

Invading and range-expanding pink salmon inform management actions for marine species on the move

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Abstract

Species redistributions, whether resulting from invasions or range expansions, pose similar challenges for conservation and management. Redistribution impacts on host ecosystems and species combine with those from climate change, which are already acute at northern latitudes. Using pink salmon *Oncorhynchus gorbuscha*, which are native to the Pacific Ocean, we employ knowledge exchange to inform decision-making in non-native marine areas: they are expanding their range to the Arctic Ocean and are invasive in the Atlantic Ocean. The predicted future marine distribution of pink salmon focuses effort on where and when pink salmon are present and informs on potential interactions with native species. Management actions taken in the Atlantic Ocean to reduce invasive pink salmon are resource-intensive, but removed salmon could be a food resource. Addressing identified gaps regarding the invasion potential of pink salmon, interactions among pink salmon and other species, and current mitigation efforts would support forward-thinking management decisions given predictions of continued environmental change. We also highlight steps that can be taken immediately to coordinate actions and better inform responses. Managed for production in the Pacific and as an invasion in the Atlantic, pink salmon provide a tangible approach to informed decision-making through collaboration for marine species on the move.

Keywords: range-expanding; management; Arctic; Atlantic; pink salmon; climate change; distribution shift; invasive species

Introduction

Range-expanding and invasive species, while often perceived differently, can pose similar management and conservation challenges (Wallingford et al. 2020). Commonly termed “species” despite movement occurring at the population level, range-expanding species track thermal niches into previously unoccupied regions (Eigentler et al. 2022), whereas invasive species are introduced outside their native range (Essl et al. 2020). As range-expanding species are essentially preserving themselves, they can be considered a benefit to biodiversity (Hodgson et al. 2009), although such impacts are rarely studied (Wallingford et al. 2020). By contrast, the focus on invasive species is often on potential impacts on host communities (Wallingford et al. 2020). The mechanism and magnitude of impacts for range-expanding and invasive species, however,

can be similar (Sorte et al. 2010, Wallingford et al. 2020) and are cumulative to the impacts of climate change and other stressors for host species and ecosystems. In the oceans, range-expanding and invasive species may become increasingly intertwined as climate change influences both global species distributions (Poloczanska et al. 2013) and the extent of species invasions via the expansion of global shipping (Sardain et al. 2019). This may be particularly acute for the Arctic, where an accelerated rate of warming (Rantanen et al. 2022) is influencing distributional shifts of many marine species (Mueter et al. 2021, Alabia et al. 2023), and where range expansions raise concerns due to potential impacts on native species and fishing (Chila et al. 2022). This convergence of disciplines, species, and perceptions provides an opportunity for scientific collaboration that will add to our rudimentary understandings of the

complex processes underpinning species redistributions and their ecological consequences (Wright et al. 2023).

Pink salmon *Oncorhynchus gorbuscha* provide a tangible epitome of this convergence and an opportunity to focus informed understandings that can guide future action. This species is natal to the Pacific Ocean but is currently spreading into the Arctic Ocean via range expansions from native distributions (NHPSEG 2023, Dunmall and Langan et al. 2024) and the Arctic and Atlantic oceans from an intentionally introduced, non-native population in northwest Russia (Lennox et al. 2023). In their Pacific distribution, where species management focuses on production (both natural- and hatchery-based) of genetically isolated even- and the more abundant odd-year broodlines (Irvine et al. 2014), overall abundance has reached record high levels (Ruggerone et al. 2023). Interestingly, even-year populations may be better suited for cooler conditions than odd-year populations, at least in the Pacific (Beacham and Murray 1988). In the eastern Pacific Ocean, odd- and even-year spawning populations abundance dynamics change with latitude, with odd-year populations tending to be dominant in more southern areas and even-year populations more dominant in northern locations. Odd-year populations in the Pacific may benefit most from warming waters (Irvine et al. 2014), including at the northern edge of their range where warming facilitates improved freshwater survival (Farley et al. 2020) and expansion into the Canadian and Russian Arctic (Radchenko et al. 2018, Dunmall et al. 2021, Dunmall and Langan et al. 2024). The southern extent of pink salmon spawning has potentially shifted north in the last century; persistent populations are no longer seen on the coast of Washington State or southward, though historical records of such populations exist (Hard et al. 1996).

Pink salmon are also invading the Barents Sea and Atlantic Ocean across Europe and into eastern North America from the introduced Russian source population (Gordeeva and Salmenkova 2011, NHPSEG 2023). In Europe, and especially in Russia, Norway, and Finland, the numbers of pink salmon present in rivers in odd-numbered years has increased rapidly since 2013, with surprisingly large increases with every subsequent generation beginning in 2015 (ICES 2022, Diaz Pauli et al. 2023, ICES 2024). Successful spawning has now been documented in Norway (Sægrov et al. 2022, Lennox et al. 2023, NHPSEG 2023), northern Finland (Erkinaro et al. 2022, 2024), northern Scotland (Skóra et al. 2023), and western Iceland (Skóra et al. 2024). In northern Norway, the abundance of pink salmon far outnumbered native Atlantic salmon *Salmo salar* in 2021 and likely also in 2023 (Berntsen et al. 2022, Norwegian Scientific Advisory Committee for Atlantic Salmon 2023b, Frøiland et al. 2024). Indeed, management of pink salmon in Norway is designed to keep their abundance as low as possible out of concern for the threats they pose to native salmon and ecosystems (Hindar et al. 2020).

Pink salmon have several attributes that make them successful colonizers (Pess et al. 2012), and their rapid range expansions emphasize their adaptive potential. The high relative abundance of pink salmon and a 10% straying rate in wild populations (Heard 1991) combined with short freshwater residency and generation times (Myers et al. 1995, Hendry et al. 2004, Krkošek et al. 2011) allow pink salmon to access, establish, and adapt quickly to new environments. This straying rate is even higher for pink salmon spawning in the intertidal (Thedinga et al. 2000). There are numerous historical examples of successful pink salmon introductions (NHPSEG 2023),

which further serve to emphasize the adaptive potential of the species. For instance, all five Laurentian Great Lakes were colonized by pink salmon within 23 years (12 generations) of an accidental introduction into Lake Superior in 1956 (Nunan 1967, Collins 1975, Emery 1981). Within 18 years (9 generations) in these freshwater ecosystems, some pink salmon in the Great Lakes began spawning as 3-year-olds (Kwain and Chappel 1978, Wagner 1978, Wagner and Stauffer 1982) as a potential response to cold temperatures and/or low productivity (Bagdovitz et al. 1986), a major deviation from their usual 2-year and saltwater-dependent life history. In the time since their introduction, these pink salmon have been reported to be spawning at any time between 1 and 4 years of age (Kwain and Kerr 1984, Kennedy et al. 2005). Pink salmon in the Great Lakes had low genetic diversity following the introduction but exhibited rapid genetic adaptations, which made them physiologically better suited to their new environment (Sparks 2023). Similarly, established odd-year pink salmon stocks in their introduced range in northwest Russia have been documented to display adaptive changes compared to their source population, including shifts in genetic character, phenological adaptations, altered morphology, and increased body weight and fecundity (Gordeeva et al. 2005, Gordeeva and Salmenkova 2011). Taken together, this evidence suggests that pink salmon are well-suited to colonizing new habitats both within and outside their native range.

Despite their potential as colonizers and history of successful introductions, it is only recently that global concern about the impacts of pink salmon on species and ecosystems has greatly increased. In the North Pacific Ocean, during recent years of naturally higher pink salmon abundances that were amplified by industrial-scale hatchery releases, there has been evidence of widespread impacts of pink salmon on other salmon species and top-down effects of pink salmon on numerous pelagic species, food webs, and ecosystem function (Ruggerone et al. 2023). On the Alaskan North Slope, where several species of range-expanding Pacific salmon are slowly becoming a subsistence resource, negative perceptions of pink salmon were focused on their presence as a pest or nuisance as an undesired species rather than concern for their potential impacts on desired species (Carothers et al. 2019). In the western Canadian Arctic, however, salmon are considered a threat to Arctic fish and traditional fishing practices, with specific concern about the potential transfer of parasites to Arctic fish and an association of an increase in observations of wounds on Arctic fish in years of higher salmon presence (Chila et al. 2022). In the Atlantic, pink salmon have been assessed as a very high-risk invasive species in Norway and moderate to high risk in the United Kingdom in terms of negative impacts on biodiversity (Cowx 2019, Hindar et al. 2020, Bean 2023, Norwegian Biodiversity Information Centre 2024), and as a large threat to Atlantic salmon and sea trout (anadromous brown trout *Salmo trutta*) (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a,b). People in the most affected areas in Norway have demanded resources to mitigate what they perceive as a major deterioration of ecosystem services provided by the fishing of highly valued native species (Guay et al. 2023). Indeed, Lennox et al. (2023) reviewed information on threats by non-native pink salmon in the Atlantic and Arctic oceans and concluded that the invasion of pink salmon has the potential to become one of the most consequential biological invasions to ever affect North Atlantic marine ecosystems. In the Pacific, Ruggerone

et al. (2023) hypothesized that increases in pink salmon and warming ocean temperatures will enhance competition among marine species and lead to the decline of all salmon species. Regardless of their origin (natural, hatchery, range-expanding, or invasive), pink salmon are benefitting from warming temperatures, and their successful expansion to non-native habitats requires that we draw from current knowledge to inform management and conservation action amidst rapid change.

Recognizing that knowledge exchange could accelerate understanding and support informed action, the International Year of the Salmon gathered experts together from the Pacific, Arctic, and Atlantic oceans to discuss pink salmon on the move (NHPSEG 2023). Participants summarized the current state of scientific knowledge regarding pink salmon abundance, range expansions, and introductions across three ocean basins to provide a foundation that emphasized immediate action and continued, coordinated collaborations (NHPSEG 2023). Building from those outcomes, our goal here is to focus on actions and planning needed to provide the information required to assess potential impacts and guide management decisions for range-expanding and invasive species in non-natal areas outside the Pacific Ocean. To accomplish this, we begin by predicting the response of pink salmon to continued warming from the perspective of future marine distribution. We then review management actions taken in the Atlantic Ocean to monitor and reduce invasive pink salmon, and discuss the related potential for developing non-native pink salmon as a food resource. Using that knowledge, we highlight what we need to know to guide future management actions and identify steps that can be taken immediately to better inform responses. Drawing from multiple disciplines and the breadth of available scientific knowledge, we provide an approach to facilitate international exchange that promotes action and informs decision-making regarding the adaptive management of range-expanding and invasive pink salmon in the circumpolar Arctic. Using knowledge exchange as a platform to launch coordinated action regarding pink salmon highlights an efficient approach that could be broadly applied to inform our understandings regarding the global redistribution of species.

What is the future marine distribution for pink salmon?

Pink salmon appear to be benefitting from a warming ocean (Irvine et al. 2014, Hindar et al. 2020, Ruggerone et al. 2023), and their future marine distribution may be predicted based on projected locations of thermally suitable marine habitats (Langan et al. 2024; Dunmall and Langan et al. 2024). This information will help focus management and conservation actions to better adapt to the spatial and temporal changes in locations where pink salmon are present in the marine environment, where to focus freshwater efforts to better understand habitat suitability, and to provide increased knowledge on interactions with native species.

Pacific Ocean

Substantial catch monitoring efforts across the North Pacific (1952–Present; <https://npafc.org/>) have demonstrated an irregular distribution of pink salmon across space and time. However, the southern extent of available suitable pink

salmon marine thermal habitat likely contracted northward during recent warm periods compared to historical conditions (Langan et al. 2024). If so, this would imply that the equatorward edge of pink salmon marine thermal habitat may continue to shift poleward under future climate change, potentially exacerbating inter- and intraspecific trophic interactions at sea (Ruggerone et al. 2023, Connors et al. 2024). At their northern distribution limit, recent trends and forecasts by climate models clearly indicate that future summers will exhibit a longer, warmer, ice-free season in the Pacific Arctic (Danielson et al. 2020, Thoman et al. 2020, Crawford et al. 2021, Walsh et al. 2022), which could result in increased opportunities for range expansion. Although many agree continued expansion is likely, the existence of robust spawning populations of pink salmon in the North American Arctic is still debated (Nielsen et al. 2013). Their ultimate establishment will depend upon successful completion of their life cycle in Arctic drainages, which may be limited by thermal tolerances during early life history stages (Dunmall et al. 2016) and access to suitable marine overwintering habitats, which may involve migrating to the Bering Sea as juveniles (Irvine et al. 2009). The recent capture of a juvenile chum salmon in the coastal Beaufort Sea extended the successful spawning distribution of chum salmon northward to the North American Arctic (Dunmall et al. 2022), implying it may be possible for pink salmon to similarly establish spawning populations during their northward expansion.

Atlantic Ocean

In the Atlantic Ocean, the extent of pink salmon expansion will likely depend on marine thermal habitat suitability, which facilitates the ability of pink salmon to access new areas. When temperature preferences associated with pink salmon distribution in the Pacific (as estimated by Langan et al. 2024) are applied in the North Atlantic, reports of pink salmon occurrences coincide with areas of predicted marine habitat suitability (Fig. 1). This pattern persists even when accounting for interannual differences in marine habitat suitability: decreased reports of pink salmon in southern locations coincided with a decrease in thermally suitable locations in 2023 when compared to 2021, when thermal conditions were more suitable and pink salmon more evident (ICES 2024) (Fig. 2). At a finer scale, these patterns also apply to the ocean region in the western Norwegian Sea, which has generally become more thermally suitable throughout the spring and summer in recent years (Fig. 3). It is likely that pink salmon are taking advantage of this productive feeding area (Diaz Pauli et al. 2023) and following the same migration routes as Atlantic salmon (Rikardsen et al. 2021) toward a range of European countries. Similarly, the number of pink salmon in rivers draining into the Barents or White sea has increased rapidly, and increased water temperatures in the Barents Sea have been correlated with the number of pink salmon returning to rivers in this region (Hindar et al. 2020, Lennox et al. 2023).

Marine thermal habitat suitability can also be used to anticipate the spread of pink salmon. Monthly patterns of suitable marine habitats, focused on the timing of river entry for pink salmon in the Atlantic (Nielsen et al. 2020, Staveley and Ahlbeck Bergendahl 2022, Lennox et al. 2023, Skóra et al. 2023), fit with reported rapid increases in pink salmon abundance in rivers and coastal areas in Scotland (Armstrong et al.

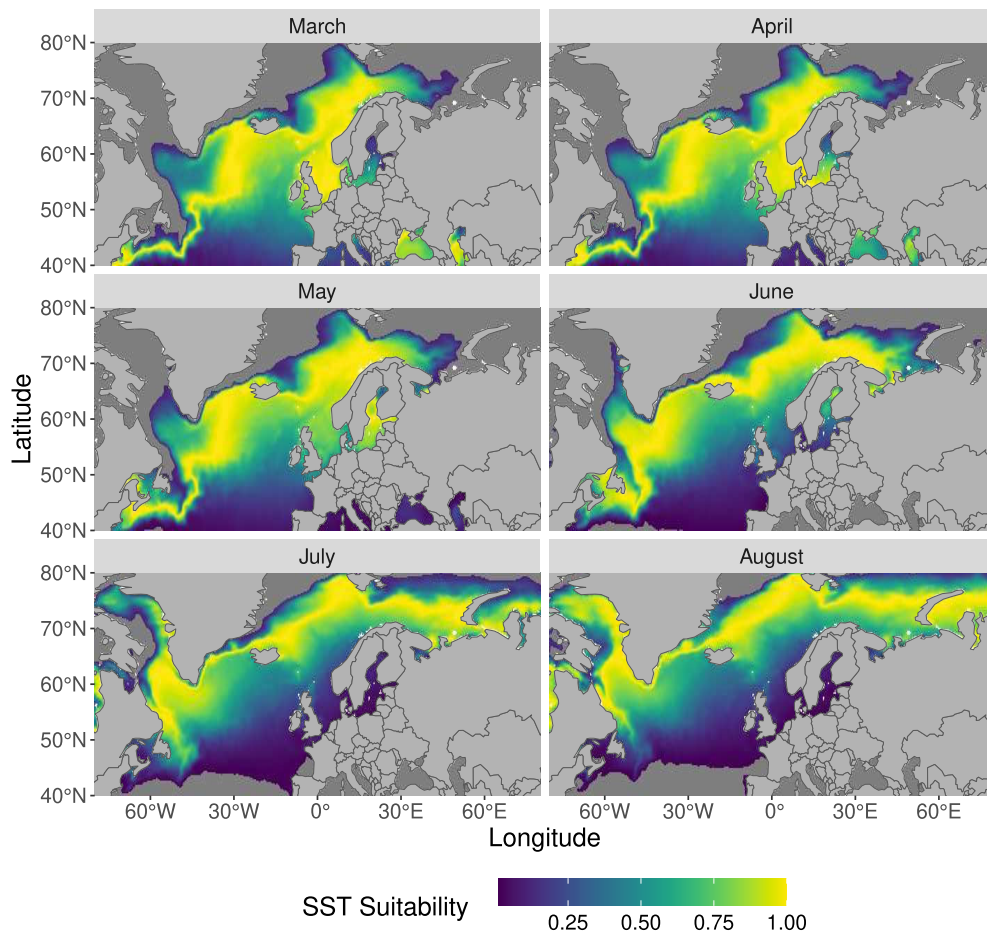


Figure 1. Patterns of mean suitable thermal habitat by month for pink salmon in the North Atlantic during 2014–2023. The April–August temperature preference curve for maturing adult odd-year pink salmon estimated by Langan *et al.* (2024) was applied to monthly mean sea surface temperatures and scaled to [0,1] as a measure of relative suitability. Temperatures outside the range at which pink salmon have been observed at sea in the Pacific in even and odd years [1.0°C, 19.4°C] are depicted in gray. Sea surface temperature data were obtained from the NOAA Optimum Interpolation Sea Surface Temperature Version 2 High Resolution Data Product (Huang *et al.* 2021).

2018), Iceland (Skóra *et al.* 2023), and Greenland (Nielsen *et al.* 2020) (Fig. 1). These monthly thermal suitability patterns, coupled with rising reported catches along the west coast of Sweden (Staveley and Bergendahl 2022), also suggest that pink salmon could enter the Baltic Sea and ultimately spawn in rivers at the northern end of the basin if they could adapt to the low salinity and other habitat conditions of the Baltic Sea. Similarly, high marine thermal suitability during late spring (Fig. 1) throughout Atlantic Canada and into the northern Gulf of Maine indicates that these areas could be vulnerable to colonization by pink salmon as well. Future warming due to climate change may also yield new spawning habitats in areas such as Svalbard and Wrangel Island, where pink salmon are currently found in highly suitable marine waters but are unable to successfully reproduce due to harsh winter stream conditions (Fig. 1, Bengtsson *et al.* 2023, <https://www.tsuren.ru/news/ostrov-vrangelya/>). In contrast, the summer thermal habitat in the Northeast Atlantic south of $\sim 60^\circ$ N was less suitable (i.e., warmer than optimal) for pink salmon in 2014–2023 compared to 1990–1999 (Fig. 3). If temperatures continue to increase, and spawning phenology remains similar to what has been observed thus far, pink salmon preference for summer habitats in

European waters south of Norway will likely decline and thereby serve to partially constrain the southern limit of pink salmon.

Marine habitat suitability also influences the range expansion of pink salmon by impacting the survival and growth of juveniles. For instance, the recent increased pink salmon abundance in Norway and Russia, near the source population in northwestern Russia, may be related to increasing ocean temperatures where juveniles enter the marine environment (Hindar *et al.* 2020, Lennox *et al.* 2023). Increased survival during this marine phase, when juvenile pink salmon are close to the coast, may be critical, as it can be the period of highest marine mortality for pink salmon (Radchenko 2012). When comparing 1990–2000 (the end of the Russian odd-year stocking program, Niemelä *et al.* 2016, NH-PSEG 2023) to 2014–2023, spring temperatures along the Kola Peninsula and Norwegian coast have become more suitable in May and June, the time juvenile pink salmon are likely entering the ocean in this region (Fig. 3, Lennox *et al.* 2023). Once offshore, a positive correlation between sea surface temperature and growth of juveniles in the northern Bering Sea has also been documented (Andrews *et al.* 2009, Farley *et al.* 2009, Wechter *et al.* 2017). Marine habitat suitability may

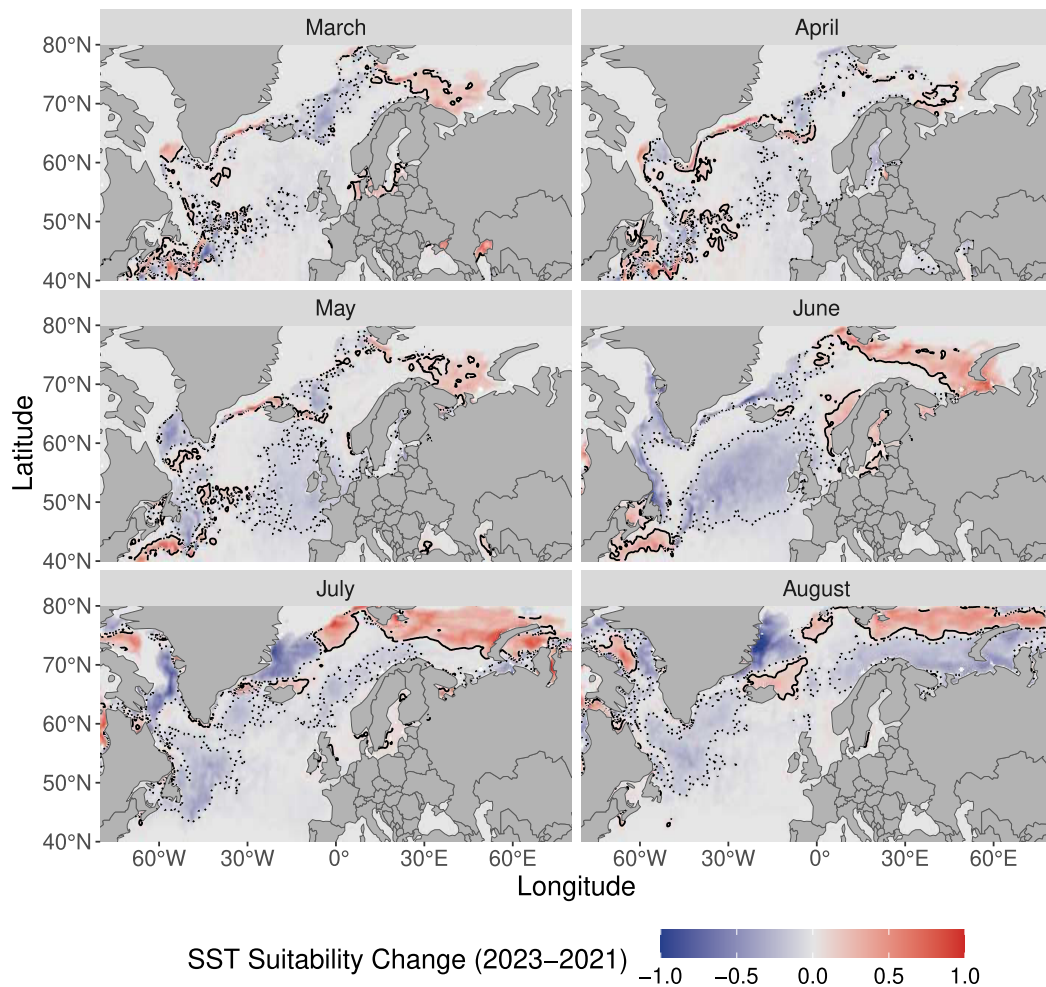


Figure 2. The difference in estimated pink salmon mean thermal suitability patterns between 2023 and 2021. The April–August temperature preference curve for maturing adult odd-year pink salmon estimated by Langan et al. (2024) was applied to monthly mean sea surface temperatures and scaled to [0,1] as a measure of relative suitability. Temperatures outside the range at which pink salmon have been observed at sea in the Pacific in even and odd years [1.0°C, 19.4°C] were set to a suitability of 0 prior to taking the difference between years. Warm colors indicate higher suitability in 2023 and cool colors a higher suitability in 2021. The solid (dotted) contour line delineates areas of a suitability change greater than (less than) 0.1 (–0.1). Sea surface temperature data were obtained from the NOAA Optimum Interpolation Sea Surface Temperature Version 2 High Resolution Data Product (Huang et al. 2021).

also have influenced the apparent decline of pink salmon in the Russian Kola Peninsula and White Sea in 2023 (Gordeev et al. 2024, Prusov 2024), although this requires further investigation.

What actions have been undertaken to manage invasive pink salmon in the Atlantic Ocean?

Due to the high risks of negative impacts of pink salmon on native species, habitats, and water quality, and the widespread interest in management intervention against pink salmon (Guay et al. 2023), efforts have increased in recent years to monitor pink salmon presence and reduce the abundance and spread of pink salmon in the freshwater and marine coastal ecosystems. In countries experiencing the highest occurrences of pink salmon (i.e., Norway, Russia, and Finland), monitoring efforts are extensive, and methods used include catch statistics, traps, snorkel surveys, and eDNA, as well as efforts

linked with Atlantic salmon monitoring programs, such as sonar, video, and counting fishways (reviewed in NHPSEG 2023). Where pink salmon are more abundant, efforts have shifted to also include pink salmon removals and attempts to disrupt potential spawning efforts in rivers. In countries with fewer pink salmon, actions are focused on surveillance (NH-PSEG 2023, Staveley 2024). In some cases, these actions are guided by risk assessments (Bean 2023). For instance, Great Britain was the first country to develop an Invasive Species Risk Assessment for pink salmon (Copp 2017, Cowx 2019). Sweden (Pettersson et al. 2018), Ireland (Millane et al. 2019a), and Norway (Hindar et al. 2020) have also created risk and impact assessment reports. Actions can also be influenced by laws. For instance, in Northern Ireland until 2023, pink salmon were treated like Atlantic salmon and, by law, had to be released if caught. Now, if an angler is confident that a pink salmon is caught, they must retain the fish and report it to the Department of Agriculture, Environment and Rural Affairs immediately, who will dispatch an officer to collect the fish.

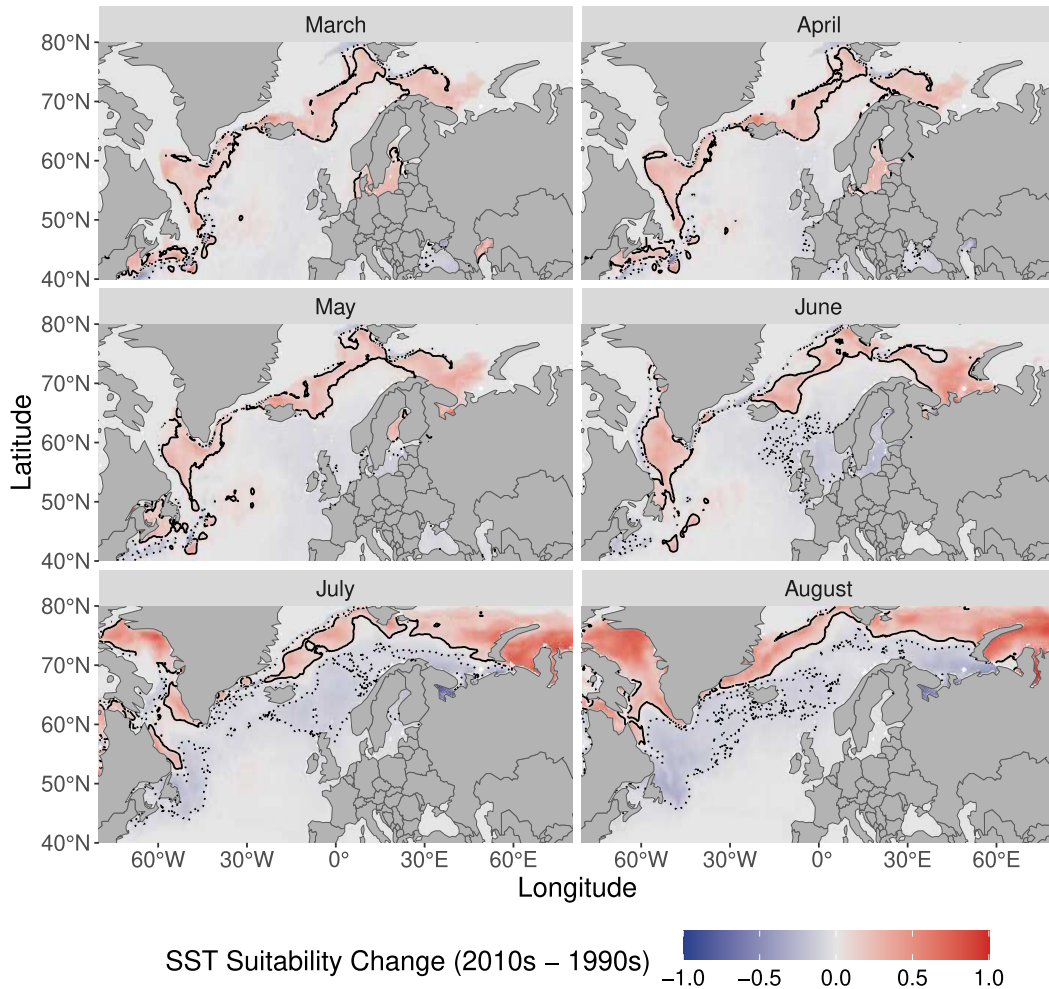


Figure 3. The difference in estimated pink salmon mean thermal suitability patterns between the 1990s (1990–1999) and late 2010s (2014–2023). The April–August temperature preference curve for maturing adult odd-year pink salmon estimated by Langan *et al.* (2024) was applied to monthly mean sea surface temperatures and scaled to [0,1] as a measure of relative suitability. Temperatures outside the range at which pink salmon have been observed at sea in the Pacific in even and odd years [1.0°C, 19.4°C] were set to a suitability of 0 prior to taking the difference between time periods. Warm colors indicate higher suitability between 2014 and 2023, and cool colors indicate higher suitability between 1990 and 1999. The solid (dotted) contour line delineates areas of a suitability change greater than (less than) 0.1 (–0.1). Sea surface temperature data was obtained from the NOAA Optimum Interpolation Sea Surface Temperature Version 2 High Resolution Data Product (Huang *et al.* 2021).

Monitoring

As the extensive monitoring efforts where pink salmon occurrences are high are summarized elsewhere (e.g., NHPSEG 2023), we focus here on monitoring efforts for pink salmon where occurrences are lower and provide examples from some Atlantic countries, recognizing that the list is not comprehensive. Where pink salmon are rare, observations from anglers and subsistence fishers are the primary surveillance method used, although other monitoring methods have been attempted or are being developed (Staveley 2024). In Wales and Northern Ireland, there are portals for the online capture of pink salmon occurrence data; however, these are not well developed due to the low numbers of pink salmon observed. In England, the Environment Agency has recently expanded the use of a pink salmon reporting app that was developed in Scotland. The ongoing coastal net fishery in Northumberland and Yorkshire also provides regular records of pink salmon but would benefit from a coordinated approach to data collection for pink salmon presence. In Ireland, monitoring is primarily with an upstream trap in the National Salmonid Index

Catchment River Erriff, which intercepts every adult salmon entering this system. In addition, some surveillance is undertaken in rivers with fish counters that have associated cameras for species verification. However, no pink salmon have been detected through this means. In 2021, no pink salmon redds were found in the River Moy during a snorkel survey after a report of potential spawning activity there. In 2023, an environmental DNA (eDNA) program was launched in 13 catchments across Ireland. In Scotland, monitoring efforts are led by the Scottish Pink Salmon Task Force, which is comprised of government agencies, salmon management organizations, and more recently, the Atlantic Salmon Trust. From 2017 to 2024, observations of pink salmon were recorded using a Pink Salmon Surveillance app. Records from the app indicated that pink salmon were more frequently observed in large rivers on the eastern side of Scotland, where more people fished for Atlantic salmon, than elsewhere. In 2023, a countrywide eDNA program was implemented to assess pink salmon presence in rivers with and without recorded observations. This eDNA program continued in 2024 and may be

expanded in 2025 to the Northern Isles of Orkney and Shetland. In 2023, a box trap, designed to intercept pink salmon, was also piloted in the River Thurso but was not particularly successful due to high flows. Pink salmon presence was also monitored in Sweden in 2023 using eDNA, including in some rivers draining to the Baltic Sea (Staveley and Ahlbeck Bergendahl 2022). In Atlantic Canada, monitoring efforts include eDNA sampling and reporting bycatch of pink salmon in recreational and subsistence fisheries (NHPSEG 2023). In the Canadian Arctic, the occurrence of pink salmon is voluntarily reported by a community-led monitoring effort called Arctic Salmon, where subsistence harvesters targeting Arctic fishes occasionally catch unusual fish species, including pink salmon (Dunmall et al. 2013, 2021).

Freshwater removals

Due to low numbers of pink salmon in the United Kingdom, few pink salmon have been removed from its rivers. In England, Wales, and Northern Ireland, for instance, there have been no targeted attempts to remove pink salmon from rivers. In Scotland, there was a brief attempt to remove pink salmon using a speargun in the River Dee, and some effort was put toward removing pink salmon using electrofishing in the River Thurso. Neither approach was massively successful nor deployed countrywide. In Scotland, there are also tensions regarding allowing anglers to fish exclusively for pink salmon because Atlantic salmon can be captured as a nontarget species. In Scotland, local attempts were made to disrupt pink salmon redds in 2017, when the species first appeared in larger numbers. Continued efforts were, however, abandoned given the number of redds, the effort required, and some safety issues associated with getting to all parts of the rivers where redds were present. There was also concern that these efforts were incidentally disrupting sea lamprey *Petromyzon marinus* redds.

In Finland, special fishing permits were issued in 2023 to catch pink salmon at the River Tana/Teno, where all other salmon fishing is banned and has been since 2021. Local Indigenous Sámi salmon fishers developed fishing methods based on traditional salmon fishing nets (e.g., drift nets, beach seines) that were specifically targeting pink salmon (Lukkari et al. 2024). These included fishing gear that was lighter than traditionally used and was therefore easier to operate in shallow areas with low flow velocity, which are typical spawning areas of pink salmon in this large river (Erkinaro et al. 2022). As this development project included testing with modified mesh sizes and thread diameters, the nets were made to avoid messy tangling of sharp-toothed pink salmon in the mesh close to spawning time. In addition, a more general pink salmon fishing opportunity was provided in 2023 when the regional fishing authority in northern Finland (Lapland) issued special permits on request for fishing rights-holders, essentially Sámi fishers (Hakaste 2023). These individuals had to submit a written application with a plan for the fishing methods used, fishing sites, times, and means to avoid bycatch of Atlantic salmon to the extent possible. These two activities resulted in the removal of 15 000 pink salmon from the River Tana/Teno. Most of the fish caught early in the season (e.g., in early June) were in good condition and edible, and part of the catch was processed, marketed and sold, or consumed in households, schools, or at other opportunities. Later in the

season, catches were used as dog food or were dumped and/or composted.

In Norwegian rivers, pink salmon have been removed with traps, nets, fishways, and even harpoons. These began as volunteer-based and opportunistic efforts by local communities in 2019 and 2021 (Berntsen et al. 2022, County Governor of Troms and Finnmark 2022). In 2023, the Norwegian government initiated large-scale measures to reduce the abundance and spread of pink salmon (Fig. 4). Funding to deploy and operate more efficient traps was provided to communities in areas with the largest increases of pink salmon. These traps were installed in the lower reaches of 50 rivers in northern Norway in 2023 (Frøiland et al. 2024). In total, nearly 250 000 pink salmon were caught using mitigation measures in 2023 (about 170 000 pink salmon in traps, 23 000 in gill nets, 41 000 in seine nets, 10 000 in fishways, and 560 by harpoons; Frøiland et al. 2024).

The traps spanned the entire width of the river to catch all upstream-migrating fish above a certain body size (Frøiland et al. 2024). Downstream-migrating fish were either let through custom-made openings in the traps or, in the case of native salmonids of smolt size, were small enough to migrate through the traps via openings between bars. Upstream-migrating native salmonids caught in these traps (Atlantic salmon, sea trout, and anadromous Arctic charr *Salvelinus alpinus*) were either sorted manually and released above the trap or could swim through a door in the trap without being handled, based on species identification using artificial intelligence or person-operated video monitoring. Although it provides an efficient means of monitoring and regulating fish movement to and from such systems, acquiring and operating traps in rivers is a relatively costly and time-consuming strategy. Once purchased, the same traps can be used in the following years, but daily operation of traps needs to be funded for several weeks every other year, targeting the high-abundance odd years, for this mitigation strategy to be effective. In the future, operational costs could be partially funded by selling pink salmon if processing and marketing the fish and roe are successful (more information provided below). There is a need to continue and strengthen the evaluation of possible impacts of traps on the upstream migration of native salmonids, and further develop trap designs in the largest rivers. In the Tana/Teno River basin, which is shared between Norway and Finland, trap operations in 2023 failed, and ~170 000 pink salmon entered the basin (Domaas et al. 2024).

Marine removals

Due to the overlap in time, space, and body size among pink salmon and native anadromous fish in the Northeast Atlantic (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a), pink salmon have been caught as bycatch in marine fisheries targeting Atlantic salmon in Norway (SSB 2023), and native salmonids will be caught as bycatch in any targeted fishery for pink salmon (e.g., bag net fishery, Fig. 5). Use of marine gears, however, is not currently part of the mitigation strategy to reduce pink salmon because of the risk of overexploitation of native Atlantic salmon, sea trout, and anadromous Arctic charr. Indeed, declining populations of native salmonids have resulted in restrictions and closures of fisheries in Norway over the last decades (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023b), high-



Figure 4. Removal fishing of non-native pink salmon in northern Norway in 2023. Upper left: Fish trap in Vestre Jakobselv (12 000 pink salmon caught in trap). Upper right: Fish trap in Vesterelva (28 000 pink salmon caught). Middle left: Fish trap in Skallelva (12 000 pink salmon caught). Middle right: Seine netting in the mouth of Syltefjordelva where almost 8000 pink salmon were caught in one deployment when the photo was taken, and in total 20 000 by using the seine net. Lower left: Pink salmon taken in traps and nets were immediately bled and stored on ice. Lower right: A local fish plant processing pink salmon and roe. Photos: Eva B. Thorstad.

lighting the importance of conserving native salmonids if targeting pink salmon via marine removal. An open hearing by the government and consultations with the Sámi Parliament (an Indigenous parliament for the Sámi people) and licensed sea fishers in 2023 demonstrated there was no support for a restricted direct fishery for Atlantic salmon in order to have a targeted sea fishery for pink salmon. Therefore, typical fishing operations for Atlantic salmon were maintained in 2023, with pink salmon only caught as bycatch (Ministry of Climate and Environment 2023).

If there were a targeted fishery for pink salmon, the proportion of bycatch, as well as the associated bycatch mortality, would vary among fishing gears. Gill nets typically kill or injure most fish and are therefore not suitable for the removal of non-native pink salmon due to the risk they pose to native salmonids caught as bycatch (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a). Use of other marine gears was also evaluated, including different types of traps and traditional gears, but due to high bycatch mortality

and/or low efficiency, they were not considered suitable for mitigation (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a). The use of purse seine nets was also evaluated, but the effectiveness of purse seine nets at capturing pink salmon at the present abundance levels is uncertain. Since a high bycatch mortality for Atlantic salmon, sea trout, and Arctic charr would be expected with the use of purse seine nets, this fishing method would only be relevant if methods were developed to minimize bycatch of native salmonids (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a). An offshore fishery similar to those conducted in Russia and Japan could limit the bycatch of sea trout and Arctic charr but not necessarily Atlantic salmon. Pink salmon, however, do not seem to aggregate in dense schools before reaching coastal areas (Heard 1991, Diaz Pauli *et al.* 2023), which is required for gear efficiency. Thus, the harvest rate outside the baseline coast would most likely be low with the present levels of pink salmon in the Atlantic Ocean.

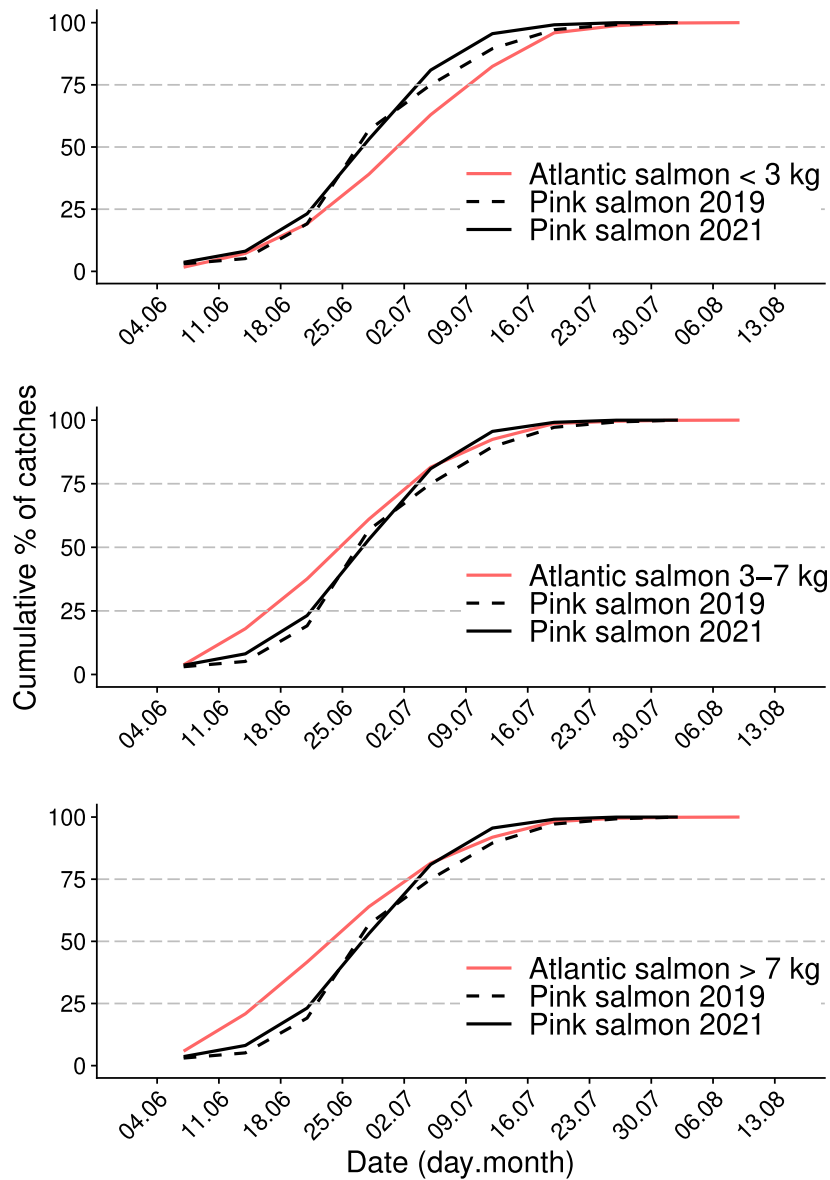


Figure 5. Cumulative catch of pink salmon and Atlantic salmon of different sizes in coastal areas in northern Norway, showing that the two species migrate through coastal areas and fjords at the same time. Catches of Atlantic salmon are the average daily catches from the period 2017–2021. From Berntsen et al. 2022. Source: Norwegian Scientific Advisory Committee for Atlantic Salmon (2023a).

In 2023, the Norwegian Scientific Advisory Committee for Atlantic Salmon (2023a) evaluated the potential use of a targeted pink salmon bag net fishery as a mitigation strategy to reduce pink salmon abundance. A central premise was that exploitation of Atlantic salmon could not be increased relative to 2021 and 2022 levels to ensure that internationally agreed-upon conservation limits and management targets were met. In 2021, the total catches of pink salmon in the licensed Norwegian bag net fishery were ~72 000 kg, which was not much lower than the total catches of Atlantic salmon in the same fishery (~98 000 kg) (Diaz Pauli et al. 2023, SSB 2023). This catch, however, represented <20% of pink salmon returning from the ocean (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a). Increasing the effort of this fishery considerably would not greatly in-

crease the catches of pink salmon because only 40% of pink salmon are large enough to be retained with the present use of bag nets with 64 mm meshes (knot to knot). Additionally, the fjord and coastal areas are vast, and the area coverage of these shore-based fixed gears is relatively small, which makes this alternative for mitigation inefficient. Increasing the effort would increase the catches of Atlantic salmon rather than pink salmon, because a larger proportion of Atlantic salmon are retained in bag nets due to their larger body size (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a). One third to more than half of the captured Atlantic salmon are dead or seriously injured after being caught in bag nets, so the bycatch mortality is large (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a).

Can management actions support the development of invasive pink salmon as a resource?

The primary goal of pink salmon management in Norway is to remove invasive pink salmon, not develop a resource for human consumption. Rather than simply waste the removed salmon, however, there is an aim to further develop the food processing chain and markets to ensure that the pink salmon captured are used as a food resource (Frøiland *et al.* 2024). In freshwater, pink salmon removed using traps have been killed and immediately bled and cooled on ice in large plastic containers (Frøiland *et al.* 2024). In areas with the largest catches, trucks continuously collect these containers to deliver pink salmon to local fish plants for processing and export while the roe are frozen for later processing. It is not known yet if this will be economically viable. In other areas, fish have been mainly used for local consumption, king crab bait, or processed for use as fish meal and biogas.

Pink salmon in Norway are not currently targeted by commercial fisheries, likely because pink salmon abundance and financial profits are both too low and because of concerns for the conservation of native species. In coastal fisheries, the price per kilo received by the fishers for pink salmon is presently much lower than that of Atlantic salmon, partly reflecting the lack of an established market for them in the northeast Atlantic. These issues have limited the economic yield from the bag-net fishery for pink salmon, and there has not been interest among the fishers to develop a targeted fishery for pink salmon instead of fishing for Atlantic salmon.

A recreational fishery for pink salmon in the sea has also been emerging in Norway (Diaz Pauli *et al.* 2023). Recent reported harvests have been low and variable (1254 and 76 pink salmon reported in 2021 and 2023, respectively); however, harvests could be underreported. An increased abundance of pink salmon in the northeast Atlantic could raise further interest for a recreational fishery and a fishing tourist industry targeting pink salmon in the sea. The fishing season for such a fishery would be short, however, with only a few weeks of opportunity every other year. For freshwater anglers in Norway, there are indications of a willingness to become involved in targeted removal of pink salmon, but cooperation may decrease if pink salmon dominate their catches (Guay *et al.* 2023).

In the White Sea of northwest Russia, where pink salmon were introduced with the intention to be a fisheries resource, the relatively low abundance and huge variation among years have contributed to pink salmon being a risky and generally economically unjustified resource for commercial fisheries (Prusov 2024). This pink salmon fishery can be perceived at present only as a small-scale, artisanal one, mainly for local consumption. This is based on high-level of involvement from local communities in the current fishery, small numbers of fishing sites, low catches, the use of small boats only, and a short fishing season close to the shore (Prusov 2024). In years of high abundance, pink salmon have become an attractive species in the recreational fishery. However, there are negative attitudes among users of fishing sites where high numbers of pink salmon may negatively affect the exclusive Atlantic salmon catch-and-release angling, while attitudes toward large runs of pink salmon are more tolerant and even positive on salmon rivers where catch-and-retain fishing also takes place (Prusov 2024).

What do we need to know to support further management actions?

As range-expanding and invasive pink salmon are a symptom of ecosystem-level changes occurring with warming impacts, we need to develop strategies that support management actions given predictions of continued change. Focusing on the fish themselves, to better predict a future global pink salmon distribution, there is a need to better understand their invasion potential. It is also important to provide better predictions of the potential impacts of pink salmon on other species and native ecosystems. Within the context of guiding management responses, additional information is required to assess scenarios of different levels of mitigation and increase the efficiency of removals. Here, we further develop each of these themes to highlight key gaps, which are described below and summarized in Table 1, to support collaborative efforts and coordinated actions regarding pink salmon.

Assess invasion potential

Forward-thinking management action must be based on potential responses of pink salmon to increasingly consistent access to warming habitats for range-expanding pink salmon from the Pacific Ocean or to generally warmer habitats for those invading through the Atlantic Ocean. There is already substantial evidence that colonizing pink salmon can adapt rapidly and establish populations in new locations, sometimes by deviating from their traditional anadromous 2-year life-history cycle. Establishment success in an anadromous species, however, is a complex process that requires an alignment of needs (e.g., habitat, food) with resources (e.g., suitable temperatures, prey) across multiple life stages in multiple ecosystems.

The marine distribution of pink salmon in the Atlantic and Arctic oceans will play a large role in determining which rivers they ultimately colonize. Therefore, patterns in the temporal and spatial dynamics associated with the southern limits of their marine distribution in the Pacific (Langan *et al.* 2024) could inform predictions and expectations regarding their expansion in the Atlantic. Similarly, understanding the northern extent of suitable marine habitats for adult and juvenile pink salmon, and how those change with environmental variation, would inform predictions of range-expansion in the Arctic (Farley *et al.* 2020, Dunmall and Langan *et al.* 2024). Model results (Langan *et al.* 2024) may be used to guide more targeted sampling of the range edge, which would provide information on spatial dynamics and changing marine habitats that may be influencing distributional shifts. Developing technologies such as eDNA also show promise as a tool to expand observational capacity and gain new insights into salmon distributions (Gargan *et al.* 2021, Deeg *et al.* 2023). Deeper investigations of these dynamics at both the northern and southern edges of the pink salmon range in the Pacific Ocean will likely provide critical insights into the future of invasive pink salmon across the Atlantic basin and those range-expanding into the Pacific Arctic and would help to guide efforts to assess establishment in new areas. Finally, as the coastal marine environment is critical to the survival of juvenile pink salmon, an improved understanding regarding the suitability of marine habitats at all life stages would inform management efforts.

The future spawning distribution of pink salmon can be predicted through a better understanding of their potential. Summarizing key details about pink salmon source populations and the potential new habitats where vagrants may

Table 1. A summary of current gaps in information needed to support the development of new fisheries opportunities and prepare for a future circumpolar pink salmon distribution in Atlantic and Arctic Ocean regions experiencing increasing pink salmon, categorized by providing a better understanding of (i) the invasion potential of pink salmon, (ii) interactions among pink salmon and other key species, and (iii) current mitigation efforts

| Invasion potential | |
|-----------------------|--|
| Overall | <ul style="list-style-type: none"> • Identify freshwater and marine habitat use patterns. This can be done using an advanced tagging program employing passive, acoustic, radio, and archival tags • Assess homing/straying rates across pink salmon populations to better identify potential source populations and explore parameters facilitating straying • Conduct wider surveillance to track the distribution of and rate of spread of pink salmon at larger geographic scales • Develop and use technologies such as eDNA to expand observational capacity and gain new insights into salmon distributions |
| Marine | <ul style="list-style-type: none"> • Increase understanding of the temporal and spatial dynamics at northern and southern range limits in the Pacific, Atlantic, and Arctic oceans • Use model outputs to inform targeted sampling of the range edges during large-scale survey efforts • Assess the global redistribution history for pink salmon to understand the breadth of parameters needed for suitable overwintering habitat (e.g., supporting growth and survival) • Improve understanding of factors influencing early marine survival of pink salmon juveniles and suitable thermal coastal habitats |
| Freshwater | <ul style="list-style-type: none"> • Understand key details about pink salmon source populations (e.g., timing of life-stage events, range in variation in tolerances at each life stage) to identify window of suitable habitats • Assess freshwater habitats in newly accessible areas to assess suitability for vagrants • For newly established and source populations, assess recruitment to support forecasts for range expansions, although recognizing this may be difficult due to remoteness, inaccessibility, or changing environmental conditions. Where opportunities permit, this could be done using nest/egg counts, fry and juvenile surveys, survival/mortality estimates, and measures of reproductive capacity such as age of maturity, frequency of reproduction, and fecundity (egg size, number, and quality) • Learning from prior colonizations, assess both the generation time needed for observed changes to occur and predict how pink salmon abundance trends will evolve • Explore the introduction attempts that were not successful at producing self-sustaining populations of pink salmon to identify barriers to successful colonizations |
| Species interactions | |
| Overall | <ul style="list-style-type: none"> • Review pathogens and parasites in pink salmon to understand the potential for pink salmon to act as a vector and/or reservoir for pathogens and parasites (marine and freshwater), and how this may affect native species and aquaculture |
| Marine | <ul style="list-style-type: none"> • Compare years of higher and lower pink salmon abundances in the Atlantic and Arctic oceans to assess top-down effects of pink salmon predation on trophic cascade |
| Freshwater | <ul style="list-style-type: none"> • Review pink salmon interactions with other salmonids in fresh water across their Pacific distribution and established introduced range to inform potential interactions. To what extent does the presence of pink salmon impact or benefit the freshwater ecosystem (e.g., the behavior, food availability, run timing, and ultimately abundance of other salmonids)? • Explore the potential for hybridization between pink salmon and native salmonids • Assess water quality due to decomposition of pink salmon adults • Assess the impacts of spawning behavior (e.g., redd digging) on freshwater invertebrates |
| Mitigation efficiency | |
| Overall | <ul style="list-style-type: none"> • Assess the efficacy of previous removal efforts (e.g., traps) to reduce pink salmon abundances in rivers and spreading among rivers • Complete analysis to understand the current and future time and resources needed to keep pink salmon at low levels in northern Norway, and to understand if these efforts are reducing the risk of further spreading to the Baltic Sea and North Atlantic Ocean • Consider the development of removal methods for pink salmon eggs and/or juveniles; assess mitigation options to prevent or postpone new establishments • Explore the extent of positive and negative effects for natal species and host ecosystems of pink salmon removals. For example: Do either the traps or schools of pink salmon at the river mouths impact the migration behavior of natal species? |

establish is a potential predictive tool (e.g., Bilous and Dunmall 2020), especially when guided by forecasts of potentially thermally suitable marine habitats that would inform pathways to newly accessible areas (Dunmall and Langan et al. 2024). From an assessment of past colonizations, it would be helpful to identify the timing of life-stage events (e.g.,

spawning, egg development, emergence, outmigration, return) and the range of variation in tolerances for source populations at each life stage to understand the window of availability to potentially suitable habitats in new environments in the future. Populations introduced to ecosystems with divergent conditions from the pink salmon native range, such

as the Laurentian Great Lakes, may be particularly valuable in evaluating adaptive potential. As colonizing pink salmon have demonstrated life history plasticity, the generation time needed for observed changes would also help to inform predictions of population growth once established. Exploring introduction attempts that were not successful at producing self-sustaining populations of pink salmon may help us identify barriers to colonizations for pink salmon, which can then be applied to scenarios of environmental change (e.g., Gordeeva and Salmenkova 2011), and perhaps could be used to develop techniques or technologies to prevent or mitigate future expansion. Assessing this global redistribution history for pink salmon may also help to address other pressing questions, including what factors facilitate and regulate expansions from established populations. It could also be used to better understand how salmon abundance trends will evolve as environmental change increases access to high-latitude habitats (Danielson et al. 2020, Thoman et al. 2020, Crawford et al. 2021, Dunmall and Langan et al. 2024). For pink salmon, assembling and critically assessing the breadth of information currently available will help to inform their adaptive potential, and therefore future distribution, across multiple ocean basins.

Better understand interactions among species

As pink salmon move to and become established in new areas, they interact with native ecosystems. While we can draw from knowledge about pink salmon to understand potential interactions among species and impacts on ecosystems, unfortunately we currently do not understand the extent or nature of this interaction, especially in new areas. This greatly hampers our ability to inform actions that would manage all species. Building from previous efforts in the Pacific (Ruggerone et al. 2023, Connors et al. 2024), more research is needed to better understand the extent of interactions among pink salmon and other species in the freshwater and marine ecosystems (Lennox et al. 2023). We believe this needs to be a priority; this information is needed immediately to guide appropriate management actions where pink salmon are considered invasive.

In the marine ecosystem, pink salmon can impact multiple aspects and species through competition for prey resources and by initiating trophic cascades that resonate from zooplankton to marine mammals and beyond (Ruggerone et al. 2023). In contrast, there is also evidence, primarily from Asia, suggesting these interactions are complementary rather than competitive (NHPSEG 2023), potentially highlighting differences in productivity across the Pacific Ocean (Diaz Pauli and Utne 2024, Somov et al. 2024). In semi-enclosed ecosystems of bays and straits with a limited carrying capacity, interspecific food competition between planktivorous nekton species is frequently reported as a result of imbalance between high fish biomass and limited planktonic food resources. In highly productive ocean ecosystems, plentiful resources of herbivorous zooplankton are utilized both by planktivorous fish and predatory planktonic animals, which in turn, are common prey items for pink salmon in the Pacific Ocean (Radchenko et al. 2018). Consumption of predatory plankton (e.g., hyperiids, mysids, chaetognaths) decreases predatory pressure on the herbivorous zooplankton resources and enhances food supply for other planktivorous fish. Such trophic triangles are an important feature of the pelagic food webs in the ocean

ecosystems. In the Atlantic Ocean, however, a lack of available information on the marine diet of pink salmon and their role in these trophic triangles limits assessments regarding the nature and extent of potential for competition among pink salmon and native fishes for food resources (Diaz Pauli and Utne 2024).

In freshwater, salmon presence and activity can be both deleterious and beneficial for native species and habitats. For instance, salmon are a source of nutrients and energy in freshwater (Gende et al. 2004, Dunlop et al. 2021) and terrestrial ecosystems (Walsh et al. 2020, Bonde and Stein 2024). Through the process of altering the substrate by digging redds, salmon may create or improve habitat for other species (Tonina and Buffington 2009). Juvenile pink salmon are also prey for other riverine fishes, such as Arctic grayling *Thymallus arcticus* and Dolly Varden char *Salvelinus malma* (Schoen et al. 2022). During spawning, however, pink salmon can be aggressive (Keenleyside and Dupuis 1988) and competition for space may occur (Dunmall et al. 2016, Thorstad et al. 2024). Pink salmon may also have the potential to hybridize with native salmonids, which should be further explored. In a laboratory setting, there is evidence of survival in progeny of Atlantic salmon females and pink salmon males (Devlin et al. 2022), although previous investigations found no survival in similar crosses (Ban et al. 2013). There may also be competition for food and space among juvenile pink salmon and Atlantic salmon and deteriorated water quality due to decomposition of dead adult pink salmon (Thorstad et al. 2024). Pink salmon may also be a new reservoir for pathogens (Lennox et al. 2023), which is a concern repeated by harvesters in the western Canadian Arctic regarding range-expanding salmon (Chila et al. 2022). Dead and dying pink salmon may impact the microbial balance in rivers by increasing the risk of opportunistic bacteria to be present (Lennox et al. 2023). The freshwater pearl mussel *Margaritifera margaritifera*, which is listed as endangered on the International Union for the Conservation of Nature (IUCN) red list, may also be negatively affected by pink salmon directly through digging activity, or indirectly through interactions with their host species, Atlantic salmon and brown trout.

Assess and increase efficiency of mitigation measures

Mitigation measures, which have occurred mostly in Norway so far, managed to remove large numbers of pink salmon but only after a significant investment of time and money. However, it is not known if this effort will result in maintaining pink salmon at present levels, cause an overall decline in the abundance in subsequent years, or result in continued growth and expansion, even with these measures in place. Hence, the resources needed to keep the pink salmon population in northern Norway at low levels in the future and reduce the risk of further spreading in the North Atlantic Ocean and Baltic Sea are unknown. Evaluating these mitigation measures to increase efficiency and benefit to native species is thus extremely important to inform current and future efforts.

Unfortunately, the information needed to evaluate mitigation efforts in freshwater is not available. Presumably, removing pink salmon from rivers had mitigated any potential negative impacts for the native species and host ecosystems; that was the intent. However, the extent of these benefits has not yet been explored. There is also little information available on

the scale of negative effects caused by these mitigation measures (but see Domaas et al. 2024). For instance, the negative impacts of the traps on native fish populations have not been fully understood. In 2019, 2021, and 2023, there were few reports of injured or dead native salmonids because of using traps and nets (County Governor of Troms and Finnmark 2022, Frøiland et al. 2024). However, it should be evaluated whether the traps either directly or indirectly impact the migration behavior of native fish species and, if so, what impact this might have on populations. Further, the efficacy of traps to reduce both the overall abundance of pink salmon in the immediate area and spreading to other areas should also be evaluated. Due to the linkages, it may be possible to evaluate the mitigation measures themselves to increase efficiency at the same time as using these mitigation measures to learn about interactions among pink salmon and native species.

In the marine environment, some actions can be taken to reduce the abundance of pink salmon in bag net fisheries and, at the same time, reach the management targets of Atlantic salmon. The ordinary sea fishery for Atlantic salmon could be closed in years with higher pink salmon abundances (i.e., in odd-numbered years). Bag nets with a smaller mesh size than commonly used for Atlantic salmon could be used to target pink salmon. The fishing period could be restricted to approximately June 20 to July 15, when most pink salmon migrate through fjords and estuaries, and all unharmed Atlantic salmon, sea trout, and Arctic charr could be released alive (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a). However, a large bycatch of sea trout and Arctic charr would still take place. Sea trout populations are healthy in northern Norway, but anadromous Arctic charr populations are in decline (Svenning et al. 2022). A targeted sea fishery for pink salmon as described above, in addition to the ordinary sea fishery, would result in a high marine harvest and an increased risk of not reaching the management conservation limits for Atlantic salmon (Norwegian Scientific Advisory Committee for Atlantic Salmon 2023a).

What actions are recommended now?

Despite the seemingly overwhelming amount of information needed immediately to support management and conservation decisions, there are also tangible actions to be taken now to assist these overall efforts (Table 2). Recognizing that pink salmon now span multiple ocean basins and jurisdictions, acquiring information must also involve a coordinated multinational approach. The formation of an International Working Group, with representation from interested agencies, institutions, rightsholders, and stakeholders, could provide the oversight needed to coordinate actions, recommend next steps, prioritize research efforts, and develop or maintain networks needed to support international collaborations. Ideally, this working group could design a standardized approach to data collection that will allow for comparisons across an array of habitats, locations, and regions. By doing so, these subject matter experts could also develop and establish universal sampling protocols, enforce data standards, and establish data sharing guidelines that will ultimately increase the efficiency of research efforts. Ideally, this working group could also facilitate processes to secure funding by distributing information about funding opportunities, supporting collaborations, connecting related efforts, and ensuring that outcomes

are used in decision-making. We recognize that the North Atlantic Salmon Conservation Organization (NASCO) has created a pink salmon working group (NASCO 2024), which is an excellent step. Broadening the representation on the working group to be inclusive of groups not currently part of NASCO and perspectives beyond the Atlantic Ocean can facilitate more extensive knowledge exchange and ensure that differing perspectives regarding pink salmon management are supported.

As part of ongoing monitoring efforts, sampling of pink salmon in areas outside their normal Pacific Ocean distribution is also needed on an ongoing basis and following standardized sampling protocols. Habitat and environmental data should be catalogued wherever pink salmon occur to identify physical and biological characteristics associated with their recruitment (e.g., water temperature, freshwater runoff, habitat and substrate types, prey resources, spawning locations). These samples and data can help address research questions and provide important insights into population biology. The use of citizen scientists, volunteers, sport fishers, students, and such could be leveraged to maximize the cost/benefit relationship, especially as protocols are developed and when training to support standardized sampling is available.

Much information can be easily collected as part of these monitoring efforts. Length, weight, gender ratios, body condition, and age of pink salmon should be collected to assess population status. Tissues can provide genetic information needed to establish invasive origins, confirm species identifications, define stock structure, and assess potential hybrids. The collection of incrementally grown skeletal structures such as scales, eye lenses, otoliths, fin rays, vertebra, and opercula will allow for age estimation, growth rate estimates, and life history reconstructions. Advances in elemental and chemical analyses of such structures could allow for the assessment of temporal changes in isotopes (C, N, O, S) and hormones (cortisol, estrogen, progesterone, estradiol) to provide insights regarding age-specific changes in movement patterns, thermal history, health status, stress levels, reproductive status, reproductive frequency, and trophic changes (Reis-Santos et al. 2022). Such data can also be used to identify natal origins as well as assess homing ability and stray rates. Collection of stomach contents and gastrointestinal swabs for genetic material will help identify prey items and assess the potential for interspecific competition. Viral, bacterial, and parasite assays of both invasive and native species should be conducted to address concerns regarding the possible introduction and spread of disease pathogens and parasites to native ecosystems. Many of these biological samples can easily be stored until the resources needed for their analysis are available. Supporting these sampling efforts, and perhaps as an outcome from the suggested working group, a centralized online relational database with strict data entry rules could be developed and supported to allow for the enforcement of data standards and security, data storage, and data sharing.

Clearly, additional research is needed across the life cycle of pink salmon to better understand the species, their potential to interact with other fishes, and their impact on host ecosystems (Table 1). In addition, we suggest that resources be directed toward the development of tools, such as eDNA, to increase the efficiency of current research and monitoring efforts. Due to the scope of this invasion and range expansion, resources will need to be focused on key systems, spread across the North Atlantic considered representative of larger regions, so that

Table 2. Actions that can be taken immediately to support understandings regarding the current and future pink salmon distribution across the Pacific, Atlantic, and Arctic oceans

| Action | Description | Outcomes |
|-------------|------------------------------|---|
| Guide | Formalize international WG | Provide recommendations and coordinate actions |
| Monitor | Continued, consistent effort | Improved understanding of trends |
| Share | Samples, data, methods | Protocols developed, efficiency increased |
| Research | Focused efforts to fill gaps | Inform management actions |
| Tools | Develop/refine options | Increased efficiency in detecting changes and impacts |
| Communicate | Sharing of information | Increased engagement, reporting |

long-term monitoring programs can be implemented. Identification of such “indicator” systems will require initial surveys designed to assess regional potential for recruitment and sustainability. These data will also help to provide information that may help predict which systems are most susceptible to future expansions.

Routine surveillance to detect the presence of pink salmon in non-natal areas is crucial to evaluate their prevalence and associated ecological implications as well as to inform appropriate management strategies. Apart from direct monitoring programs, effective communication and awareness campaigns targeted at key “on the ground” stakeholders, such as recreational and commercial fishers, as well as rightsholders across the Canadian Arctic and beyond, are important additional components to enhance reporting rates, facilitate the retention of specimens for verification purposes, and provide biological material for subsequent scientific investigations (Dunmall *et al.* 2013, Armstrong *et al.* 2018, Millane *et al.* 2019b, Nielsen *et al.* 2020, Staveley and Ahlbeck Bergendahl 2022). Such awareness can provide an early warning mechanism to alert the responsible authorities to the presence of pink salmon and provide a much wider informal surveillance network than otherwise feasible (Nuñez *et al.* 2012, Caffrey *et al.* 2014, Nielsen *et al.* 2020, McNicholl *et al.* 2021). In this regard, responsible authorities should establish accessible platforms where stakeholders can report any pink salmon encountered (adult and/or juvenile). Ideally, there will also be guidance provided on how to appropriately record catch information and, if appropriate, how to preserve the salmon or samples for use in future analyses. Awareness-raising initiatives should be undertaken through both traditional and social media platforms and widely circulated via formal and informal networks. Key information to share would include this reporting process, identification guides, nontechnical educational material on species biology, and historical occurrence. Ongoing and proposed research and management initiatives would also be informative with further promotional material and results outcomes generated during the season as new instances of the species are reported.

Conclusions

There is a global redistribution of marine species underway, with implications for ecosystems and people, drawing an acute need for informed conservation and management actions. In the Atlantic and Arctic oceans, where range-expanding or invasive species, including pink salmon, are increasingly co-occurring with native species, a continued exchange of knowledge is needed to best inform decision-making. For native species and their habitats, these biodiversity changes are cumulative to the impacts of climate change, which are rapid and

acute at northern latitudes (Lennox *et al.* 2023). Recognizing that management approaches taken for non-native species are influenced by their potential impact on host ecosystems and species, informing decision-making using all available knowledge is critical. Perceptions about non-native species are also important to consider; initial concern and suspicion (e.g., Chila *et al.* 2022) can shift as their use for human consumption increases (e.g., Nuñez *et al.* 2012) or over time (e.g., Carthey and Banks 2012). Drawing from management approaches supporting production to inform those focused on co-occurrence or removals, we have provided several key takeaways, including (i) a strategy to focus future research and monitoring efforts in key locations; (ii) gaps needed to better understand redistributions; (iii) steps that can be taken immediately to start advising actions; and (iv) a tangible approach to informed decision-making through collaboration. While focused on pink salmon, the information derived and collaborative approach developed contribute to our understandings regarding species redistributions and inform forward-thinking management and conservation strategies. Together, we can help to support a pace of management response that meets the rate of environmental change.

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Author contributions

All authors (Methodology, Resources, Validation, Writing—original draft, Writing—review & editing), Karen M. Dunmall (Conceptualization, Project administration, Visualization of Tables 1–2), James R. Irvine (Conceptualization), Joseph A. Langan (Formal analyses and Visualizations in Figs 1–3), Eva B. Thorstad (Visualization in Fig. 4), and Henrik H. Berntsen (Formal analyses and Visualization in Fig. 5).

Conflict of interest : None declared.

Data availability

The environmental data supporting this article are publicly available from the NOAA Optimum Interpolation Sea Surface Temperature Version 2 High Resolution Data Product at <https://psl.noaa.gov>. Catch data supporting this article are

publicly available from Statistics Norway at <http://www.ssb.no>.

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