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NASCO	*Pink salmon in rivers: current knowledge, overlap and potential interactions with Atlantic salmon*	Agenda item: 7a)

Pink salmon in rivers: current knowledge, overlap and potential interactions with Atlantic salmon

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Summary

We summarise the current knowledge of and possibilities for interactions between pink salmon and Atlantic salmon in river systems. Pink salmon overlap with Atlantic salmon in timing of river entry and upstream migration of adults, spawning habitats and juvenile habitats, but spawn earlier in the season. Pink salmon can reach and spawn on most river stretches where Atlantic salmon occur. Over the next years and decades, pink salmon has the potential to substantially spread and increase in abundance within the distribution range of Atlantic salmon in the north Atlantic region.

Threats to Atlantic salmon from pink salmon are:

1) Competition for space, out crowding and aggressive attacks from adult pink salmon during the upstream migration and spawning – which may lead to migration delays, altered behaviour, and altered distribution of adult Atlantic salmon.
2) Competition for food and space between juvenile pink salmon and Atlantic salmon which could cause reduced growth and survival of Atlantic salmon.
3) Deteriorated water quality due to decomposition of dead pink salmon after spawning – which may cause eutrophication and hypoxia in existing nutrient rich rivers and increased river productivity with uncertain outcomes for Atlantic salmon in nutrient-poor rivers.

The impact of pink salmon on Atlantic salmon in rivers depends on their abundance and thousands of pink salmon will likely have a large impact. We now know that pink salmon do occur in very large numbers in many rivers in northwest Russia and northern Norway, and the possibility for interactions between these species in freshwater is large. However, there are huge knowledge gaps regarding the impacts of pink salmon on Atlantic salmon in rivers. Research is urgently needed to fill in these gaps and understand the role and potential future impacts of pink salmon and to what level subsequent migration measures might be employed.

Introduction

Pink salmon is an invasive species to areas in and around the Barents Sea and North Atlantic Ocean. They spread to this region after repeated, intentional introductions to north-west Russia, beginning in the 1950s. They are native to the north Pacific area and like most Pacific salmon, they die after the first spawning season. Pink salmon usually have a strict 2-year life cycle (figure 1), with some rare exceptions. They spawn in rivers in late summer and early autumn, and the eggs hatch in winter or spring. Then pink salmon migrate to the sea as smolts in the spring or early summer the same year as they hatch, when they are approx. 3-6 cm long. They spend about one to one and a half years feeding at sea and return to the rivers in the summer usually as 0.5-3 kg adult fish.

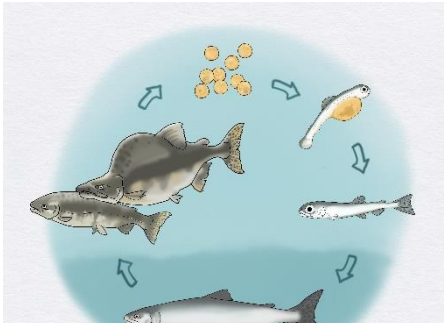

Figure 1. *Pink salmon life cycle. Illustration: Sigrid Skoglund, ©Norwegian Institute for Nature Research*

After some weeks in the river, they spawn and die. Hence spawners one year will be the parents of spawners two years later.

Pink salmon is the most abundant Pacific salmon in their native range, with some populations constituting hundreds of thousands of fish (Heard 1991) and is thus a much more numerous species than Atlantic salmon. In northwest Russia and northern Norway, many rivers now receive thousands of adult pink salmon in odd years (figure 2), outnumbering, by far, the spawners of Atlantic salmon. Pink salmon overlap in time and space with Atlantic salmon in the rivers both during the spawning migration and juvenile phase. The possibility for interactions between pink salmon and Atlantic salmon in freshwater environments is therefore large.

Figure 2. *Pink salmon occur in large numbers in some rivers in Northern Europe. Photo: Malin Solheim Høstmark ©County Governor of Troms and Finnmark.*

Here we summarise the current knowledge of and possibilities for interactions between pink salmon and Atlantic salmon during different stages of the freshwater phase. We begin with the upstream migration of adult salmon in rivers and follow the life cycle through spawning and the juvenile phase until they leave the rivers and enter the sea.

Upstream migration of adults

In the Barents Sea and North Atlantic Ocean region, pink salmon usually enter rivers and migrate upstream in July and during the first half of August, but some enter rivers as late as September (Prusov & Zubchenko 2021, Sandlund *et al.* 2019, Norwegian Environment Agency 2024). So far, at least in Norway, there seems to be no north-south pattern in the seasonal timing of river ascent (Diaz Pauli *et al*. 2023).

Pink salmon can exhibit short upriver migrations and even spawn in the intertidal zones of rivers (Scott & Crossman 1973, Hanavan & Skud 1954, May et al. 2023). However, they can also migrate long-distances upstream, up to several hundred kilometres (Heard 1991). For example, in the Fraser River in Canada, pink salmon must negotiate several reaches with rapids and steep gradients before reaching spawning sites (Crossin *et al*. 2003). Hence, pink salmon would be expected to pass an array of challenging river reaches in the shorter and often less steep Atlantic rivers (Lennox *et al*. 2023). In northwest Russia, pink salmon migrate more than 300 km upstream in the Ponoy and Tanya rivers, and in Norway/Finland, pink salmon have been encountered > 200 km upriver from the sea in the Tana/Teno river system (Bakshtansky 1980, Niemelä *et al*. 2016). Introduced pink salmon may gradually occupy more remote spawning grounds as the abundance increases over time (Veselov *et al*. 2016), which has indeed been the case in some Norwegian rivers.

Adult pink salmon have been regarded as relatively poor swimmers (Heard, 1991) but are, as pointed out by Lennox *et al*. (2023), in fact strong and energetically efficient swimmers that can attain instantaneous swim speeds of 1.5-2 m/s (Standen *et al*. 2002, Crossin *et al*. 2003). Pink salmon is also the superior species of Pacific salmon in terms of adults' aerobic scope and thermal tolerance (Clark *et al*. 2011). Clark *et al*. (2011) found the optimal aerobic scope at 21 °C and pointed out that this may confer a selective advantage over other species when river temperatures increase with climate change.

In the weeks before spawning, there may be negative interactions between adult pink salmon and Atlantic salmon in rivers, particularly when pink salmon occur in high densities. Most Atlantic salmon enter the rivers during the same period as pink salmon (VRL 2023, Klemetsen *et al*. 2003), but in some areas, for instance in Scotland, Atlantic salmon enter rivers all year round. According to anecdotal observations, pink salmon and Atlantic salmon have been observed swimming together in rivers seemingly undisturbed; nonetheless, agonistic behaviours from pink salmon towards Atlantic salmon can occur (figure 3, Veselov & Zyuganov 2016, Frøiland *et al*. 2024). The presence of high densities of pink salmon may in itself lead to Atlantic salmon altering behaviour and habitat use. For instance, in some cases, hundreds and thousands of pink salmon gathered below traps aimed at removing pink salmon in the lower parts of rivers in Norway in 2023. People operating the traps reported that Atlantic salmon were delayed in the river mouths downstream of the pink salmon and did not move further upstream before the pink salmon were removed (Frøiland *et al*. 2024). This indicates that Atlantic salmon are reluctant to enter areas with high densities of pink salmon, which has also been observed by Veselov & Zyuganov (2016).

Figure 3. *There may be negative interactions between adult pink salmon and Atlantic salmon in the rivers, particularly when pink salmon occur in high densities. Photo shows an Atlantic salmon (left) outside a group of pink salmon in a river in northern Norway. Photo: Malin Solheim Høstmark ©County Governor of Troms and Finnmark.*

Atlantic salmon usually hold position in the river close to their spawning area up to several weeks or even months before spawning (Økland *et al*. 2001, Thorstad *et al*. 2008). Atlantic salmon may be disturbed and stressed, and perhaps crowded out from their normal holding areas, if large numbers of pink salmon are present during this period (Hindar *et al*. 2020). Pink salmon can be aggressive at their spawning sites and have been reported to attack Atlantic salmon at these sites (Veselov & Zyuganov 2016). The result of this agonistic behaviour by pink salmon could cause Atlantic salmon to move to river sections less suitable as holding areas prior to, and during, spawning.

Studies of the interaction between pink salmon and Atlantic salmon during the upstream migration in rivers are largely lacking. A Norwegian risk assessment (Hindar *et al*. 2020) nevertheless concluded that agonistic behaviour by pink salmon in the weeks before the spawning period of native salmonids is likely to occur in rivers with pink salmon. They further

concluded that it is likely, with high confidence, that pink salmon will compete with native salmonids for space in the river in the weeks before and during the pink salmon spawning.

Spawning

Pink salmon spawn in both main rivers and tributaries. Spawning by pink salmon in the Barents Sea and North Atlantic Ocean region generally occurs in August, but there are also reports of spawning in September. This means that pink salmon usually spawn earlier than Atlantic salmon and brown trout, but there may be overlap between the latest spawners of pink salmon and the earliest spawners of particularly Arctic char, but also brown trout in northern Norway (Hindar *et al*. 2020). However, there are also some reports of spawning pink salmon as late as October in northwest Russia (Bakshtansky 1980, Efremov 2021, Prusov & Zubchenko 2021), which would overlap with the spawning period of Atlantic salmon in many areas. Efremov (2021) suggested that the spawning migration of pink salmon has been extended since 2017, and that late entering pink salmon spawning together with Atlantic salmon can have negative consequences for Atlantic salmon.

Like Atlantic salmon, pink salmon females dig nests in the riverbed, called redds, where the eggs are laid and then covered by gravel. Pink salmon aggressively defend their redds before, during, and for some days after spawning until they are too weak and die (Scott & Crossman 1973).

Figure 4. *Pink salmon and Atlantic salmon can spawn in the same area. Photo shows eggs and one-year old Atlantic salmon juveniles and pink salmon smolts caught at the same site. Photo: ©Rune Muladal, Naturtjenester i nord.*

The habitat requirements for spawning are very similar between pink salmon and Atlantic salmon; both species prefer to spawn in areas with coarse gravel with a flow through of aerated water. Pink salmon sometimes tend to spawn closer to riverbanks, in shallower water, and in finer substrate than Atlantic salmon. However, there are also observations of common spawning areas between Atlantic salmon and pink salmon in several rivers in Norway and Russia (figure 4, Alekseev *et al*. 2019, Anon. 2022, Kanstad Hanssen & Monsen 2022, Muladal & Fagard 2020, 2022, Sørvik 2022, Vistnes 2017), which can lead to redd superimposition for pink salmon. There are several records of pink salmon juveniles together with eggs of Atlantic salmon, with pink salmon seemingly having a high survival even though the Atlantic salmon must have spawned in the same redd after the pink salmon have spawned (Kanstad Hanssen & Monsen 2022, Muladal & og Fagard 2020, Muladal & Fagard 2022). Lennox *et al*. (2023) concluded that it is not clear whether the superimposition of late-spawned Atlantic salmon redds over earlier spawned pink salmon redds will have a negative effect on the ability of pink salmon to colonize new watersheds. Bakshtansky (1980) suggested that spawning pink salmon could have a beneficial effect on the gravel, clearing it of silt and organic material, to the benefit of Atlantic salmon spawning later in the autumn. On the other hand, there are worries that extensive digging activity by large numbers of pink salmon will cause mortality of freshwater pearl mussels living in this habitat (Veselov & Zyuganov 2016).

Hybridization between pink salmon and Atlantic salmon has not been documented in the wild, and in the laboratory, pink salmon crossed with Atlantic salmon have only produced sterile offspring (Devlin *et al*. 2022, reviewed by Hindar *et al*. 2020 and Lennox *et al*. 2023). Hybridization between pink salmon and Atlantic salmon is not expected, but also cannot be excluded (Hindar *et al*. 2020).

Death of spawners

After they die, decomposing pink salmon (figure 5) affect the water quality of rivers. Pink salmon gain most of their body mass at sea but die naturally in rivers, which leads to the transport of organic matter and nutrients from marine to freshwater environments. Dead and decomposing pink salmon are utilized by all types of scavengers and may therefore affect both freshwater and terrestrial food webs and biodiversity (Cederholm *et al*. 1999, Dunlop *et al*. 2021a).

Figure 5. *Decomposing pink salmon affect water quality of rivers. Photo: Eva B. Thorstad, Norwegian Institute for Nature Research.*

In nutrient-rich rivers, excess nutrients and increased oxygen demand resulting from decomposition of pink salmon may result in hypoxia and negative consequences for the river ecosystems by eutrophication. In nutrient-poor rivers, extra nutrients lead to increased productivity, which may eventually enhance the growth of juvenile Atlantic salmon. The outcome of enhanced juvenile growth for individuals and populations of Atlantic salmon is uncertain, and whether this may be regarded as positive or negative for population growth may vary among populations and needs to be investigated. The worst-case scenario is that Atlantic salmon smoltify at an earlier age and size, which may lead to lower marine survival in Atlantic salmon (e.g. Gregory *et al*. 2018, 2019). The impacts of dead and decomposing pink salmon on water quality and ecosystems likely depend on the number of pink salmon, river morphology and current nutrient status of the river (Hindar *et al*. 2020). Alekseev *et al*. (2019) pointed out that for acidified and cold-water rivers in northwest Russia, river eutrophication is connected to the slower decomposition of dead fish than in warmer rivers in the Pacific, and that the fauna of microorganisms, invertebrate detritivores, and vertebrate scavengers is poor in these northern rivers.

From hatching to juveniles leaving the rivers

Pink salmon eggs hatch during winter or early spring depending on timing of spawning and river temperature. The alevins stay in the gravel until the yolk sac has been absorbed, and when they are approx. 30 mm long, they are saltwater tolerant and can swim up from the gravel. In their native range, they are commonly known to immediately migrate to sea before they start feeding. Though some feeding on nymphal and larval insects may occur in some rivers where there is a long migration distance to the sea (Scott & Crossman 1973) or where they migrate through lakes (Robins *et al*. 2005).

It may seem more common that pink salmon smolts start feeding and remain in the rivers for some weeks or months before migrating out to sea in the Barents and Atlantic region than in their native range, but this is not well studied. However, several studies from northwest Russia,

Norway, Finland, and Iceland have reported that smolts caught in different rivers have been feeding (figure 6, Bakshtansky 1980, Veselov *et al*. 2016, Sandlund *et al*. 2019, Erkinaro *et al*. 2024, Skóra *et al*. 2024). Food items reported from these studies were cyclopoid copepods, and larvae and pupae of Chironomidae, Simuliidae and Ephemeroptera. Also, smolts caught in Scottish rivers were assumed to have been feeding based on the length of time they had spent in the rivers (Skóra *et al*. 2023). Pink salmon juveniles may even start eating copepods and early instar chironomid larvae while some yolk remains (Veselov *et al*. 2016, Sandlund *et al*. 2019). Veselov *et al*. (2016) found that, in the Russian Kola Peninsula, late captured smolts (June) were a couple of cm longer (total length 4.4-4.8 cm) than the smallest early migrating smolts (May), and that 84 % of the early captured smolts and 100 % of the late captured smolts had food in their stomachs. They pointed out that greater abundance of late migrants of pink salmon smolts may cause competition for food resources with native fish species. More recently, Erkinaro *et al*. (2024) concluded that the active freshwater feeding of non-native juvenile pink salmon suggests potential resource competition with native fluvial fishes, particularly salmonids.

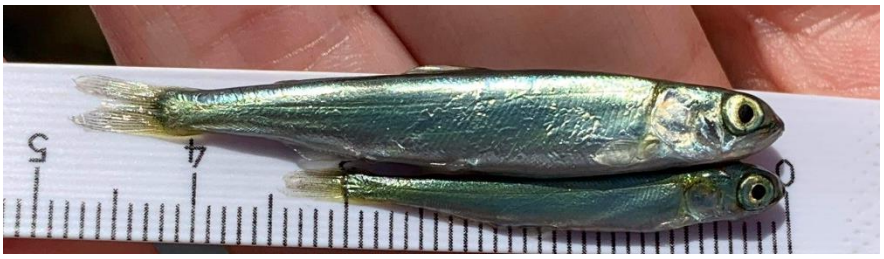

Figure 6. *Pink salmon juveniles caught in a river in northern Norway, showing the size (cm) of a newly hatched juvenile (under) and one that has been feeding in the river (above). Photo ©Håvard Vistnes.*

Hindar *et al*. (2020) concluded that pink salmon juveniles and smolts impact juveniles of native salmonids in the Barents and Atlantic regions through competition for food and space and the invertebrate fauna through predation (Hindar *et al*. 2020). The impact depends on pink salmon densities and on the duration of their stay in the rivers. Fry densities of 0.1 to 589 per square meter (average 250) have been observed in stream sections consistently favoured by spawning Pacific salmon (Bailey *et al*. 1975). Availability of spaces to hide among the gravel is important both for pink salmon and Atlantic salmon, and competition for space in terms of a safe place to feed and hide may occur. Hence, competition for space may impact Atlantic salmon negatively when high densities of pink salmon occur, but this has not been well studied.

Eggs and juveniles of pink salmon may be a food source for Atlantic salmon. Dunlop *et al*. (2021b) found that although egg foraging and assimilation of marine-derived nutrients in fish body tissues were minor at the population level, a few juvenile Atlantic salmon and trout had eaten large quantities of pink salmon eggs. There have also been anecdotal observations of individual Atlantic salmon eating pink salmon smolts (Sandlund *et al*. 2019).

More research is needed to understand the ecological implications of pink salmon in rivers in the North Atlantic Ocean and Barents Sea region during the juvenile and smolt stage.

Conclusion

In rivers, the threats to Atlantic salmon from pink salmon are through: 1) competition for space, out crowding and aggressive attacks from pink salmon during the upstream migration and until the pink salmon spawning is over – which may lead to migration delays, altered behaviour and altered distribution of adult Atlantic salmon; 2) competition for food and space between juveniles of pink salmon and Atlantic salmon, which may lead to reduced growth and survival of Atlantic salmon, and; 3) deteriorated water quality due to decomposition of dead pink salmon after spawning – which may lead to eutrophication and hypoxia in already nutrient-rich rivers.

In addition, should pink salmon evolve towards a later spawning period, this may lead to direct interactions between pink salmon and early spawners of Atlantic salmon at spawning grounds. Pink salmon eggs and juveniles can be eaten by Atlantic salmon, but it is unknown if this can serve as an important food source and have any population-level consequences for Atlantic salmon.

The impact of pink salmon on Atlantic salmon in rivers depends on their abundance, where a few pink salmon will likely have minor impacts, but thousands of pink salmon will likely have a large impact. We now know that pink salmon do occur in very large numbers in many rivers in northwest Russia and northern Norway. Pink salmon have the potential to reach and spawn on most river stretches where Atlantic salmon occur around the North Atlantic, and they can, in addition, reproduce in intertidal areas in river mouths. Pink salmon may be a climate winner in temperate and sub-Arctic regions. With a short life, they can adapt quickly to new conditions, as seen after the introduction in the Great Lakes in North America. Over the next years and decades, pink salmon has the potential to substantially spread and increase in abundance within the distribution range of Atlantic salmon in the North Atlantic.

As an additional note, recreational anglers in Norway have reported widespread dislike of invasive pink salmon (Guay *et al*. 2024). If pink salmon come to dominate the number of salmonids in rivers, this will likely also negatively affect the economic value and ecosystem services of Atlantic salmon angling in rivers (Hindar *et al*. 2020).

In conclusion, the possibility for interactions between pink salmon and Atlantic salmon in freshwater is large. However, there are huge knowledge gaps regarding the impacts of pink salmon on Atlantic salmon in rivers, because very few studies have been so far conducted. New research is needed to understand the role and potential future impacts of pink salmon and which level of mitigation measures are subsequently needed.

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