Pink salmon at sea: Current knowledge, overlap and potential interactions

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1. Spatial and temporal distribution in the North Atlantic Ocean.

Pink salmon, *Oncorhynchus gorbuscha*, is a new species in the Atlantic Ocean due to intentional introductions to create new fishing opportunities. Attempts of introductions occurred in the early 20th century in the east coasts of USA and Canada, and in the northwest coast of Russia (NHPSEG 2023). There is also a record of one stocking in southern Norway in 1978 (Sandlund *et al.* 2019). It is believed that the introduction in 1984 of ova to Kola Peninsula rivers in Russian from rivers in the Magadan region was the only successful one that led to natural spawning in rivers flowing to the North Atlantic Ocean (NHPSEG 2023). Up to date, presence of pink salmon has been recorded in odd years in rivers in the Fennoscandian peninsula, Svalbard, Scotland, Germany, France, Netherlands, Denmark, Ireland, Faroe Islands, Iceland, Greenland, and as far as Newfoundland and Nunavut in the Northwest Atlantic. Reports of even-year pink salmon outside the Fennoscandian peninsula has remained low with only one report in UK (ICES 2022; NHPSEG 2023; and references therein). Other records outside the native range of pink salmon have been in the Western Canadian Arctic, were strayers originated from Pacific populations due to warning temperatures and expansion of their native range (NHPSEG 2023). These results were confirmed by genetic analyses (NHPSEG 2023). In addition, those genetic analyses concluded that even-year pink salmon from all areas analysed were more alike than odd-year pink salmon. Moreover, Norwegian odd-year samples genetically diverged from the samples representing the Russian odd-year source population (Asian Pacific), while the Norwegian even-year samples were still genetically similar to the source population (NHPSEG 2023). A recent ecological niche modelling and population genomics study suggested that the river Neiden in northern Norway could be serving as source population for secondary spread of pink salmon in Norway and North Atlantic (Maduna *et al.* 2024).

Pink salmon is experiencing distribution changes both in their native and introduced areas due ocean warming. Many southern populations are negatively impacted, while northern ones have increased in abundance and expanded distribution to Arctic waters in North America and Asia (Farley *et al.* 2020; NHPSEG 2023). Expansion of distribution in the Atlantic has also been linked to high temperatures by different models. VKM *et al.* (2020) found a positive correlation with sea surface temperature in May around Finmark coast and Svalbard with the number of pink salmon returning to rivers the following year. Maduna *et al.* (2024) concluded that habitat suitability in rivers was driven by temperature and precipitation at the time of river ascent, and identified a high number of suitable habitats across Arctic and North Atlantic Oceans. Therefore, there is potential for expansion of pink salmon in the North Atlantic towards southern Europe and the northwest in the coming decades (Maduna *et al.* 2024).

2. Potential migration patterns

The above presented range of pink salmon in the North Atlantic is based on river records. Little is known of their distribution and behaviour in their offshore areas in the Atlantic as there are no targeted large-scale and comprehensive monitoring programs on neither side of the Atlantic (NHPSEG 2023). Norway has the most experience collecting data on pink salmon. In coastal waters, this data comes from a licensed salmonid fisher using bag-nets, and recreational fishing, using angling, gillnetting, or trolling. In offshore waters, data comes from bycatch in commercial fisheries reported by the Norwegian Reference Fleet (Clegg and Williams 2020) and in scientific trawl surveys targeting other pelagic fish such as the International Ecosystem Survey in Nordic Seas (IESNS) (Diaz Pauli *et al.* 2023). This Norwegian pink salmon bycatch is mainly adult individuals caught in May and June in the Norwegian Sea during their migration back to rivers (from 2013-2023: N =274). In addition, there were 12 post-smolts caught in the Barents Sea in December 2018, 8 post-smolts caught in the Barents Sea in August 2022, and 4 more post-smolts caught by the coast of Finmark in October 2022. A possible sea migration pattern could be that some individuals stay the whole marine life cycle in the Barents Sea, while others go westward to the northern and western Norwegian Sea, which is a feeding and overwinter area for Atlantic salmon (Jacobsen and Hansen 2001; Rikardsen *et al.* 2021). The latter ones could migrate with Arctic water flowing southward during the winter, potentially explaining the strays in Ireland and Scotland and the presence of pink salmon in the southern Norwegian Sea (Diaz Pauli *et al.* 2023). Some pink salmon may probably migrate in spring northwards from southern Norwegian sea, relatively close to the coast, after spending one year in the sea until reaching rivers in northern Norway and Russia (Diaz Pauli *et al.* 2023). However, it should be noted that the temporal and spatial patterns are linked, limiting our ability to make clear conclusions. Little is known about the individuals staying in the Barents Sea. One possibility is that post-smolts are rapidly taken eastwards by the Norwegian coastal currents towards Novaja Zemlya, as post-smolts occupy the upper layers (Farley *et al.* 2020). This could explain why pink salmon post-smolts are very seldom caught in Norwegian surveys in the eastern and central Barents Sea catching other small pelagic fish. Whether these two different migration patterns result in different populations exploiting different feeding grounds remains unknown.

3. Marine diet in the Northeast Atlantic

Pink salmon diet in the Norwegian Sea and around Svalbard was dominated by Euphausiids, fish and amphipods (Bengtsson *et al.* 2023; Diaz Pauli *et al.* 2023), and is similar to that observed in the Pacific Ocean (Radchenko *et al.* 2018). However, the relative abundance of the dominant prey species in the pink salmon diet depend on their geographical distribution. Pink salmon preyed most on herring, saithe, pricklebacks when caught on the shelf along the Norwegian coast and into the Barents Sea, while they preyed on Mueller's pearlside and lanternfishes when caught south in the Norwegian Sea. Pink salmon caught in the deep basin of the Norwegian Sea (north of 67.5ºN) mainly preyed on the amphipod *Themisto sp*. (Diaz Pauli *et al.* 2023). Finally, pink salmon caught around Svalbard preyed mainly on the amphipod *Onisimus litoralis* (Bengtsson *et al.* 2023). Preliminary unpublished stable isotopes analyses indicate pink salmon exploit feeding grounds over a wide area in the North Atlantic and at different trophic levels (Skóra *et al.* 2023), as also observed in the stomach content analyses presented above.

4. Potential interactions: Overlapping diet and distribution

Data on interactions between pink salmon and native salmonids is lacking from both the river and the sea phases in the North Atlantic making any prediction difficult (VKM *et al.* 2020). From the data on geographic distribution and diet in the Norwegian Sea presented above, one could conclude that migration patterns and diet preference of pink salmon overlaps with that of Atlantic salmon, *Salmo salar*, and there is a potential for interaction (Diaz Pauli *et al.* 2023).

There is no consensus on the pink salmon impact on marine ecosystem in the Pacific Ocean (NHPSEG 2023). Most publications concluding that pink salmon impose top-down effects on other marine species are from North America, while most publications concluding negligible effects are from Asia and mostly written in Russian (NHPSEG 2023). In the North American side, pink salmon can initiate trophic cascades by reducing herbivorous zooplankton and engage in interspecific competition with many economically important forage fish as well as other marine species (Ruggerone *et al.* 2023). However, there is also evidence suggesting that the feeding areas and habits among Pacific salmon species often indicate complimentary interactions, instead of competitive (NHPSEG 2023). The different impact of pink salmon on the ecosystem in the American and Asian part of the Pacific Ocean could be related with their differences in productivity. The Pacific Ocean provided approx. 58% of the total marine catches in the world in 2020, but from this, 24% occurred in the Northwest Pacific area (i.e. total 19.15 million tonnes) and 4% in the Northeast Pacific (i.e. total 2.86 million tonnes; FAO 2023). The Atlantic Ocean provided 26% of the marine catches in 2020, from which 11% was caught in the Northeast Atlantic (i.e. total 8.31 million tonnes) and 2% in the Northwest Atlantic (i.e. total 1.54 million tonnes; FAO 2023). The higher productivity in the Northwest Pacific relative to the Northeast Pacific could potentially explain why the impact of pink salmon is lower in the Northwest. The Northeast Atlantic is a relatively high productive area, and thus it might be more comparable to the Northwest Pacific when considering the potential influence of pink salmon on other species.

Just for comparison, in the Northwest Pacific Ocean, 146 423 tonnes of pink salmon were fished at sea in 2022, while 112 085 tonnes of pink salmon were fished in the Northeast Pacific Ocean in the same year (NPAFC 2023). This is roughly equivalent to 179 473 000 individual pink salmon fished in the Pacific Ocean in 2022. In Norway in 2023, approx. 350 000 individual pink salmon were fished out, including license salmon fishery and removal of individuals from mitigation programs (SSB 2023). Given an individual body weight of 2.0 kg (average body weight of pink salmon caught in the recreational fishery in rivers in 2023), the biomass of pink salmon caught in Norway in 2023 was 700 tonnes, which is equivalent to 0.08 % of the total fish catches in the Northeast Atlantic in 2020. Despite little knowledge about pink salmon species interactions offshore in the North Atlantic, the biomass of pink salmon is presently too low to have a noticeable grazing effect on the large offshore ecosystems which supports large pelagic or semi-pelagic marine stocks such of herring, capelin, saithe, haddock, mackerel, and blue whiting. However, pink salmon might have some local impact on estuaries, fjords, and coastal areas both during the smolt migration and the spawning migration (Diaz Pauli *et al.* 2023).

Sea trout, *Salmo trutta*, are distributed from the Bay of Biscay in the south to the Barents Sea in the north, and sea-going Arctic char, *Salvelinus alpinus*, is common in polar regions such as Canada, Iceland, Norway, Sweden, and Russia (Klemetsen *et al.* 2003), and these species mainly feed in coastal waters. Therefore, adult pink salmon feeding intensively in coastal areas when migrating towards rivers can potentially have a negative impact on prey availability for Arctic char and sea trout along the coast. The only direct diet comparison between pink salmon and native salmonids that we are aware of is from Svalbard with Arctic char (Bengtsson *et al.* 2023). They sampled Arctic char and pink salmon in six locations around Svalbard between 2015 and 2018 and concluded that their invertebrate diet overlap was intermediate to high ($O_{obs} = 0.59$), when both species co-occurred in the same fjord (1 out of 5 fjords studied; (Bengtsson *et al.* 2023). However, pink salmon fed more on intertidal invertebrates. In addition, the salmonid species differed in their fish diet. Arctic char ate most pelagic fish, while pink salmon ate demersal species, indicating that they occupy different areas and parts in the water column. Bengtsson *et al.* (2023) concluded pink salmon fed in intertidal areas on bottomdwelling prey, while Arctic char fed both in pelagic areas further offshore than in the intertidal zone. It should be noted that all pink salmon sampled were adults with developed gonads. which might explain their preference toward the intertidal zone, while juveniles were present in the Arctic char samples (Bengtsson *et al.* 2023). Therefore, adult pink salmon feed close to the coast and fjords, before entering the rivers, where they could potentially impact food availability for other salmonids, such as Arctic char and sea trout.

There is no information about how long pink salmon remains in estuaries in their introduced habitat before their sea migration. While in their native range they might remain between a few weeks to a few months in estuaries and inshore waters, depending on availability of resources (Radchenko *et al.* 2018; NHPSEG 2023). Evidence from the Pacific shows that pink salmon in estuaries feed heavily on pelagic zooplankton, and less on benthic and intertidal forms (VKM *et al.* 2020). Pacific pink salmon growth rate in the estuary and first months at sea is extraordinarily high (Radchenko *et al.* 2018). Recent work of Erkinaro *et al.* (2023) showed that pink salmon juveniles sampled in the estuaries in late May and June have stomachs 50-75% full. Therefore, there is a potential for competition for resources with other species in estuaries and inshore waters. However, in these areas, salmonids also suffer great mortality, mainly by predation. In this case, small individuals, like pink salmon are expected to be most vulnerable to a wider range of potential predators, as it has been observed in estuaries of the Pacific (Duffy and Beauchamp 2008). Thus, in estuaries and inshore areas, pink salmon might be a good food source for other salmonids (ICES 2022). Little is known about when migration to open ocean occurs in either the native or introduced ranges. It does not seem related to size or time in freshwater, but there are some indications that could be driven by an increase in temperature (Radchenko *et al.* 2018). Knowledge about this life history phase in the introduce range is important for understanding potential interspecific interaction with native species.

Lack of knowledge is the limiting factor in assessing the ecological impact of pink salmon in the Northeast Atlantic. Studies from their native range are very useful for predicting potential impacts. However, there is evidence that the introduced population are rapidly adapting to the new environment. Thus, the comparison with the native range might be less relevant than previously expected. Comparison of individuals (adults, juveniles and smolts) from the Ola River (source of the introduction in Russia) and several rivers in the basins of the White and Barents seas (introduction areas) showed that native and introduced individuals differed in body weight, and various morphological and life-history traits (reviewed in Gordeeva and Salmenkova 2011). The differences between source and introduced populations were due to a mixture of adaptation, phenotypic plasticity and random genetic change (Gordeeva and Salmenkova 2011). Changes in morphology in the introduced odd year populations seem to be linked to the slower flow and the larger size of gravel in the rivers of the White Sea basin (Gordeeva and Salmenkova 2011). Changes in life cycle and reproduction in odd year populations were larger than the morphological ones. The start of the smolt migration occurred one month later, while the spawning migration happened earlier, resulting in a shorter foraging marine phase in the introduced population compared to the source. However, the introduced individuals were on average equal in size or larger, and hence they grew faster than the individuals in the source area (Gordeeva and Salmenkova 2011, and references therein). The extended freshwater phase in the novel habitats was probably due to later water warming in spring and early decrease in water temperature in fall (Gordeeva and Salmenkova 2011). Introduced pink salmon in Russian rivers also had higher fecundity but lower ovary weight and smaller eggs. The migration-cost hypothesis in salmonids postulates that reproductive investment directly depends on migration distance, and therefore populations with longer migrations generally have smaller eggs (Kinnison *et al.* 2001). If this is true, Gordeeva and Salmenkova (2011) postulated that the migration routes of introduced pink salmon in the North

Atlantic could be longer than those of the source population in the Pacific Ocean. Another example showing differences between introduced and source pink salmon populations come from the Great Lakes, where introduced pink salmon are no longer anadromous and spawn as three years olds (Anas 1959). Overall, there is little knowledge on the introduced pink salmon ecology in the marine phase. Particularly important is the beginning and the end of the marine phase, as pink salmon impact might be strongest in local habitats, as estuaries, fjords, and coastal areas. A key question is whether post-smolt stay inshore for months where they are important prey and predators or whether they are taken by currents rapidly offshore. Communication and collaboration among researches throughout the whole pink salmon distribution is crucial for ensuring knowledge is evenly distributed among all areas where pink salmon may have an impact (NHPSEG 2023). However, pink salmon is not only on the move, but also changing and adapting to the new environments, and thus knowledge might not always be directly applicable in the new introduced areas. Therefore, direct research on pink salmon ecological impact on introduced areas is key, as well as assessing changes in its life history relative to native areas to better understand its invasive potential.

5. References

Anas, R. E. 1959. Three-year-old Pink Salmon. Journal of the Fisheries Research Board of Canada 16, 91–94.

Bengtsson, O., Lydersen, C., Christensen, G., Węsławski, J.M. and Kovacs, K.M. 2023. Marine diets of anadromous Arctic char (*Salvelinus alpinus*) and pink salmon (*Oncorhynchus gorbuscha*) in Svalbard, Norway. Polar Biology 46, 1219–1234.

Clegg, T. and Williams, T. 2020. Monitoring bycatches in Norwegian fisheries — Species registered by the Norwegian Reference Fleet 2015-2018. *Rapport fra havforskningen* 2020.

Diaz Pauli, B., Berntsen, H.H., Thorstad, E.B., Homrum, E.ì, Lusseau, S.M., Wennevik, V. and Utne, K. R. 2023. Geographic distribution, abundance, diet, and body size of invasive pink salmon (*Oncorhynchus gorbuscha*) in the Norwegian and Barents Seas, and in Norwegian rivers. ICES Journal of Marine Science 80, 76–90.

Duffy, E.J. and Beauchamp, D.A. 2008. Seasonal patterns of predation on juvenile Pacific salmon by anadromous cutthroat trout in Puget Sound. Transactions of the American Fisheries Society 137, 165–181.

Erkinaro, J., Orell, P., Kytökorpi, M., Pohjola, J.-P. and Power, M. 2023. Active feeding of downstream migrating juvenile pink salmon (*Oncorhynchus gorbuscha*) revealed in a large Barents Sea River using diet and stable isotope analysis. Journal of Fish Biology, 104, 797-806

FAO, 2023. The state of world fisheries and aquaculture. Sustainability in action. *FAO, Rome*.

Farley, E.V., Murphy, J.M., Cieciel, K., Yasumiishi, E.M., Dunmal, K., Sformo, T. and Rand, P. 2020. Response of pink salmon to climate warming in the northern Bering Sea. Deep-sea research II 177, 104830

Gordeeva, N.V. and Salmenkova, E.A. 2011. Experimental microevolution: transplantation of pink salmon into the European North. Evolutionary Ecology 25, 657–679.

ICES, 2022. Distribution and abundance of pink salmon across the North Atlantic. In *Report of the ICES Advisory Committee, 2022*.

Jacobsen, J.A. and Hansen, L.P. 2001. Feeding habits of wild and escaped farmed Atlantic salmon, *Salmo sal*ar L., in the Northeast Atlantic. ICES Journal of Marine Science 58, 916–933.

Kinnison, M.T., Unwin, M.J., Hendry, A.P. and Quinn, T.P. 2001. Migratory costs and the evolution of egg size andnumber in introduced and indigenous salmon populations. Evolution 55, 1656–1667.

Klemetsen, A., Amundsen, P.-A., Dempson, J.B., Jonsson, B., Jonsson, N., O'Connell, M.F. and Mortensen, E. 2003. Atlantic salmon *Salmo salar*, brown trout *Salmo trutte* and Arctic char *Salvelinus alpinus* (L.): a review of aspects of their life histories. Ecology of Freshwater Fish 12, 1–59.

Maduna, S.N., Aspholm, P.E., Hansen, A.-S.B., Klütsch, C.F.C. and Hagen, S.B. 2024. Ecological niche modelling and population genomics provide insights into the geographic and demographic 'explosion' of a non-indigenous salmonid. Diversity and Distributions 00, 1–20.

NHPSEG 2023. A Review of Pink Salmon in the Pacific, Arctic, and Atlantic Oceans. Technical Report No. 21. North Pacific Anadromous Fish Commission.

NPAFC, North Pacific Anadromous Fish Commission 2023. NPAFC Pacific salmonid hatchery release statistics. North Pacific Anadromous Fish Commission. Available at: https://www.npafc.org [accessed 3 July 2024]

Radchenko, V.I., Beamish, R.J., Heard, W.R. and Temnykh, O.S. 2018. Ocean Ecology of Pink Salmon. In *The Ocean Ecology of Pacific Salmon and Trout* pp. 146. American Fisheries Society: Bethesda (Maryland).

Rikardsen, A.H., Righton, D., Strøm, J.F., Thorstad, E.B., Gargan, P., Sheehan, T., Økland, F., *et al.* 2021. Redefining the oceanic distribution of Atlantic salmon. Scientific Reports 11, 12266.

Ruggerone, G., Springer, A., Van Vliet, G., Connors, B., Irvine, J., Shaul, L., Sloat, M. and Atlas, W. 2023. From diatoms to killer whales: impacts of pink salmon on North Pacific ecosystems. Marine Ecology Progress Series 719, 1–40.

Ruggerone, G.T. and Nielsen, J.L. 2004. Evidence for competitive dominance of pink salmon (*Oncorhynchus gorbuscha*) over other Salmonids in the North Pacific Ocean. Reviews in Fish Biology and Fisheries 14, 371–390.

Sandlund, O.T., Berntsen, H.H., Fiske, P., Kuusela, J., Muladal, R., Niemelä, E., Uglem, I., *et al.* 2019. Pink salmon in Norway: the reluctant invader. Biological Invasions 21, 1033–1054.

Skóra, M.E., Jones, I., Townhill, B., Bean, C.W., Berntsen, H.H., Couce, E., Davies, G.D. and Eliasen, K. 2023. Using stable isotopes to describe pink salmon feeding grounds at sea. In *3rd International Seminar on Pink salmon in the Barents region and in Northern Europe 2023.* Miljødirektoratet/ Norwegian Environment Agency.

SSB 2023. Statistics Norway. www.ssb.no/statbank/table/09243 and 08991.

VKM, Hindar, K., Hole, L.R., Kausrud, K., Malmstrøm, M., Rimstad, E., Robertson, L., Sandlund, O.T., *et al.* 2020. Assessment of the risk to Norwegian biodiversity and aquaculture from pink salmon (*Oncorhynchus gorbuscha*). Norwegian Scientific Committee for Food and Environment (VKM) report 2020:01, Oslo, Norway.