the 20-teens show considerable variability over the time series with a few stocks showing higher run sizes up to the late 1960s and some surges in higher abundance in the 1980s and after 2000 (Figure 12). Age 2 Prince Rupert District herring abundance shows a sharp decline in the early 1960s and remains low through to the late 1970s. There does not appear to be any consistent association between run size of coho salmon and Age 2 herring abundance for PRD (Figs. 12-13). Plots of eight North coast coho salmon run sizes versus PRD age 2 herring abundance show only one mildly positive association (R-squared of 16%) between coho salmon run size and age 2 herring abundance suggesting that larger coho run sizes are weakly associated with larger age 2 herring abundance and vice versa (Fig. 14). Here, lower Skeena coho run size shows a depletion during the time of the PRD herring stock collapse in the late 1960s and a subsequent recovery with the rebound in age 2 PRD herring abundance in the late 1970s (Fig. 13 A.). However, despite age 2 herring abundance remaining a fairly high levels since the early 1980s, the lower Skeena coho run size dropped to lower levels in the mid-1990s and has remained low since. This suggests that it is plausible that mechanisms other than herring abundance are responsible for lower run sizes for lower Skeena coho salmon. Furthermore, there were no significant associations between coho salmon stock run size and PRD age 2 herring abundance for the seven other North coast coho stocks (Fig. 14).

Figure 12. Time series of Northern B.C. coho salmon run sizes. A. Skeena River coho salmon. B. North Coast coho salmon.

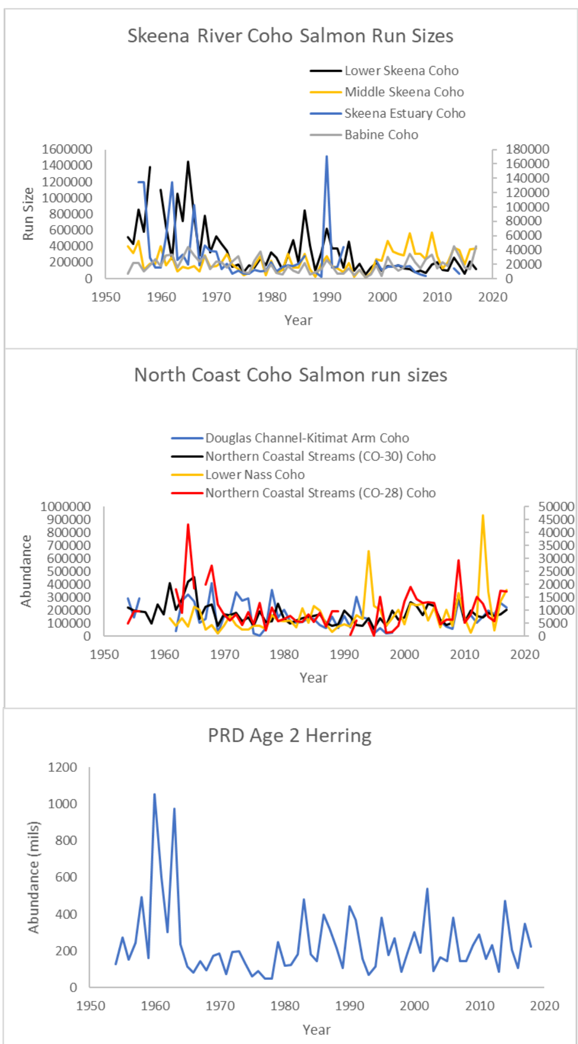
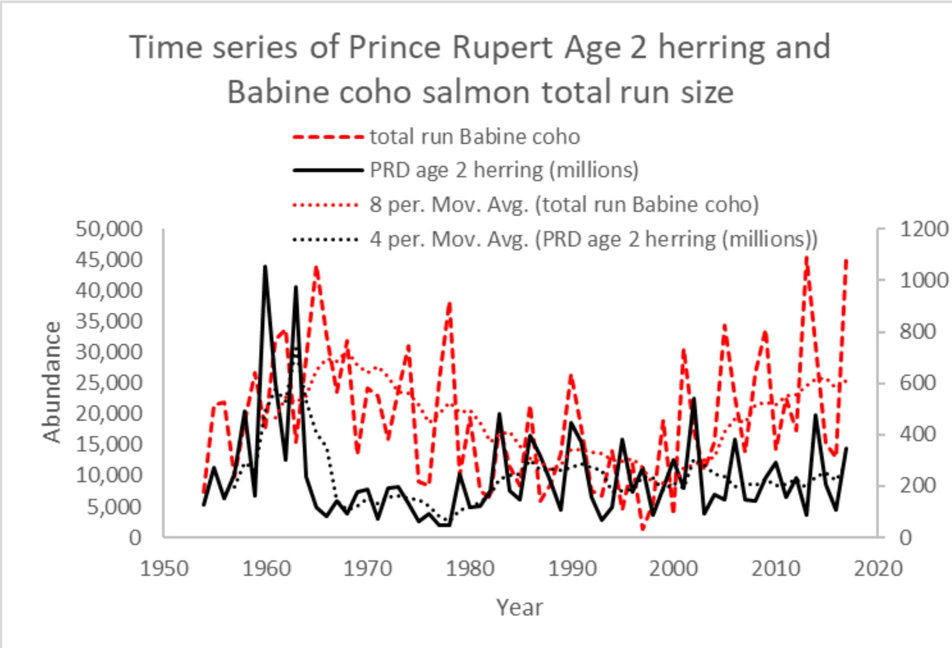


Figure 13. Time series of A. Babine and B. lower Skeena coho salmon run size and Prince Rupert District Age 2 herring abundance.



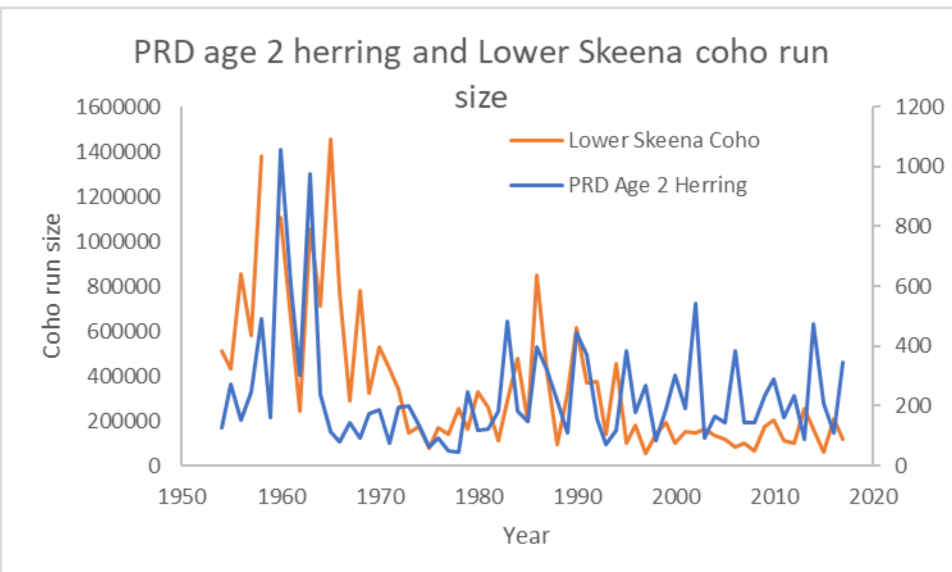
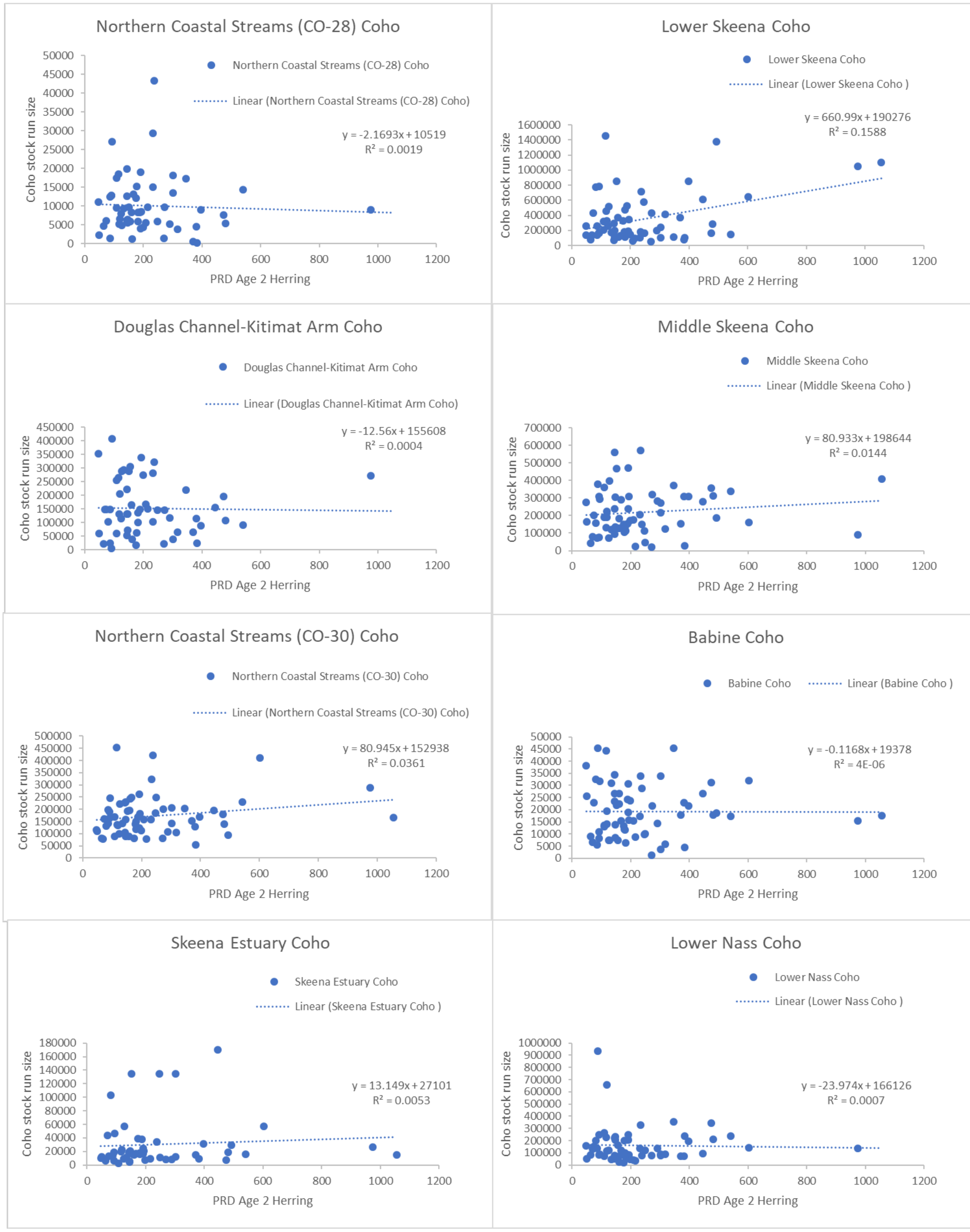


Figure 14. Plot of North Coast coho salmon run size versus Prince Rupert Age 2 herring abundance 1954-2017. Source: G. Oldfield, DFO.



Time series of Age 2 herring and Coho salmon abundance in on the B.C. Central Coast

In the four B.C. central coast coho stocks for which long time series of run size data were available there were no apparent associations between their run sizes and Central Coast age 2 herring abundance (Figs. 15 and 16).

Figure 15. Time series of B.C. Central Coast coho salmon run size and Central Coast Age 2 herring abundance.

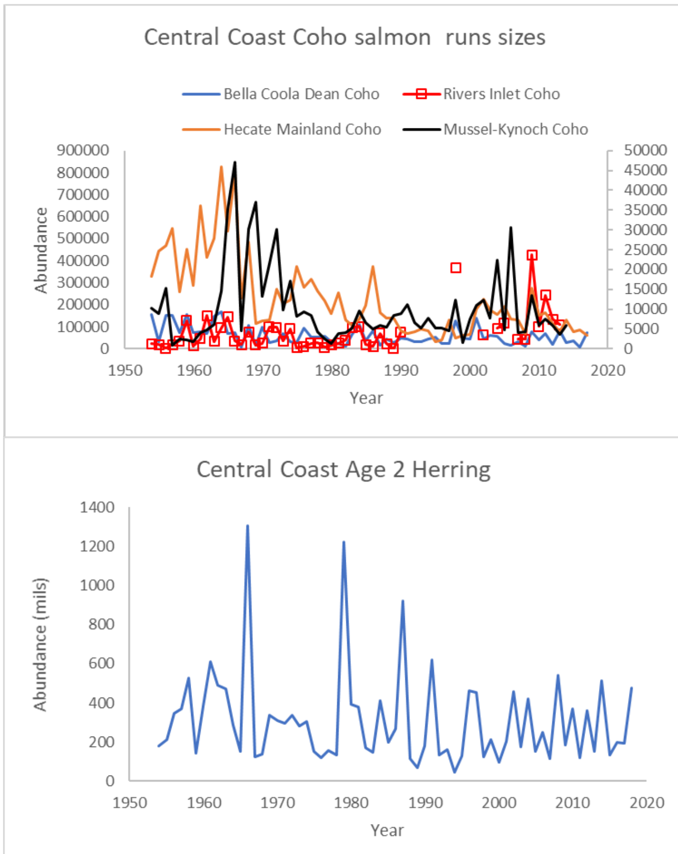
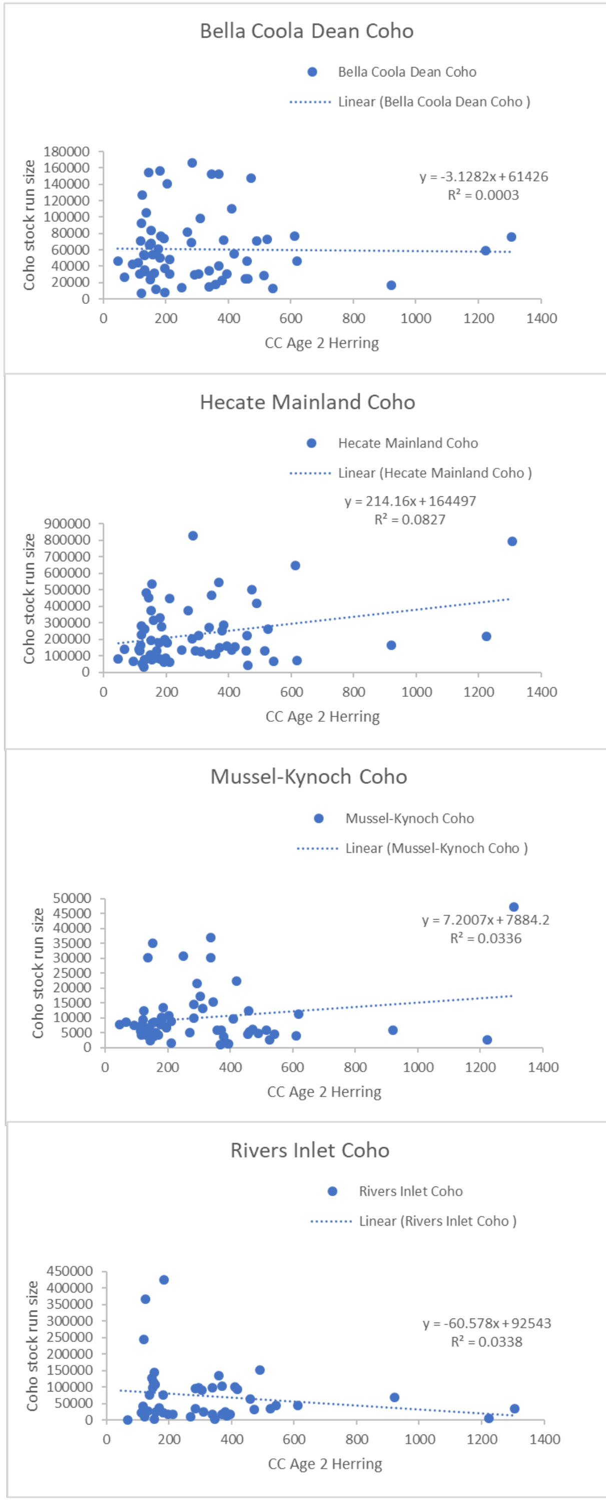


Figure 16. Plot of Central coast coho salmon stock run size versus Central Coast Age 2 herring abundance 1954-2017. Source: G. Oldfield, DFO.



Time series of Age 2 herring and Coho salmon abundance in Haida Gwaii

In the two Haida Gwaii coho stocks for which long time series of run size data were available there were no apparent associations between their run sizes and Haida Gwaii age 2 herring abundance (Figs. 18 and 19).

Figure 18. Time series of Haida Gwaii coho salmon stock run size and Central Coast Age 2 herring abundance.

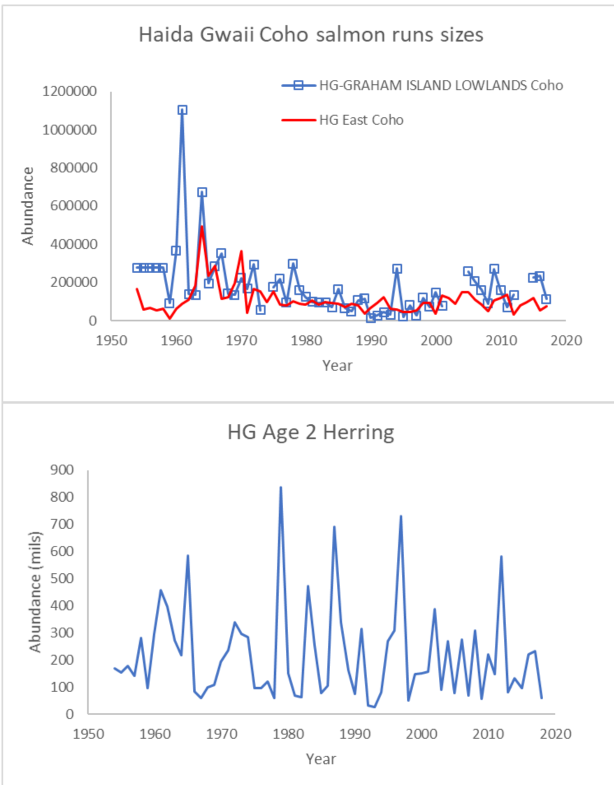
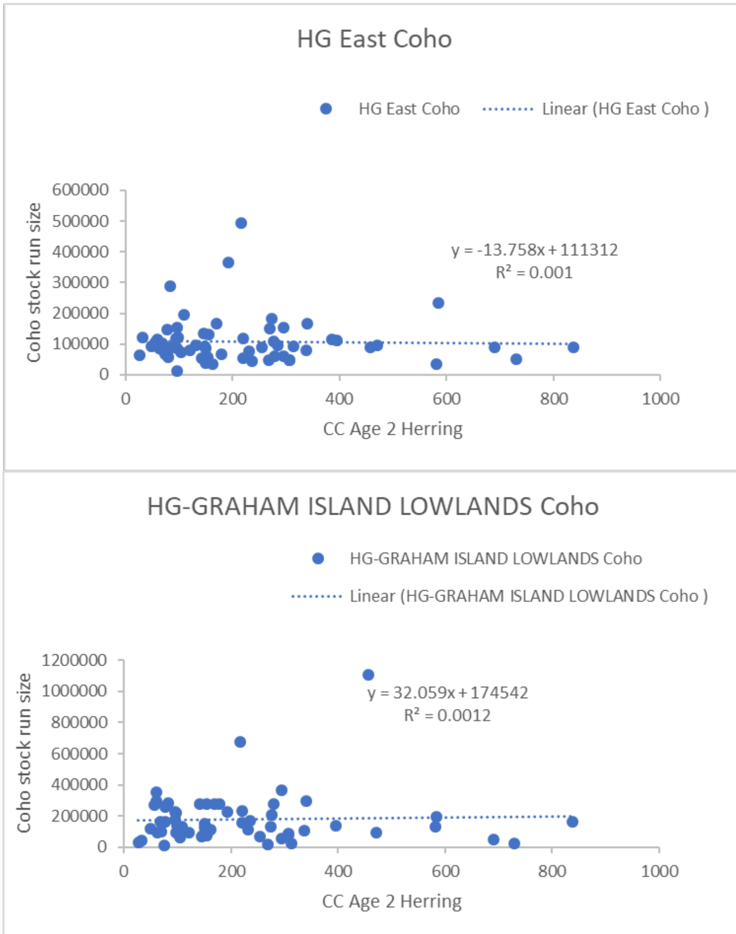


Figure 19. Plot of Haida Gwaii coho salmon stock run size versus Haida Gwaii Age 2 herring abundance 1954-2017. Source: G. Oldfield, DFO.



DFO Stock Assessment evaluations of alternative harvest rates on B.C. herring

In its stock assessments of B.C. herring, DFO routinely evaluates the potential consequences of alternative harvest policy options for herring stock status. A series of different catch limits are applied in herring stock projections from the present into the future. The 2018 stock assessment showed that catches that were associated with harvest rates up to 20% for the Strait of Georgia management area held relatively low risks of herring stock depletion (see below Table 18 copied out of DFO 2018). For example, a TAC of 26,200 tons would result in a mean harvest rate of 20% and a 2.5% probability of depleting stock biomass below 30% of average unfished abundance. However, the probabilities that stock biomass would fall below 30% of B_0 were higher for catch limits associated with 20% harvest rates for the other four herring management areas (DFO 2018).

Table 12. Probabilistic decision table for Strait of Georgia, AM2 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(SB_{2018} < 21,200)	Med(SB_{2018} < 21,200)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.003	2.951	0.000	5.910	0.000	0.000	0.000
12,000	0.008	2.729	0.000	5.466	0.010	0.422	0.094
12,800	0.009	2.714	0.000	5.436	0.016	0.500	0.100
14,000	0.010	2.692	0.000	5.391	0.030	0.616	0.109
15,000	0.011	2.671	0.000	5.353	0.047	0.695	0.117
17,500	0.013	2.623	0.000	5.259	0.116	0.842	0.136
20,000	0.015	2.573	0.000	5.166	0.210	0.918	0.154
26,200	0.025	2.453	0.000	4.937	0.501	0.983	0.200
30,000	0.031	2.382	0.001	4.798	0.671	0.992	0.228
35,000	0.041	2.291	0.002	4.617	0.824	0.997	0.263
36,000	0.044	2.273	0.003	4.582	0.848	0.997	0.270
38,000	0.049	2.236	0.003	4.508	0.883	0.998	0.285

Conclusions

In the above analyses I reviewed reconstructions of coho salmon and Chinook salmon stock run sizes for stocks in the Strait of Georgia, and coho salmon stocks in the central coast, Haida Gwaii and Prince Rupert District herring management areas going back to the 1950s. I also reviewed DFO estimates of herring abundance in these same management available in DFO's 2018 stock assessment. All five B.C. herring stocks showed extreme depletions in abundance in the late 1960s and subsequent recoveries in the late 1970s and early 1980s. I evaluated the apparent associations between chinook salmon and coho salmon run size and herring stock abundance for aggregate stock run sizes for Strait of Georgia chinook and coho stocks and found that these showed progressive declines in abundance from the 1950s to the most recent years where data were available. Severe depletions in herring stock abundance in the 1960s were not associated with drops in run size of Strait of Georgia chinook and coho salmon stocks. Instead the run sizes of Strait of Georgia chinook and coho salmon stocks remained at relatively very high levels during and within a decade after the severe stock collapse of Strait of Georgia herring in the 1960s.

The time series of age 2 herring abundance for the Strait of Georgia shows a less severe pattern of depletion in the 1960s during the herring stock collapse. This is presumably due to density dependent compensation in survival rates of juvenile Pacific herring. While the availability of adult herring may have been depleted very severely during the stock collapse, juvenile herring abundance thus depleted but not as severely. With the switch from the reduction fishery on herring up to the mid-1960s to a herring roe fishery in the late 1970s, herring abundance recovered quite swiftly and juvenile herring abundance in the Strait of Georgia appears to have averaged at considerably higher levels after the 1970s. However, the run sizes of Chinook salmon and coho salmon in the Strait of Georgia showed long-term marked declines running through to the end of the time series in 2017 and 2018 and were not helped by the increases in abundance of Strait of Georgia herring.

For the several central coast, Haida Gwaii and Northern B.C. coho salmon stocks for which long time series of run size estimates were available, there were no consistent patterns of coho salmon run size depletion during or just after the sharp herring stock collapses that occurred in the CC, PRD and HG herring management areas in the late 1960s and early 1970s. And there was also no consistent positive or negative association between coho salmon run size and age 2 herring abundance in these central coast, Haida Gwaii and Northern B.C. coast areas. Thus, where sharp and severe stock collapses occurred in the HG, PRD, and CC herring management areas in the 1960s and early 1970s, there was no associated consistent decline in estimated run sizes for 13 of the fourteen coho salmon stocks. A mildly positive association between coho run size and age 2 herring abundance was found for only one of the fourteen coho salmon stocks. The lack of a consistently positive association between coho salmon run size and herring abundance for the fifteen coho salmon stock groupings investigated and for Strait of Georgia chinook salmon taken together refute the notion that high harvest rates for herring, and low herring stock sizes will negatively impact Chinook salmon and coho salmon productivity and abundance.

Given that studies of B.C. chinook salmon and coho salmon diets show that both of these salmon species eat a wide variety of prey species, including herring, also suggests that should herring stocks drop to low levels, Chinook and coho salmon would switch to other prey species than herring and that their productivity would not necessarily be compromised by low abundances of herring. Also, given that the survival rates of juvenile herring exhibit compensation, i.e., when total herring abundance is low, juvenile herring survival rates increase, we see that juvenile herring abundances deplete considerably less than adult herring abundance when there are higher harvest rates on mature herring and lower adult abundances. Therefore, the apparent depletion of herring as a food source for salmon may be less than would seem apparent when total herring stock abundance becomes depleted.

Finally, at least for the Strait of Georgia herring stock, the recent DFO stock assessments show that stock status has remained in good order and that catch limits associated with a 20% harvest rate would have a very low probability of depleting the stock to low levels, e.g., to less than 30% of average unfished stock size (DFO 2018). Therefore, available stock assessment modeling and available run reconstructions of coho and chinook salmon refute the notion that salmon stocks that are known to feed on herring would benefit from lowering or eliminating target harvest rates where commercial harvests have recently been permitted.

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