Did Recent Marine Heatwaves and Record High Pink Salmon Abundance Lead to a Tipping Point that Caused Record Declines in North Pacific Salmon Abundance and Harvest in 2020?

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Total abundance of Pacific salmon returning from the North Pacific Ocean increased following the 1977 ocean regime shift, peaking in 2018 when approximately 950 million pink, chum, and sockeye salmon returned from the ocean (Fig. 1). In 2019, salmon abundance remained exceptionally high (~854 million salmon). Together the 2018/2019 period was the highest two-year period of salmon abundance on record since 1925, nearly 20% greater than the previous two-year high in 2009/2010, and more than 3.2 times higher than average abundance during relatively low salmon production years from 1960 to 1975.

Fig. 1. Total abundance of pink, chum, and sockeye salmon (catch plus spawning escapement) returning from the North Pacific Ocean to streams in North America and Asia, 1925–2020. Updated from Ruggerone and Irvine (2018); see Irvine et al. (2021) for description of methodology for 2016–2020 values and Table 2 here.

Pink salmon continue to dominate the abundance of Pacific salmon returning from the North Pacific, reaching approximately 700 million maturing fish in 2018 and nearly 640 million fish in 2019 (Fig. 1). The exceptional return in 2018 is highly unusual because pink salmon abundance is typically highest in odd-numbered years (Irvine et al. 2014). Approximately 88% and 68% of total pink salmon returned to Asia rather than North America in 2018 and 2019, respectively (Table 1). In contrast, peak abundance of pink salmon in North America occurred in 2013 and 2015 (more than 300 million fish per year). Overall, pink salmon represented approximately 74% of total salmon abundance in 2018/2019. Most pink salmon are of natural origin, but abundance of hatchery pink salmon during 2005 to 2015 was greater than abundance of wild chum salmon and approximately equal to abundance of wild sockeye salmon. Total chum and sockeye salmon represented only 14% and 12%, respectively, of total salmon abundance in 2018/2019. These values exclude Chinook and coho salmon, whose combined reported catch was 1.5% of total salmon catch from the North Pacific during 2018/2019 and approximately 5% of total salmon catch, on average, during 1925 to 2019 (NPAFC 2020).

Table 1. Total abundance of pink, chum, and sockeye salmon (catch plus spawning escapement) returning from the North Pacific Ocean to streams in Asia and North America, 2016 to 2020. These values extend the 1925 to 2015 salmon abundance database (Ruggerone and Irvine 2018; Irvine et al. 2021), primarily using Approach 3.

Year	Asia			North America			Total			
	Pink	Chum	Sockeye	Pink	Chum	Sockeye	Pink	Chum	Sockeye	Total
2016	335	110	24	97	39	79	432	150	104	686
2017	287	74	21	226	49	79	513	123	101	737
2018	614	98	23	87	42	86	701	140	109	950
2019	435	74	24	203	37	81	639	111	104	854
2020	205	68	17	110	23	71	315	92	87	494

Table 2. Revised abundance of sockeye salmon (millions of fish) returning to the Mainland and Islands region of Russia (M&I), as originally reported by Ruggerone and Irvine (2018). During the 2020 update of the salmon abundance database, we noticed that interceptions of sockeye salmon in the Kuril Islands that began in 2001 were not included in the database. The missing Kuril Islands sockeye catch led to very small increases in the M&I sockeye abundance values from 2001–2005 (<1%), increasing to 10% in 2006–2008, then to 60% in 2009 to 2013, and to 160% in 2014 and 2015. Inclusion of these intercepted sockeye salmon led to a maximum increase of 5% in sockeye abundance returning to Asia and 1% to North America and Asia combined (in 2015). Some of these sockeye salmon would have returned to Kamchatka, but we have assumed for simplicity that all returned to the Mainland and Islands region.

Year	M&I	Asia	North Pacific
2001	0.5	8.5	65.6
2002	0.3	13.8	70.7
2003	0.2	9.8	73.6
2004	0.1	9.1	89.8
2005	0.7	13.0	87.2
2006	0.8	12.6	89.1
2007	0.5	18.3	84.8
2008	0.4	14.5	74.8
2009	0.5	14.8	75.5
2010	0.6	15.1	105.2
2011	1.0	17.3	83.0
2012	0.8	21.1	79.0
2013	0.9	22.4	74.3
2014	0.9	18.2	106.5
2015	1.7	21.9	110.2

Unexpectedly, the high abundance of Pacific salmon came to an abrupt end in 2020. Preliminary commercial catch statistics for all salmon species indicate Pacific salmon harvests, which provide an index of abundance, declined more in 2020 than in any other period on record since 1930 (Fig. 2). Commercial salmon harvests declined by approximately 187 million fish compared with average harvest during the previous 10 years (2010–2019; Fig. 2, NPAFC 2020). Although the COVID-19 pandemic may have reduced commercial harvests to some extent in some regions, most fishery reports and preliminary escapement estimates indicate low abundance rather than harvest impacts from the COVID-19 pandemic led to unusually low harvests of Pacific salmon in 2020.

Harvests of each species of Pacific salmon declined 35%, on average, in 2020 when compared with the previous 10-year average. This decline was greater than in any previous period. Harvests of Chinook salmon in 2020 were the lowest on record since 1925, declining 54% compared with the previous ten years. Chum salmon harvests in 2020 declined 42%, followed by pink (40%), coho (27%), and sockeye (10%). Sockeye salmon harvests declined relatively little because returns to Bristol Bay in the southeastern Bering Sea remained robust and offset the exceptionally low harvests of sockeye salmon in the Gulf of Alaska, British Columbia, Washington, and the Columbia River. Pink salmon returning to the Norton Sound region in northern Alaska in 2020 continued with relatively high returns that began in 2016 (J. Menard, jim.menard@alaska.gov, personal communication), providing evidence for the beneficial effects of the warming ocean on salmon in the extreme north.

Fig. 2. Change in the commercial catch of Pacific salmon (pink, sockeye, chum, coho and Chinook) relative to the average catch during the previous ten years, 1930–2020. Catch values include both Asia and North America. Data sources: NPAFC (2020, 2021), Choi et al. (2021), Marchenko et al. (2021), Miyauchi and Saito (2021), Munro (2021), PFMC (2021), Velez-Espino et al. (2021).

We hypothesize that a tipping point was reached in the North Pacific Ocean, leading to the substantial decline of all five species of Pacific salmon in 2020. We infer that the tipping point was caused by the combined effects of unusually frequent marine heatwaves since 2014 (Krovnin et al. 2019; Gupta et al. 2020; Litzow et al. 2020) and exceptional back-to-back year abundances of pink salmon in 2018/2019 (Fig. 1). This hypothesis is partially supported by Connors et al. (2020), who reported the combined effects of sea surface temperature (SST) and pink salmon abundance on productivity (return per spawner) of 47 sockeye salmon populations (brood years 1976–2009) ranging from the Fraser River in British Columbia to Bristol Bay, Alaska. Investigators found that a 1.5°C increase in SST (1 standard deviation) was associated with a 23% increase in sockeye productivity in the Bering Sea, a 9% productivity increase in the Gulf of Alaska, but with a 12% decline in productivity in the southern region (British Columbia and Southeast Alaska). The frequent heatwaves following the period considered by Connors et al. (2020) likely contributed to the growing abundance of pink salmon in the north while also contributing to a northward shift in the adverse effects of high SST on production of other salmon species.

Connors et al. (2020), while simultaneously considering the influence of ocean warming, also reported that a 119 million increase in pink salmon abundance (i.e., 1 standard deviation) was historically associated with a 9% decline in sockeye productivity in the Bering Sea and the Gulf of Alaska, and a 21% decline in British Columbia (e.g., Fig. 3). This finding is consistent with the trophic cascade caused by abundant pink salmon (Batten et al. 2018) and other studies indicating adverse effects of pink salmon on the growth, age-at-maturation, survival, and abundance of sockeye salmon, Chinook salmon, coho salmon, chum salmon, marine fishes, seabirds, and potentially southern resident killer whales (Ruggerone and Nielsen 2004; Ruggerone et al. 2016a, 2019; Ruggerone and Irvine 2018). Support for the adverse interaction between pink salmon and other marine species is strengthened by biennial patterns in marine species that are consistent with the biennial pattern in pink salmon in most years; these biennial patterns cannot be explained by physical oceanography. The adverse effect of numerous pink salmon on vital rates of other salmon species is far-reaching because salmon are known to migrate 1,000s of kilometers at sea. For example, 11–38% of Chinook salmon sampled on the southeastern Bering Sea shelf during 2005–2010 originated from the west coast of the contiguous United States (Larson et al. 2013).

Fig. 3. Effects of a 1 standard deviation increase in both SST (1.5°C) and pink salmon abundance (119 million fish) and the combined effect of both variables on the percentage change in sockeye salmon return per spawner. Empirical model based on 47 sockeye salmon populations (1976 to 2009 brood years) spanning the Bering Sea, Gulf of Alaska, and West Coast (Southeast Alaska through British Columbia) of North America. Thin lines represent each stock; thick lines represent mean of 47 stocks. Source: Connors et al. 2020.

In summary, both pink salmon abundance and high SST were extreme leading up to the salmon decline in 2020, and more extreme than observed in the Connors et al. (2020) study, which ended with the 2009 sockeye salmon brood year. Furthermore, pink salmon abundance in 2018 did not decline as in past even-numbered years. We hypothesize that a tipping point was caused by the record-setting back-to-back-year abundances of pink salmon and unique ocean conditions leading up to the salmon decline in 2020. This hypothesis is consistent with research that has uncovered non-stationary effects of ocean temperatures on salmon catch in the Gulf of Alaska, including negative effects of recent heatwaves on catch (Litzow et al. 2020).

Preliminary 2021 commercial harvest data indicate at least some populations improved from the low numbers in 2020. Alaska and Russia pink salmon abundances appear to have rebounded to the exceptionally high values in 2019. Sockeye salmon returning to Bristol Bay, Alaska, set a new record high in 2021 (66 million fish (catch and escapement); T. Sands, ADF&G, personal communication), apparently in response to favorable early marine growth in the Bering Sea (e.g., Ruggerone et al. 2007) and relatively few maturing pink salmon in 2020 (Ruggerone et al. 2016b). In contrast, commercial harvests of Chinook, coho, chum, and sockeye salmon remain somewhat low in many regions of Alaska and Russia. Further evaluation of 2021 and 2022 harvests and returns of Chinook, coho, chum, pink, and sockeye salmon are needed to evaluate the validity of our tipping point hypothesis.

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