North
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Commission

TECHNICAL REPORT 21

A Review of Pink Salmon in the Pacific, Arctic, and Atlantic Oceans

Technical Editor: William Stanbury

Vancouver, Canada, 2023

A Review of Pink Salmon in the Pacific, Arctic, and Atlantic Oceans

A report produced by the Northern Hemisphere Pink Salmon Experts Meeting, held: October 2–3, 2022, Vancouver, Canada.

Northern Hemisphere Pink Salmon Experts Meeting Organizers

ICES Working Group on Science to Support Conservation Restoration and Management of Diadromous Species (WGDIAD)
NPAFC Working Group on the International Year of the Salmon (IYS WG)

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ISSN 1029-5917

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Northern Hemisphere Pink Salmon Expert Group
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THIS PAPER MAY BE CITED IN THE FOLLOWING MANNER:
Northern Hemisphere Pink Salmon Expert Group. 2023. A review of pink salmon in the Pacific, Arctic, and Atlantic oceans. North Pacific Anadromous Fish Commission Tech. Rep. 21. 58 pp. (Available at https://npafc.org/)

Abstract

The Northern Hemisphere Pink Salmon Expert Group Meeting was held on October 2–3, 2022 in Vancouver, Canada, immediately preceding the International Year of the Salmon (IYS) Synthesis Symposium. The rapid expansion of pink salmon was the theme for the meeting, and experts came together to discuss the current state of knowledge for pink salmon. Specific topics of focus included the range expansion into the Atlantic and Arctic oceans, trends in distribution and abundance, research and monitoring approaches, potential inter-specific interactions, mitigation efforts, and plans for future collaborations. The outcomes of the meeting were presented at the IYS Synthesis Symposium and are further disseminated through this NPAFC Technical Report. The Executive Summary section of this report provides a brief background, a condensed overview of each topic, and concludes with overarching takeaway messages that are intended to guide future collaborations.

Contents

List of Abbreviations

ADF&G—The Alaska Department of Fish and Game

AHRP—Alaska Hatchery Research Program

BASIS—Bering-Aleutian Salmon International Survey

CU—Conservation Units

DFO—Fisheries and Oceans Canada

ICES—International Council for the Exploration of the Sea

IYS—International Year of the Salmon

LUKE—Natural Resources Institute Finland

NAC—North Atlantic Council or North American Commission, NASCO

NASCO—North Atlantic Salmon Conservation Organization

NEAC—North East Atlantic Commission, NASCO

NPAFC—North Pacific Anadromous Fish Commission

PICES—The North Pacific Marine Science Organization

WGC—West Greenland Commission, NASCO

WGBAST—ICES Assessment Working Group on Baltic Salmon and Trout

WGDIAD—ICES Working Group on Science to Support Conservation, Restoration and Management of Diadromous Species

WGNAS—ICES Working Group on North Atlantic Salmon

Executive Summary

Introduction

The International Year of the Salmon (IYS), which ran from 2018 until 2022, acknowledged the need to collectively generate and share new knowledge regarding the current state of salmon and engage communities to support the resilience of both salmon and the people who depend on them. An important aim of the IYS therefore was to bring scientists together and promote knowledge exchange on Pacific and Atlantic salmon. Through that initiative, the North Pacific Anadromous Fish Commission (NPAFC) and the International Council for the Exploration of the Sea (ICES) Working Group on Science to Support Conservation, Restoration and Management of Diadromous Species (WGDIAD) recognized there was potential for an inter-ocean-basin collaboration on salmon. On September 1, 2021, the NPAFC and WGDIAD launched their first joint (online) meeting in the form of a 'Pacific-Atlantic Salmon Round Table' where 70+ salmon experts from both ocean basins, as well as the Arctic, discussed a range of relevant issues. The topic that generated the most discussion was the recently observed range expansion of pink salmon. It became clear that there was a great desire for knowledge on this topic from scientists working in areas where this expansion was a relatively recent phenomenon, and to benefit from the knowledge present among scientists who had been working on this topic, and pink salmon ecology in general, for years. Therefore, a selection of experts (see Appendix A for list of participants and affiliations) in pink salmon ecology, stock assessment, and genetics, as well as a limited number of stakeholders, attended the first meeting of the Northern Hemisphere Pink Salmon Expert Group, which was held 2–3 October 2022, immediately preceding the IYS Synthesis Symposium. They discussed the current state of knowledge for pink salmon, focusing on the range expansion into the Atlantic and Arctic oceans, including trends in distribution and abundance, research and monitoring approaches, potential inter-specific interactions, mitigation efforts, and plans for future collaborations. The outcomes of the meeting were presented at the IYS Synthesis Symposium and further disseminated through this NPAFC Technical Report. This summary provides an overview of the topics discussed and more detailed information about each topic is provided in the relevant section of this report.

Topic 1: Trends in Distribution, Abundance, and Productivity of Pink Salmon

Pink salmon are small but mighty fish on a warming planet. Already the most widely distributed Pacific salmon species in the northern hemisphere, they have expanded in recent years. In the Atlantic, they have likely produced self-sustaining populations in northern Norway, Scotland, and Iceland and have been observed as far south as France. Vagrants have also been observed in eastern Canada from Nunavut to Newfoundland while non-anadromous populations occur in the Great Lakes. Pink salmon are also observed in the Arctic, with rapidly increasing catches from introduced and now self-sustaining populations in north-western Russia, and increasing trends in distribution and occurrence of presumed vagrants in the North American

Arctic. In the Pacific, pink salmon are the most numerous naturally-spawned Pacific salmon species in recent decades that typically display biennial patterns of abundance (more numerous in odd-numbered years). Warming temperatures may be fuelling increased pink salmon production at their northern distributional extent whereas those in the south are struggling with the cumulative impacts of environmental change.

Topic 2: Current Approaches to Assessment and Monitoring of Pink Salmon

Changes in pink salmon abundance and distribution in oceans and rivers have been documented using multiple monitoring approaches. In Alaska, surface trawls are used to assess pink salmon distribution and abundance in the northern Bering Sea as part of an ecosystem assessment. In north-eastern Russia, trawls similarly assess pink salmon distribution and abundance, with results from immature salmon predicting returns the following year. In rivers, adult pink salmon returns may be assessed and monitored by multiple means, and juvenile out-migration can be similarly monitored through the use of traps. Where pink salmon are rare, changes in distribution and occurrence may be monitored through community-led programs that monitor pink salmon harvested as bycatch in subsistence fisheries. Similarly, pink salmon range expansions in the Atlantic are monitored primarily in Norway through bycatch in scientific surveys and commercial or recreational fishing targeting other species and by river monitoring programs for Atlantic salmon. In other countries across the Atlantic, including Sweden, Ireland, Scotland, England, Wales, Faroe Islands, Greenland, Iceland and eastern Canada, pink salmon catches are lower than in Norway and they are mainly reported from recreational angling in rivers.

Topic 3: Competition and Interactions Between Pink Salmon and Other Species

Pink salmon spend approximately 18 months growing and rearing in the ocean but only weeks to a few months in freshwater before migrating to the ocean (they spend, on average, less time in fresh water after emerging from the gravel than other Pacific salmon species). The ecosystem consequences of interactions between expanding numbers of pink salmon, especially in certain years (as odd- and even-numbered years have different pink salmon abundances, depending on the geographic area), and other aquatic species remains a topic of scientific debate. Further research is needed, especially as pink salmon access new areas where effects may differ from those in areas of traditional occupancy. In the ocean, pink salmon overlap in diet with many other species and high abundances of pink salmon can deplete food resources. When numerous, pink salmon may affect the growth or mortality of non-salmon species, including fish, seabirds, and marine mammals, due to potential competition for zooplankton and other prey species. However, the ocean remains highly productive and pink salmon only consume a small fraction of the resources compared to more abundant species (e.g., walleye pollock). Pink salmon are also flexible foragers, eating a variety of prey and finding preferred feeding areas best suited to their traits. Indeed, the foraging areas and feeding habits among Pacific salmon species often indicate complimentary, rather than competitive, interactions. In fresh water, adult and juvenile pink salmon rarely feed but, as fry, they can be important prey for other species after they emerge from the gravel in spring and quickly swim to the ocean. As adults returning to spawn in the fall, they can be aggressive on the spawning grounds, and may compete for spawning locations if suitable areas are sparse. They die after spawning and thus provide nutrients that can boost freshwater productivity.

Topic 4: Genetic Stock Delineation of Pink Salmon

The increase and range expansion of pink salmon is more pronounced in odd-numbered years, rather than in even-years, a trend that is especially prominent in the Atlantic Ocean. These odd- and even-year pink salmon populations are genetically distinct even within the same rivers, due to their strict two-year life cycle that prevents mixing among lineages. In fact, there is greater differentiation between these odd- and even-year lineages than among geographic regions, and odd-year pink salmon show more genetic diversity than the even-year salmon. There is genetic differentiation among pink salmon at a broad regional scale, however, as pink salmon group into Asia/Beringia or Gulf of Alaska/Pacific Northwest origins in the Pacific, and those sourced from the introduced, self-sustaining populations in north-western Russia. The geographic origins of expanding pink salmon can be explored using this differentiation; an effort that will require ongoing collaborations at an international level that will expand our understanding of biodiversity change amidst climate change.

Topic 5: Approaches to Monitoring and Predicting Future Changes in Marine Distribution

Pink salmon are on the move, but assessing the extent of these distributional shifts and predicting future change are difficult. Distribution models for both odd- and even-year pink salmon are being developed for the Pacific Ocean from historic catch records dating back to the 1950s. It appears that these lineages occupy similar habitats on the high seas and prefer similar temperatures. These thermal preferences may be used to understand current, and predict future shifts in distributions, especially as they move into Arctic waters.

Topic 6: Selective Methods and Removals, Opportunities for New Fisheries

The recent rapid expansion of pink salmon across the Atlantic has resulted in efforts to remove or eradicate them in rivers to mitigate potential effects on native species and ecosystems. Norway is the first country to implement an official strategy to eradicate pink salmon. Using various methods, over 100,000 pink salmon were estimated to have been removed from rivers across Norway in 2021. Experiences learned from those efforts guided the development of national mitigation measures now in place for 2023. In other areas with increasing pink salmon, like Quebec, Scotland, and Ireland, anglers are encouraged to remove and report any pink salmon which are legally caught. Other removal systems, such as the placement of a trap, may be deployed on a trial basis in the lower reaches of the River Thurso in Scotland. It is also unclear how successful these efforts will be at eradicating pink salmon from Atlantic countries, especially if the general trends of increasing occurrences remain unchanged. The level of investment in eradication per country might be proportional to the perceived potential negative impacts of pink salmon. This underscores the need to better understand the potential impacts of expanding pink salmon on native species and freshwater ecosystems to inform appropriate management responses. Although there is limited interest in developing a commercial fishery for pink salmon in the Atlantic Ocean, this has not been pursued due to the risk of bycatch and increased mortality on native anadromous fish. In Norway, pink salmon are managed as an invasive species, with the focus on eradication.

Topic 7: Environmental DNA as a New Tool to Monitor Changes in Fresh Water Distribution

Environmental DNA (eDNA) is a new and cost-efficient tool that is being applied to monitor the occurrence of pink salmon and the related expansion in distribution. For instance, eDNA analyses from the Tana/Teno River demonstrated that pink salmon were distributed across all parts of the watershed in 2021, and that their distribution had increased since 2019. The different life-stages and age classes of Atlantic salmon and pink salmon present in rivers makes it difficult to assess differences in the relative abundance or biomass between the two species using eDNA. Pink salmon expansions into eastern Canada were also assessed using eDNA. While 39 rivers were sampled across nearly 1500 kilometres (km) of coastline from the Hudson Bay to the Ungava Bay, a single detection in Ungava Bay added growing evidence that, while pink salmon were present, they were likely not widely distributed and abundant in northern Quebec in 2021. Continued advances in eDNA approaches will increase opportunities for assessments of pink salmon expansions.

Topic 8: Information Exchange and Future Collaborations

The Northern Hemisphere Pink Salmon Expert meeting provided a venue for information exchange and highlighted the value of continued collaboration. Knowledge of pink salmon is unevenly distributed, yet there is an immediate need for information about pink salmon in areas experiencing abrupt population increases to guide and support management or conservation actions. Ongoing collaborations would facilitate the continued exchange of information and address topics of interest. The Northern Hemisphere Pink Salmon Expert group recommended the establishment of a Salmon Expert Group to provide the flexibility to address timely issues related to all salmon species. The NPAFC and ICES expressed interest in setting up this Salmon Expert Group, which would be science-based and thus complementary to the North Atlantic

Salmon Conservation Organization (NASCO) pink salmon working group, which is management-based.

Conclusions

The need to assess shifts in species distribution and the resulting potential impacts and opportunities, is an acute and increasingly international challenge across a rapidly changing planet. Pink salmon, a quintessential Pacific species, are increasing in abundance in the northern Pacific Ocean, are accessing the Arctic Ocean, and have been rapidly expanding across the eastern Atlantic Ocean in recent years. United in addressing this challenge, experts came together to share knowledge and developed takeaways that will guide further collaborations:

Takeaway 1. *The commonality of change highlights connections among our oceans and differences in perspectives*. The natural, slow northward progression of pink salmon in the Pacific basin leads to a management approach that focuses on production, whereas the invasive, rapidly expanding presence of pink salmon in the Atlantic basin shifts the management strategy to eradication. The Canadian Arctic will need to straddle the strategies as subsistence harvesters targeting Arctic species increasingly catch pink salmon originating from both basins.

Takeaway 2. *The pace of change catalyses the pace of response*. The immediate need for management and conservation action in the Atlantic basin can be guided by knowledge inherent to the Pacific basin, where the species is well-studied. Across the northern hemisphere, however, there is a fundamental gap in understanding the effects of interactions between pink salmon and other species in freshwater and marine ecosystems where the pink salmon are new or expanding in range and/or abundance and with species that have not encountered pink salmon before. There is an opportunity to apply what is known to better understand what is not known.

Takeaway 3. *The scale of change requires a similar scale of collaboration*. Monitoring and assessing the shifting distributions of pink salmon across the broad expanse of the northern hemisphere requires a continued coordinated approach to the exchange of information, methods, samples, and technology that is on pace with the changes taking place. Sharing what is known about pink salmon will assist in prioritizing knowledge gaps and will guide future strategies. A structured process facilitates this exchange.

Pink salmon are clearly on the move in the northern hemisphere. Although they represent one species among a global redistribution of life, they also represent an opportunity to better understand broad-scale biodiversity change across our connected ocean.

1. Pink Salmon Ecology, Distribution, and Abundance

Pink Salmon Ecology

As a biological species, pink salmon *Oncorhynchus gorbuscha* have existed for about 5 million years and are likely the most recently evolved of the salmon species (Glubokovsky 1995). In their native range, pink salmon have an almost exclusive two-year lifecycle, the shortest of the Pacific salmon species, with populations that spawn in odd- or even-years having evolved into distinct genetic entities. Paired seasonal runs (early and late, or "summer" and "autumn") with distinct morphological characteristics and spawning areas within river basins separate most pink salmon stocks. Emerging pink salmon fry migrate downstream from late February to August. In the northern regions, timing of downstream migration is usually latest, and juvenile salmon are smaller than in the south. Rates of offshore migration are likely related to feeding conditions of a specific year (Radchenko et al. 2018, and references therein).

Both odd- and even-year types spawn during late summer and autumn in the clean, coarse gravel in areas of shallow (10–100 cm) pools and riffles of small to large rivers. Pink salmon prefer moderately fast (30–150 cm/s) currents and generally avoid spawning in deep, slow-moving water or on muddy, sandy, or silted substrate (Heard 1991). Water temperatures during the peak of spawning range from about 5°C to 15°C and are generally higher for southern populations. Pink salmon, especially from late-run stocks, tend to spawn closer to the head-of-tide than other species of Pacific salmon, generally within 50 km of a river mouth (Heard 1991). However, pink salmon populations from large river systems such as the Fraser River and Skeena River in Canada are known to migrate up to 500 km upstream to spawn, and a substantial portion of other populations may spawn intertidally (Jones 1978).

Pink salmon mature at the smallest average size of any species of Pacific salmon (1.0–2.5 kg) and show marked sexual dimorphism (Beacham and Murray 1985). Spawning populations throughout much of their natural range may be extremely large, often exceeding hundreds of thousands of fish (Heard 1991). Freshwater mortality of juvenile pink salmon is high, ranging from about 75% to over 99%, and mostly occurs before emergence from the gravel (Hunter 1959). After emerging, pink salmon juveniles migrate rapidly downstream, generally in schools and usually during the hours of darkness (Heard 1991). Juveniles grow most rapidly during their residence in the nearshore marine environment. Preferred marine prey are small crustacea, such as copepods, euphausiids, amphipods, and cladocerans (McDonald 1960; Karpenko 1998). The proportion of insects and fish larvae in the diet of pink salmon also is substantial in many regions (Karpenko 1998). After residing in estuaries and nearshore habitat for a few weeks to a few months, pink salmon move offshore where they migrate at sea for 12–16 months (Heard 1991). Adult pink salmon prey preferences include zooplankton, squid, and fish (Davis et al. 2009).

Smolt to adult survival in pink salmon appears to vary widely among years and locations. Cross et al. (2008) reported rates varying between 3–8% in Prince William Sound, Alaska. Radchenko (2007) estimated survival rates for the Sea of Okhotsk basin between 2.0–8.7% for 1989–2004 year classes. Kaev (2021) reported rates between 1–18% in populations from Sakhalin Island, Russian Federation. Early marine growth has repeatedly been correlated with overall survival in Pacific salmon species. Although there is a lack of understanding of the exact mechanism, the timing, magnitude, and sources of stage-specific marine survival and early growth of pink salmon are probably governed by a combination of prey availability, smolt quality, inter/intra-specific competition, predation and ocean conditions (Cross et al. 2008).

The levels of straying in pink salmon, or attempt reproduction at non-natal sites (Quinn 1993), varies widely among populations and within populations under different conditions. Pink salmon may stray at higher rates than other species of Pacific salmon (e.g., Horrall 1981), with rates > 50% observed in some studies, whereas other studies reported lower rates between 0.1 and 12% (Hard et al. 1996). However, there is substantial evidence of rapid range expansion in pink salmon when conditions are favourable (e.g., Heard 1991; Pess et al. 2014, and references therein). The frequent occurrence of pink salmon in areas without permanent spawning populations well outside the usual spawning range (Figure 1) also suggests that pink salmon homing behaviour is highly plastic (Hard et al. 1996).

Pink Salmon Distribution

Natural Distribution

Pink salmon are the most widely distributed species of Pacific salmon along the Pacific Rim (Augerot 2005) (Figure 1). On the North American side, significant spawning populations of pink salmon extend from Puget Sound, the Strait of Georgia, the Fraser River northward to north-west Alaska. Spawning populations of the odd-year broodline tend not be self-sustaining below 47°N latitude on the Pacific coast of North America, although pink salmon have recently been observed in fresh water below 37°N, as far south as the Salinas River in 2011 (Skiles et al. 2013), and successful spawning has been detected in streams near 38°N latitude (Moyle et al. 2008). Populations belonging to the even-year broodline are probably not self-sustaining south of 49°N, going through short cycles of founding and extirpation (e.g., Snohomish River, Washington, WDFW 2022). Pink salmon can also access the Arctic Ocean coasts in the north; however, the existence of robust spawning populations of pink salmon in the North American Arctic remains debated (Nielsen et al. 2013). Based on the locations of commercial catches in the North American region, pink salmon stocks are in greatest abundance in central and south-east Alaska, including Prince William Sound, but are also present in large numbers in British Columbia during some years (Heard 1991; Fisher et al. 2007).

Along the Asian coasts, pink salmon spawn in rivers from northern Honshu Island in Japan and the northern Korean Peninsula to the north-east of Siberia. The most productive pink salmon stocks and main fisheries in this region are located on the eastern coast of Sakhalin and Iturup Islands and the western and eastern coast of Kamchatka (Radchenko et al. 2007; Shuntov and Temnykh 2008). Feeding areas in the open ocean extend from about 39°N in the Pacific Ocean (38°N in the Sea of Japan) to the northern Bering Sea. Along the coasts, pink salmon migration routes extend an additional 1–2° to the south, and to the Lena River mouth in Siberia.

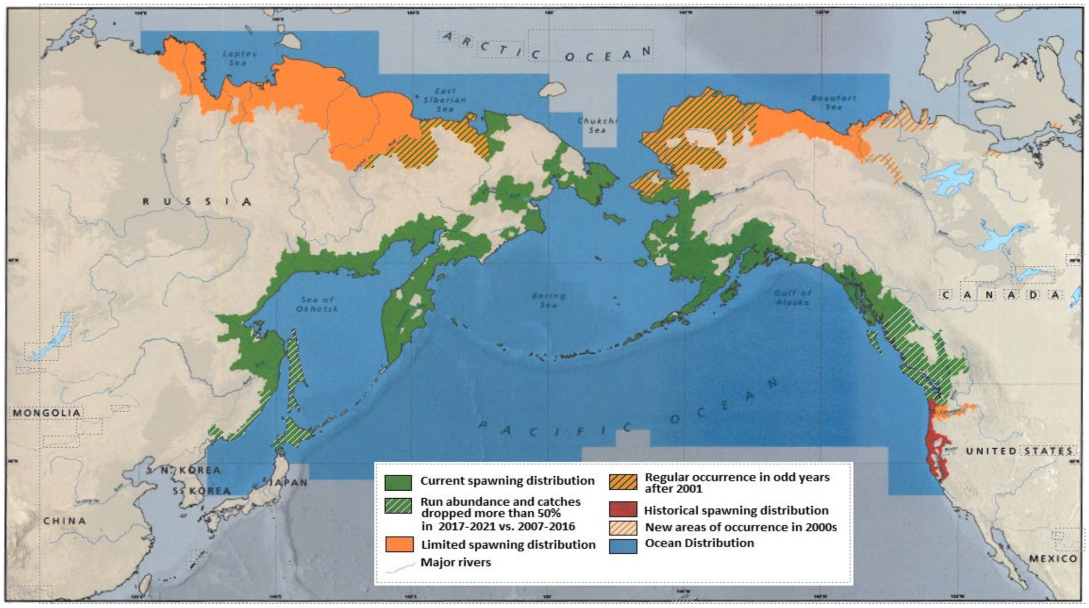

Figure 1. Pink salmon distribution (Augerot 2005) updated based on the recent reports on its penetration to the Arctic (Golub and Golub 2011; Dunmall et al. 2013; Farley et al. 2020; Stafford et al. 2022).

Introduced Distribution

Since the early 20th century, attempts have been made to introduce pink salmon outside its native range with the aim to create additional fishing opportunities (Heard 1991). One of the earliest attempts at pink salmon introduction into the North Atlantic Ocean was undertaken in the USA, when more than 40 million eggs were transplanted into the Gulf of Maine rivers between 1906 and 1926 (Ricker 1972; Lear 1975). This produced significant returns of subsequent year classes (several thousand fish) and their natural spawning. After 1927, however, few adult fish were observed (Gritsenko and Bakshtansky 1975; Heard 1991), although pink salmon were planted in Maine once again in 1982 (Randall 1984). Another introduction of pink salmon in the North Atlantic Ocean occurred in Newfoundland, Canada, between 1956 and 1966. Despite a maximum of 8,500 natural spawners in the peak year 1967, runs declined throughout the 1970s (Lear 1975). Pink salmon were captured on the east coast of Canada in northern Labrador and in Newfoundland up to the late 1970s (Dempson 1980). Pink salmon were also observed in New Brunswick in 1983 (Randal 1984) and in Nova Scotia (Crossman 1991). Small naturally occurring populations of pink salmon in Newfoundland remained a possibility in the 1980s (Dempson 1980). In the Hudson Bay area in northern Ontario, Canada, pink salmon ova, fry, and fingerlings were stocked into Goose Creek in 1956, but no adult pink salmon were subsequently reported from the Hudson Bay (Ricker and Loftus 1968).

In the Great Lakes in the USA and Canada, pink salmon were accidentally introduced into Lake Superior in 1956, and have since been firmly established in Lake Superior, Lake Huron, Lake Erie, and Lake Ontario (Heard 1991; Kwain and Lawrie 1981). Some notable differences between these populations that complete their life cycle in freshwater and the anadromous donor population from the Lakelse River in British Columbia (Canada) are lower fecundity, smaller size, variable ages at maturity (three- and four-year-old adults are reported), and a different body shape (Heard 1991). These appear to be adaptations to the less favourable growth conditions in freshwater relative to the marine environment, possibly facilitated by rapid genetic drift due to small population size and genetic isolation from other pink salmon populations (Berg 1979). For Lake Superior and Lake Huron, catch-per-unit-effort was greater in even years (57 fish/night) than in odd years (30 fish/night) (Kennedy et al. 2005) indicating that the even-year broodline was likely more abundant.

In the north-western part of the Russian Federation, pink salmon were introduced into the river basins of the Barents and White Seas. In 1956–1972, about 199 and 46 million salmon eggs, respectively, were brought to the north-western region. Transportations of fertilised eggs initially were from the Sakhalin and Iturup Island hatcheries in late October to early November (Zubchenko et al. 2004). A relatively small amount of pink salmon eggs, about 2 million, from the western Kamchatka coast and 0.5 million eggs from the Magadan region, were transported to streams flowing into the Barents and White seas in 1959 and 1961. An additional 19.5 million eggs from the Magadan region were stocked out between 1984 and 1988 (Zubchenko et al. 2004). Since 1961, pink salmon fry hatched from ova collected from fish returning to local Kola Peninsula rivers of the Barents Sea were also released into these streams. Numbers of such releases reached a noticeable amount only twice, including about 2 million eggs in each of 1961 and 1973. In other years, releases varied from 50,000 to about 1.5 million eggs with one- to eight-year cessations until the program ended in 1999. Despite the relatively high pink salmon returns to rivers of the Kola Peninsula, Karelia, and Arkhangelsk regions in first years after introduction (e.g., 76,300 fish in 1960; 220,500 in 1973; 215,300 in 1975; and 162,700 in 1977), a decline in numbers of spawning fish was subsequently observed. Without the transport of new eggs, pink salmon returns rarely exceeded two to three thousand fish in odd years, whereas they were essentially zero in even years (Kudersky 2005; Dorofeyeva 2009). A restoration of pink salmon runs occurred after the resumption of ova transportation from rivers of the Magadan region to Kola Peninsula rivers in 1984. In 1987, the first pink salmon return was recorded from natural spawning in the local rivers. Catches ranged between 96–339 metric tonnes (mt) in odd years from 1989–2003 (Kudersky 2005).

Attempts of pink salmon introduction into the Caspian, Black, and Baltic seas have been unsuccessful. In 1962 and 1963, six million fertilised pink salmon eggs were transported to a trout hatchery in the Black Sea basin, but no information was available to assess survival after the two years of releases (Gritsenko and Bakshtansky 1975). Small pink salmon catches (about 1500 in total) were observed in the north-western Caspian Sea after the introduction of 2 million eggs in 1964 (Magomedov 1970; Karpevich et al. 1991). In the Baltic Sea, including along the Sweden coast, a few to several hundred pink salmon returned only in the year following release. Thus, pink salmon were able to feed and grow in the brackish Baltic Sea environment, but natural reproduction did not occur (Kudersky 2005).

Some attempts were made to commercially grow pink salmon in brackish-water lakes of the Krasnoyarsk region (Central Siberia). Pink salmon grew satisfactorily and reached sexual maturity. In 1979, 7.9 mt of marketable fish and food caviar were obtained. This project, although it was experimental in nature, showed the possibility of pink salmon commercial aquaculture in brackish waters (Kudersky 2001).

No other attempts of pink salmon introductions are known from the north-eastern Atlantic area, except for a small introduction attempt in southern Norway in 1976 (Sandlund et al. 2019).

In Japan, pink salmon eggs from the north-eastern Hokkaido rivers were introduced to Yurappu River, southern Hokkaido, in the 1950s–1960s (Ishida 1967) and to Akka River, Iwate Prefecture, Honshu Island, in the 1990s (K. Morita, personal communication). Sano and Kobayashi (1953) reported that the return rate of introduced marked pink salmon in the Yurappu River was 0.5%. In the case of Akka River, it is difficult to determine if these transplantations were successful or not, because small numbers of native pink salmon were present in these rivers. Although about 90% of released pink salmon fry were marked by a fin clip, marked fish were not recaptured. The recapture of only non-marked wild pink salmon in the returns suggest that the marked introductions were unsuccessful.

Range Expansion

Pacific to North-eastern Russia and Western Canadian Arctic Connection

Pink salmon have also extended their natural distribution range in the marine environment into the Russian and Canadian Arctic. In 2007, high abundances of juvenile pink salmon were reported from the Chukchi Sea, suggesting that the Arctic marine ecosystem may provide viable habitat in some years (Moss et al. 2009). Warming temperatures may facilitate increased pink salmon production at the northern extent of their natural range (Farley et al. 2020), and may also contribute to the occasional harvest of adult pink salmon in subsistence fisheries targeting other species across the Canadian Arctic (Dunmall et al. 2013). In the western Canadian Arctic, these occurrences have increased from the sporadic catch of individual fish prior to 2003 to more catches being reported in both even- and odd-numbered recent years, and across a wider geographic area (Dunmall et al. 2018, 2021). Pink salmon have also been reported, although rarely, from the eastern Canadian Arctic in recent years (McNicholl et al. 2021).

In the Russian Arctic, pink salmon westward penetration was also noted since 2011, when the abundance of pink salmon runs to the Chukotka Peninsula coasts sharply increased and reached 10 million fish (Golub & Golub 2011). The westernmost observations of pink salmon spawning in the (Asian) Russian Arctic are from the River Lena area around 127°E (Shuntov and Temnykh 2008). The Taymyr Peninsula appears to be a natural border that divides the pink salmon native and introduced ranges in the Russian Arctic (Prusov and Zubchenko 2022). Salmon straying to non-natal regions tend to reproduce poorly (due to maladaptive spawning dates and other factors, e.g., Zolotukhin 2006).

North-western Russia to Atlantic Connection

Currently, pink salmon are distributed over a wide range in north-western Russia. Prior to 2021, pink salmon were primarily recorded in the White Sea rivers and also east of the Kola Peninsula in the rivers flowing into the Barents and the Kara seas (Rivers Pechora, Ob, Taz, Yenisey, and others) (Figure 2, Figure 3), whereas in the Barents Sea rivers of the Murmansk region, adult abundance was modest. Between 2001 and 2021, the Pyasina river, in the southwest of the Taymyr Peninsula, is the easternmost location of pink salmon distribution in the Kara Sea basin (Figure 2, Figure 3) (Bogdanov and Kizhevatov 2007, 2015).

Observations of pink salmon in the North Atlantic have been reported from a much larger geographical area and occurrences have increased noticeably since 2017 (ICES 2022a, b). Outside the Russian Federation, pink salmon have been observed in a wide range of countries such as Norway and Finland (Sandlund et al. 2019), Faroe Islands (Eliasen and Johannesen 2021), Scotland (Armstrong et al. 2018; Skóra et al. 2023), Ireland (Millane et al. 2019a, b), Iceland, Germany, France, Netherlands, and Denmark (Bean, 2017; ICES 2022a) and Greenland (Nielsen et al. 2020). In France, odd-year fish have been observed as far south as the Élorn River in the north-eastern Atlantic area. Pink salmon have probably established successfully reproducing populations as far west as the Norwegian region of Finnmark in recent years (E. Thorstad/K. R. Utne/H. Berntsen, personal communication), with reports of smolts as far south and west as the Jølstra River in the Sunnfjord in western Norway (Sægrov et al. 2022) (Figure 3). In addition, smolts were reported from rivers in northern Scotland and western Iceland (Skóra et al. 2022) in recent years (Figure 3). In Norway, compared to 2001 (Figure 2) when frequent spawning was observed as far west as the Varanger Fjord in Norway and occasional spawning to the town of Gamvik (E. Thorstad/K. R. Utne/H. Berntsen, personal communication), the 2021 limits are much farther west and south. Reports of even-year fish outside northernmost Norway/Finland/Russia remained very low between 2017–2021 with only a single report from the UK (ICES 2022a).

In the north-western Atlantic area, pink salmon have been observed as far north as Clyde River, Nunavut (McNicholl et al. 2021) and as far south as the Gander River in Newfoundland (ICES 2022a).

The increase in abundance of pink salmon since 2017 is discussed in section 1.3 of this report.

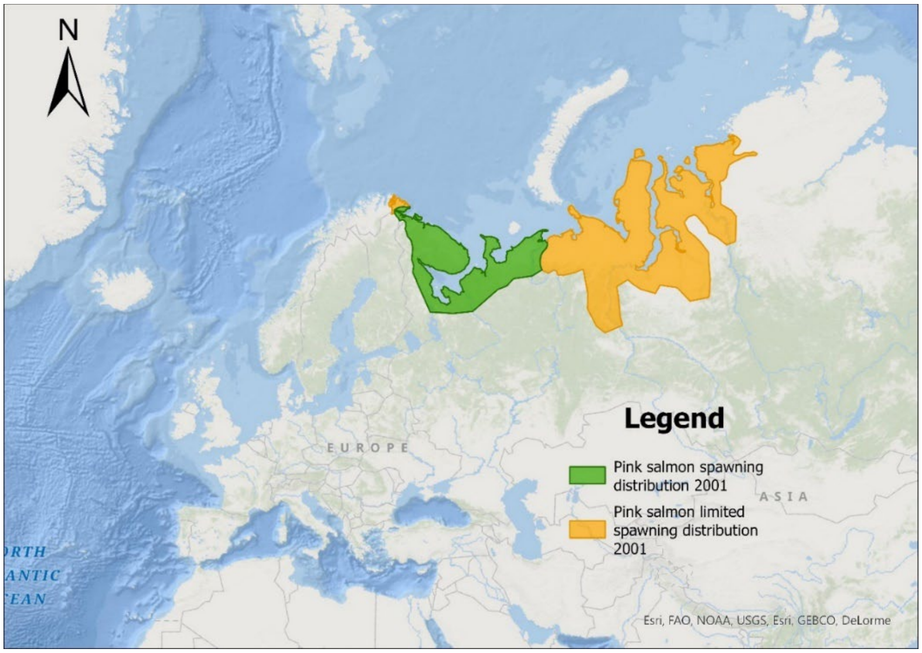

Figure 2. Pink salmon distribution in the Northeast Atlantic in 2001. Areas where pink salmon occurred and spawn regularly in odd years are highlighted by green, areas of adult pink salmon occurrence with limited or unknown spawning success are highlighted by orange.

Figure 3. Pink salmon distribution in the Northeast Atlantic in 2021. Areas where pink salmon occurred and spawn regularly in odd years are highlighted by green, areas of adult pink salmon occurrence with limited or unknown spawning success are highlighted by orange.

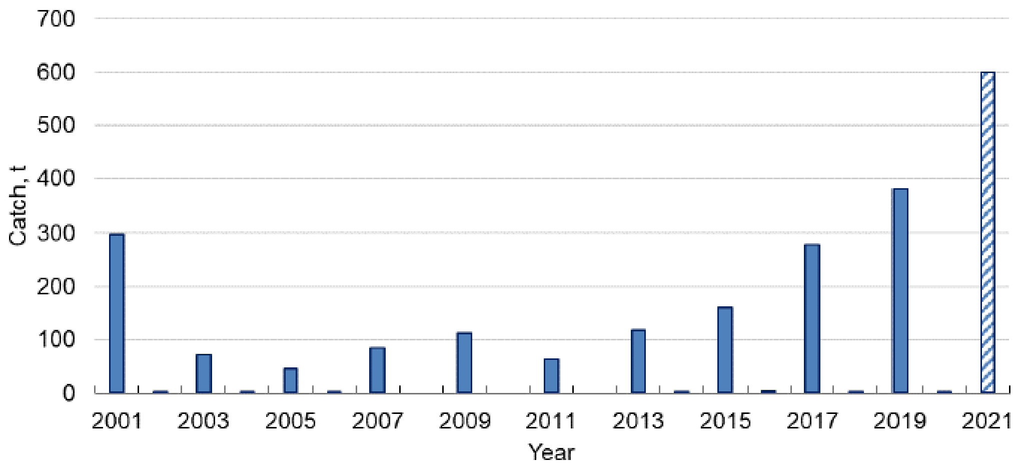

Figure 4. Pink salmon catches in Murmansk region in 2001–2021. Catch for 2021 is provisional (Prusov and Zubchenko 2022).

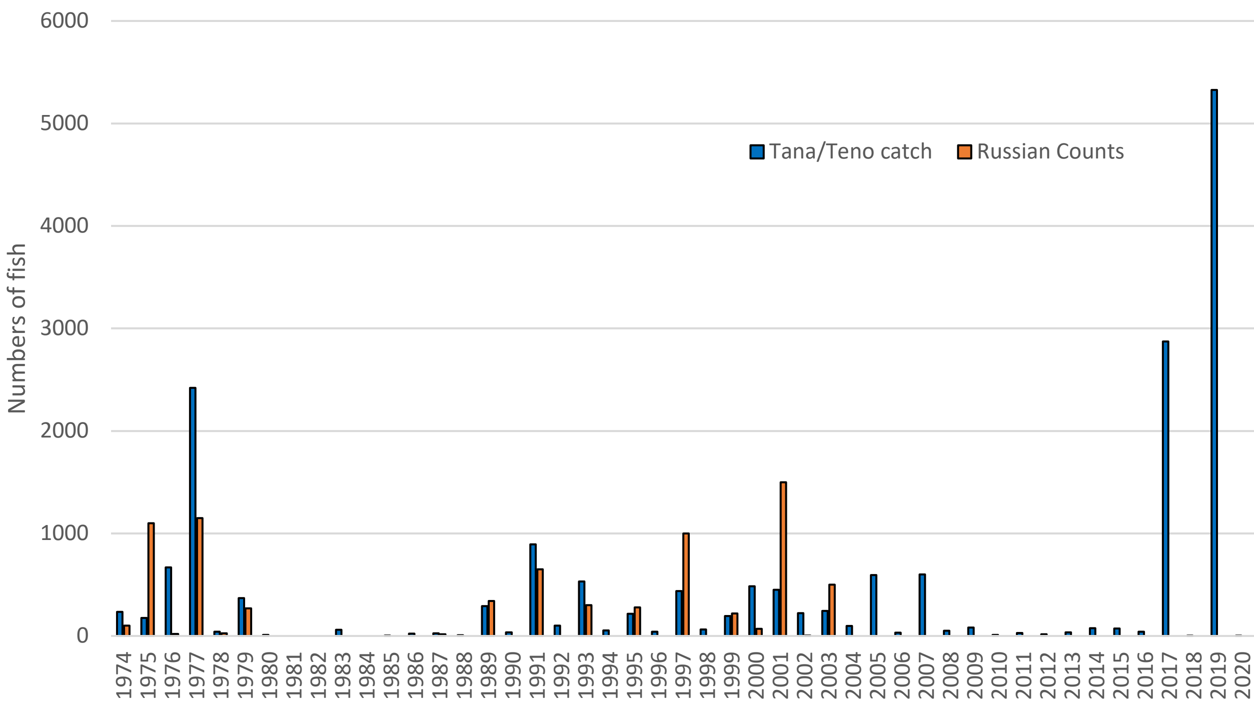

Figure 5. Sum of recorded catches of pink salmon in the river Tana/Teno in Norwegian and Finnish waters, 1974–2020 (data from LUKE and Tanavassdragets fiskeforvaltning, www.tanafisk.no), and counts of adult pink salmon in Russian catches 1974–2003 (Zubchenko et al. 2004).

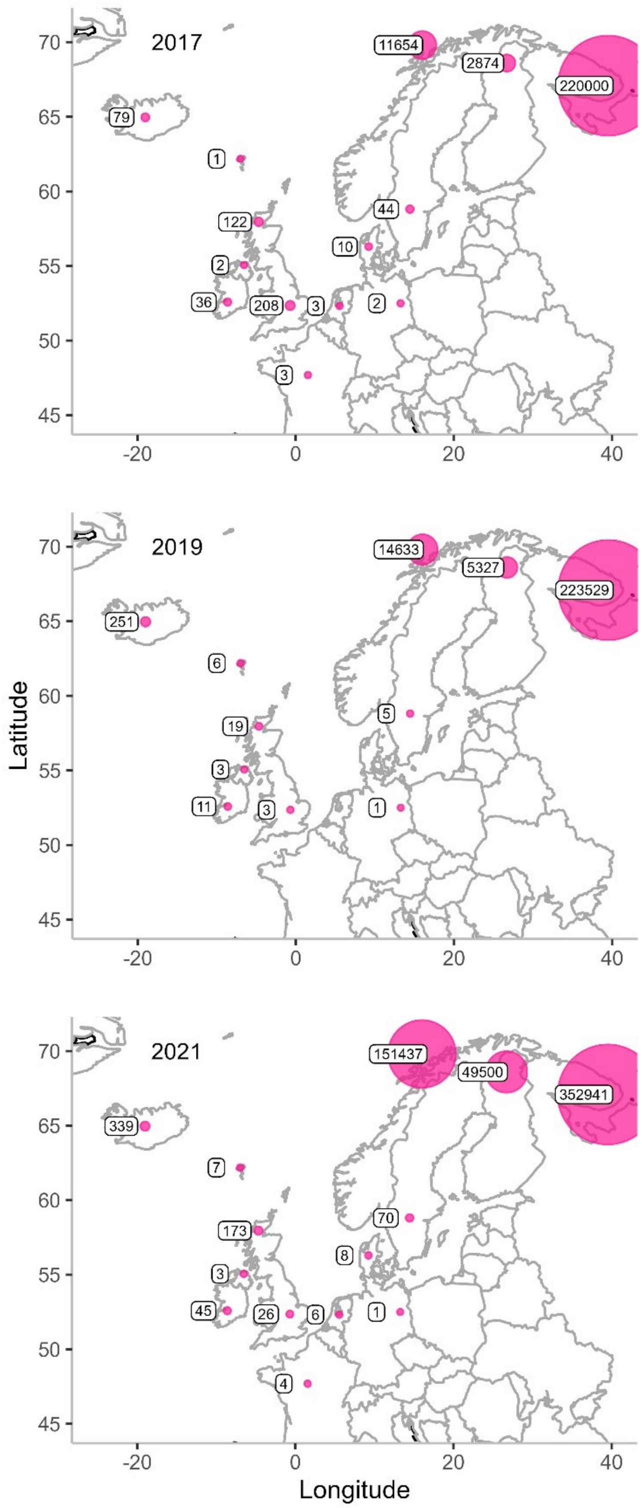

Figure 6. Numbers of pink salmon reported by jurisdiction in the NEAC area (2017, 2019, and 2021).

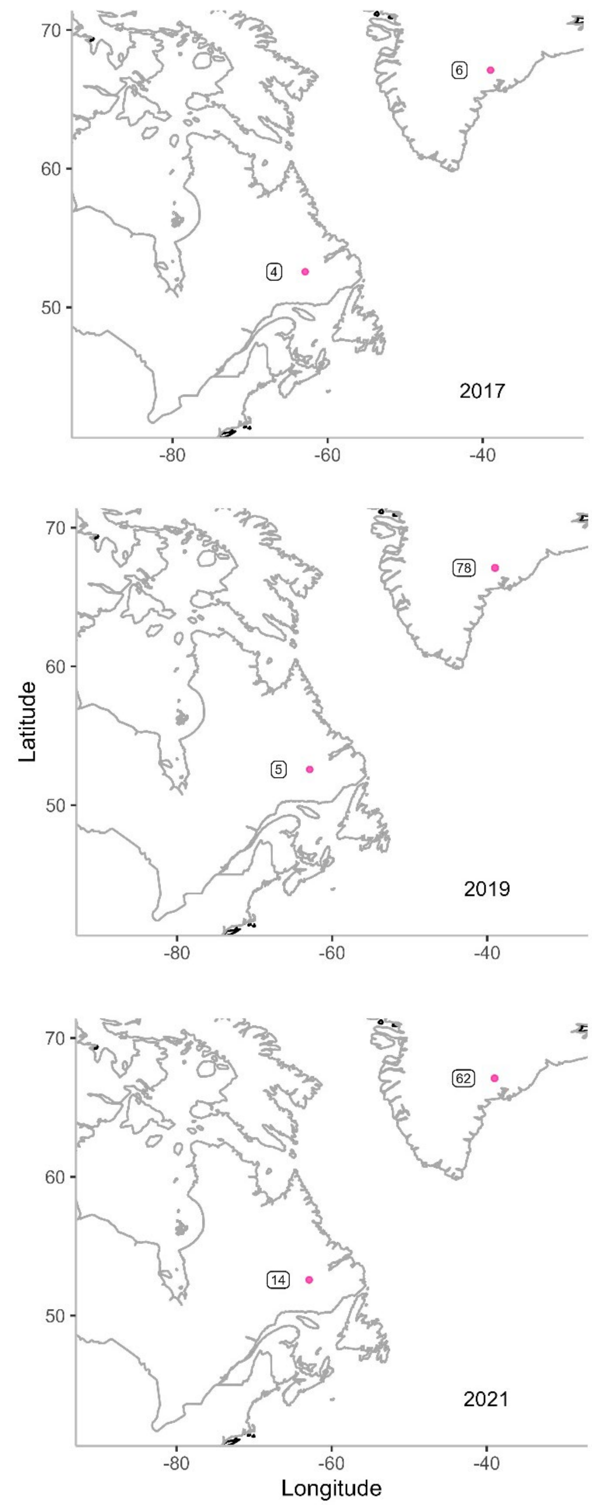

Figure 7. Numbers of pink salmon reported by jurisdiction in the NAC and WGC areas (2017, 2019 and 2021).

Pink Salmon Abundance

In the North Atlantic, pink salmon abundance pre-2000 was closely linked to the stocking activity in north-western Russia. Large numbers of adults were observed in rivers of the Kola Peninsula, Karelia, and Arkhangelsk regions in first years after introduction in the late 1950s (e.g., 76,300 fish in 1960; 220,500 in 1973; 215,300 in 1975; and 162,700 in 1977). During this time period large numbers of pink salmon were occasionally observed outside of north-western Russia, such as in 1960 when 20–25 mt were caught in northern Norwegian waters (Berg 1961). After stocking ceased in 1999, odd-year pink salmon catches in the Murmansk area increased to 300 mt in 2001 before settling close to 100 mt on average between 2003 and 2013 (Prusov and Zubchenko 2022). Catches then substantially increased above 100 mt again after 2015 reaching record numbers in 2019 (close to 400 mt) and 2021 (600 mt) (Figure 4). Even-year populations remained at low numbers during this time period. Abundant pink salmon runs in the White Sea coast rivers in 2021 led authorities to allow a commercial as well as a subsistence fishery on pink salmon. Predictions are that 1,200 mt of pink salmon will be harvested there in 2023.

Long-term time-series of pink salmon abundance outside north-western Russia are rare. The Sandlund et al. (2019) overview of catches in the Norwegian/Finnish Tana/Teno system in northernmost Norway and Finland between 1974 and 2017 (Figure 5) reported high catches in the 1970s, followed by a decline to zero after the first attempt to establish self-sustaining populations ended in 1979. In the 1990s, catches increased again to about 400–1000 individuals for odd-years, and below 100 for most even-years. Despite Russian stocking ceasing in 1999, odd-year catches between 2001 and 2007 reached their highest levels since 1977 and 1991, which means all these fish naturally spawned. Between 2007 and 2015 catches markedly decreased to some of the lowest levels seen for both odd- and even-years in the time-series. This was mirrored in a 2007–2017 time-series of pink salmon catches in the nearby Neiden River (Sandlund et al. 2019).

Since 2017, pink salmon catches and observations of odd-year fish have increased dramatically, both in the Russian Federation, northern Fennoscandia, and much further south such as central and southern Norway, the UK and Ireland, and as far south as France (Armstrong et al. 2018; Millane et al. 2019a; ICES 2022a, b) (Figure 6) and west and east Greenland (Nielsen et al. 2020; ICES 2022a, b). In 2017, pink salmon numbers reported to the International Council for the Exploration of the Sea (ICES) Working Group on North Atlantic Salmon (WGNAS) exceeded 230,000. In 2019, the number of pink salmon reported increased again to over 238,000 but with a much-reduced southern distribution. In 2021, the total number increased to well over 500,000 with record numbers reported from as far south as Scotland, Ireland, the Netherlands, and France. The north-west Atlantic area has also experienced an increase in pink salmon occurrences in 2017 and 2019 (Dunmall et al. 2018; McNicholl et al. 2021), and a record number of 14 individuals reported in 2021 (Figure 7). Even-year reports outside northernmost Norway/Finland/Russia remained very low between 2017–2021 with only a single report from the UK (England and Wales).

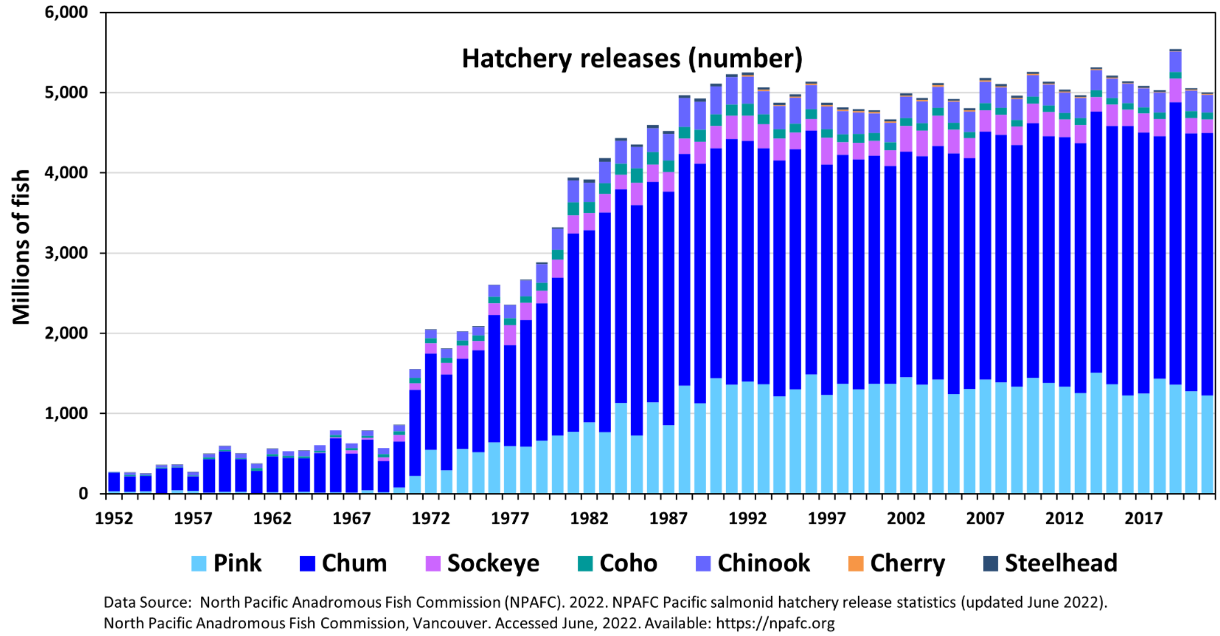

Figure 8. North Pacific Anadromous Fish Commission Pacific salmonid hatchery release statistics (NPAFC 2022b)**.**

In the Pacific, there have also been substantial increases in pink salmon abundance in recent years. However, a potentially complicating factor to establishing natural abundance in the Pacific is the hatchery releases of juvenile pink salmon undertaken by various countries to supplement natural production with a view to increase fishing opportunities. Hatchery supplementation of pink salmon in the Pacific has been relatively stable since 1990 with about 1,360 million juvenile pink salmon released annually (Figure 8).

Pink salmon have been the numerically dominant salmon species in the North Pacific Ocean since approximately 1990. In recent years, pink salmon comprised 67% of the total number and 48% of the biomass of all salmon in the North Pacific Ocean (Ruggerone and Irvine 2018). Naturally-spawned pink salmon were especially numerous during 1990–2015, averaging 379 million fish and up to 595 million fish (or 81% of the combined abundance of the three species) in peak years 2009 and 2011. Although even-year spawning pink salmon tended to be more abundant than odd-year fish during 1925–1935, odd-year spawning pink salmon were 27% more abundant than even-year pink salmon across the full period and 37% higher abundance during 1990–2015.

There is a clear north/south divide in the recent increased abundance of pink salmon in the Pacific. Conditions favour the pink salmon in the northern Pacific regions, where many large salmon populations occur in relatively intact habitats. Warming temperatures may facilitate increased production of pink salmon at their northern distributional extent (Farley et al. 2020) and pink salmon occurrences have also increased in the western Canadian Arctic in recent years (Dunmall et al. 2018, 2021). Contrastingly, many southern populations are adversely impacted by habitat degradation, oceanic conditions, interactions with hatchery salmon, and overharvest in mixed-stock fisheries, resulting in abundance declines (Malick and Cox 2016; Ruggerone and Irvine 2018). Irvine et al. (2014) also observed declining abundances in some southern even-year pink salmon conservation units (biological units that are genetically and/or ecologically distinct from each other) in British Columbia, although not in odd-year populations (Figure 9). Significant negative interactions between even- and odd-year broodlines were found for several of the BC regions, but there was little evidence of competition between broodlines in the marine environment. Irvine et al. (2014) suggested that a more-southerly glacial refugium for odd-year than even-year pink salmon and temperature-related survival differences between these broodlines may be benefiting odd-year returning pink salmon more than even-year salmon during global warming.

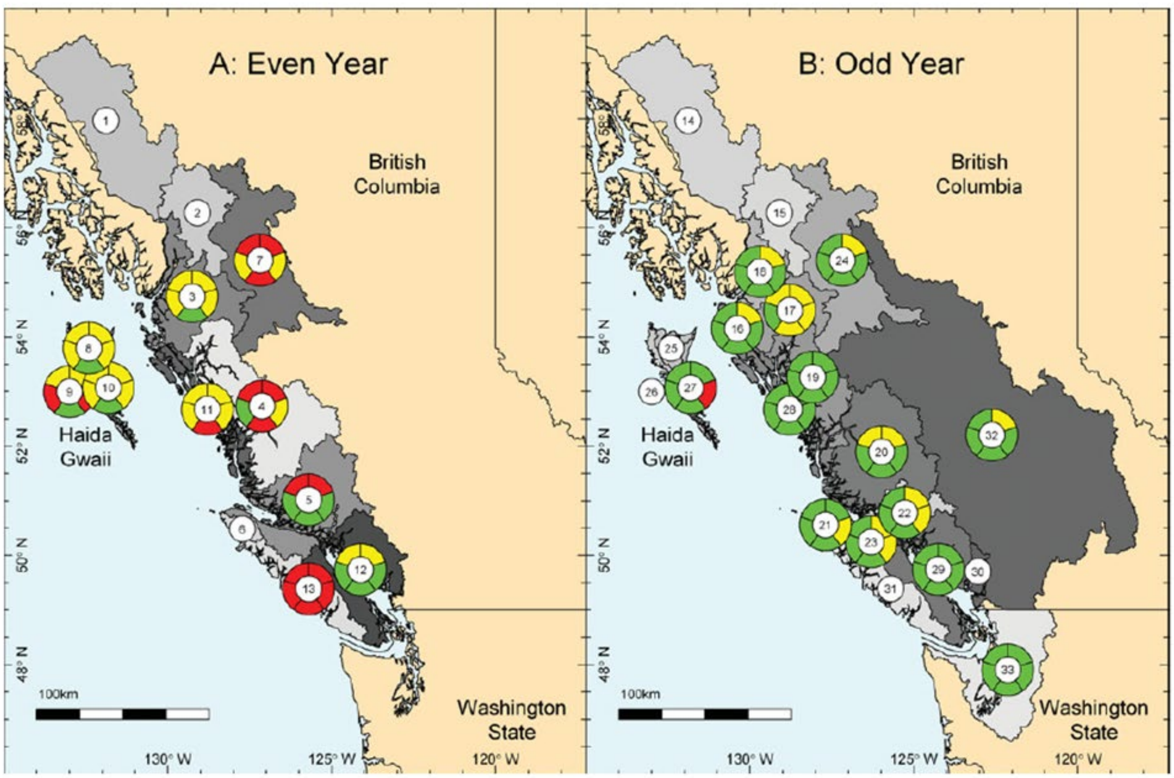

Figure 9. Status of (A) even-year and (B) odd-year pink salmon Conservation Units (CU) in British Columbia and Puget Sound (Washington State) depicted by five-piece circles in which the central number references the CU name and each piece shows the results from one time series approach. Green colours represent increasing numbers, yellow means no significant difference over time and red indicates decreasing numbers. See Irvine et al. (2014) for details.

2. Assessment and Monitoring: Current Schemes

Pacific Basin

The first Pacific salmon research programs in offshore waters were based on sampling conducted by the same gear as the commercial fisheries—gillnets, longlines, and purse seines. Offshore distribution, migration patterns, and feeding were studied, and a large amount of biological information was collected (Manzer et al. 1965; Neave et al. 1967; Takagi et al. 1981). In 1984–1990, the Russian research institute TINRO explored using a large-dimensioned rope trawl net to study migratory salmon and estimate their numbers in the Bering and Okhotsk Seas and adjacent Pacific Ocean as a part of pelagic ecosystem studies. A more practical two-season trawl survey was then developed with an abundance assessment of juvenile pink salmon migrating oceanward in October and an assessment of maturing returning fish in June–early July. With few exceptions, these surveys have been conducted in the north-western North Pacific annually since 1991 (Shuntov and Temnykh 2008, 2011; Radchenko et al. 2018). Extensive information was obtained on distribution, abundance, ecology, physiology, and trophic relationships of Pacific salmon that significantly supplemented and, in some cases, radically changed our existing knowledge base. Based on the trawl catches, annual calculations of pink salmon abundance, survival rate, and estimates of run magnitude, as well as abundance of all other fish and invertebrates' species in the survey areas, were made. In-season forecasting of pink salmon run magnitude and timing was mostly successful and notably contributed to the fishery season output.

Scientists from other NPAFC member countries have also tested the advantages of the new method of Pacific salmon studies on the high seas. In 1990–1991, Soviet and Canadian scientists conducted joint trawl surveys aboard the R/V *TINRO* in the central and eastern North Pacific Ocean (Morris et al. 1991, 1992). Since 1992, Canadian scientists have conducted trawl surveys on Pacific salmon aboard R/V *W.E. Ricker* and chartered Canadian fishing vessels (Beamish et al. 2003). In 1998, U.S. scientists developed salmon trawl surveys, off the north-western coast of the United States to study juvenile coho and Chinook salmon, and in the Gulf of Alaska to study all salmon species in the coastal area, and in Bristol Bay focussing on oceanward migrations of juvenile sockeye salmon (Farley et al. 1999). In 1997–2012, monthly trawl surveys across the Southeast Alaska straits were used to estimate pink and coho salmon production in the region (Orsi et al. 2013). In 1992, 1996, and 2006, Japanese scientists with colleagues from other NPAFC countries conducted salmon trawl surveys from the large-tonnage R/V *Kayo maru* (Ueno et al. 1996). In 1992, the first December offshore survey of salmonids in the North Pacific Ocean was conducted since the 1960s (National Research Institute of Far Seas Fisheries 1993).

An international research program called BASIS (the Bering-Aleutian Salmon International Survey) was developed by the NPAFC and implemented in 2002–2016. In 2002, the trawl survey aboard Japanese, Russian, and U.S. research vessels covered the whole Bering Sea and adjacent Pacific waters (about 3 million km^2). The goal was to clarify how Pacific salmon respond to climate change in the Bering Sea. The role of Pacific salmon as consumers of food resources in the pelagic fish communities of the Bering Sea was also assessed. The Pacific salmon distribution in the western and northern Bering Sea was influenced, not only by the food supply, but also by increased advection of Pacific waters since the early 2000s. BASIS became a precursor to the expeditionary part of the IYS program (Radchenko 2022a).

Surface water trawl surveys in the Northern Bering Sea (NBS) were initiated by NOAA's Alaska Fisheries Science Center (AFSC) in 2002 as part of the BASIS program (Murphy et al. 2021). These surveys were continued through 2007 as part of the BASIS survey for the eastern Bering Sea shelf. The NBS was not sampled in 2008, but it has been sampled on an annual basis since 2009 to support research objectives on the ecology of salmon in the NBS and to improve our understanding of how the NBS ecosystem is changing in response to warming climate and loss of Arctic sea ice.

The NBS survey has supported a range of different survey operations and research objectives. Survey operations have included the following: surface and midwater trawl sampling for pelagic nekton, midwater acoustics, seabird and marine mammal observations, bongo net sampling for zooplankton and ichthyoplankton, electronic conductivity, temperature, depth (CTD) data, and water collections for chlorophyll-a, phytoplankton, and nutrients. The survey supports research objectives on salmon and other pelagic fish resources, including: juvenile salmon abundance and run-size forecasts (Murphy et al. 2017; Howard et al. 2019; Howard et al. 2020; Farley et al. 2020), size-selective mortality (Murphy et al. 2013; Howard et al. 2016), energy allocation (Andrews et al. 2009; Murphy et al. 2013; Moss et al. 2017), diet (Farley et al. 2009; Andrews et al. 2016; Cook and Sturdevant 2013; Honeyfield et al. 2016; Garcia and Sewall 2021), and species distribution (Murphy et al. 2009; Murphy et al. 2016; Andrews et al. 2016). The BASIS survey was the first to observe mass migrations of juvenile pink and chum salmon into the Chukchi Sea (Moss et al. 2009).

Data from the NBS survey were recently used to develop models for pink salmon life-history and provide insight into pink salmon production dynamics for this region (Farley et al. 2020). Arctic ecosystems, including freshwater and marine ecosystems in the northern Bering Sea, are warming at a rapid rate. Due to their two-year life-cycle, pink salmon respond rapidly to ecosystem change and can provide unique insight into ecosystem impacts of warming Arctic conditions. Life-cycle models suggest a lack of density-dependence for adult pink salmon spawners in the Yukon River but the potential for some density-dependence for adult pink salmon spawners in the Norton Sound region. Life-history models identify a significant positive relationship between the abundance index for juvenile pink salmon and average air temperature in Nome, Alaska during their freshwater residency (August to June). This relationship supports the notion that warming air temperatures in the Norton Sound region of Alaska (as a proxy for river and stream temperatures) are contributing to improved freshwater survival or increased capacity of freshwater habitats to support pink salmon production. Life-history models also demonstrate the number of adult pink salmon returning to Norton Sound and the Yukon River is significantly related to juvenile abundance in the northern Bering Sea. This indicates that much of the variability in survival for northern Bering Sea pink salmon occurs during early life-history stages and that juvenile abundance is an informative predictor of adult pink salmon runs to this region.

In Alaskan rivers, escapements are monitored annually using a variety of ground-based methods, such as weirs, sonar, counting towers and foot/boat surveys, or aerial surveys (see Tables 19–22 in Munro and Brenner (2022) for additional information). Because of the large number of streams where pink salmon spawn and the remoteness of many of them, most assessment in Alaska is by aerial survey. For example, in Southeast Alaska, wild pink salmon spawn in approximately 2,500 short, coastal streams and in-season escapement assessments are based on aerial surveys and peak aerial survey counts for about 700 streams (Heinl et al. 2021; Zadina et al. 2004). Aerial survey counts are used to estimate an annual escapement 'index' (i.e., not a total count) and to develop sub-area escapement goals. In Alaska, escapement assessments are used to assist with in-season management of the salmon fisheries and to determine annually if escapement goals are achieved (Munro and Brenner 2022).

In the Russian far east, the Sea of Okhotsk and the Bering Sea are monitored for Pacific salmon with medium-tonnage trawlers, with the primary goal to support forecasting purposes. These surveys study the abundance of salmon and environmental conditions that are relevant to salmon (including physical oceanography, plankton and nekton samples). Results for maturing salmon are predictive of the return of pink salmon in that year, whereas those for immature salmon predict the return in the following year (Shuntov 2010). This monitoring provides information on the spatial distribution of pink salmon (breadth and length of the migration flow), and on the sex ratio of the leading and trailing components of the migration. Samples are also collected for stock identification. Driftnet assessments in the Russian far east conducted from 1991–2008 began in May, whereas the current integrated trawl-based monitoring is focused mainly on pink salmon and begins in June. Both programs have shown that temperatures affect migration, altering route and timing relative to endogenous phenology as measured by gonado-somatic indices (e.g. Radchenko and Chigirinsky 1995). Scale patterns and body size have also been useful in detecting large fluxes of pink salmon to non-natal habitats (Kaev and Zhivotovsky 2017).

In nearshore and freshwater ecosystems of the Russian far east, programs to assess spawning ground and smolt abundances are also conducted within select coastal reference areas that represent multiple regions. Amongst other goals, this work informs escapement and hatchery production policies (Shuntov 2010).

Pink salmon are the most abundant Pacific salmon species in British Columbia (Radchenko et al. 2018), yet accurate and precise estimates of their abundance are often lacking, as are recent population assessments. This is probably due, in part, to a lack of recent conservation concerns for this species, as well as their relatively low commercial value. Pink salmon are not listed amongst the various stocks of concern in the most recent Integrated Fisheries Management Plans for Northern or Southern BC (Fisheries and Oceans Canada 2022a, b respectively), and most fisheries targeting pink salmon are primarily restricted due to concerns about catching non-target species.

Various indices of BC pink salmon abundance exist, each with strengths and weaknesses. These indices include expanded weights from canneries and other processing methods (e.g., Argue and Shepard 2005), commercial catch data (NPAFC 2022a), spawner abundance data (available from or by request from Canada's open data portal https://open.canada.ca/data/en/dataset/c48669a3-045b-400d-b730-48aafe8c5ee6), and various combinations of catch plus spawner estimates (e.g. Ruggerone and Irvine 2018, Pacific Salmon Explorer 2022). Cannery data from the early 1900s are useful indices of abundance for Skeena/Nass and Fraser stocks but difficult to compare with other time series. Catch time series are often the best single abundance index but do not account for varying fishing effort and are best suited for large geographic areas. Spawner escapement estimates are often specific to a watershed or conservation unit (Fisheries and Oceans Canada 2005), but the effort and approaches used are highly variable. For instance, in BC, the most common spawner estimation methods are peak live-plus-dead counts and area-under-the-curve estimates, but there are also partial and total fence counts, mark-recapture, test fishery catch-per-unit-effort (CPUE), visual surveys from the ground and air, and expert opinion (Cousens et al. 1982; Jantz et al. 1990; Irvine and Nelson 1995).

In the Fraser River, BC, the return migration of pink salmon in odd-numbered years is monitored for abundance, run timing, and marine migration route. Much of the information for this monitoring is provided by test and commercial purse seine catch and biological sampling (including DNA for stock composition analysis). The Secretariat Staff of the Pacific Salmon Commission are responsible for collecting, compiling, and integrating this information for fisheries managers (Hague et al. 2022). Fisheries and Oceans Canada (DFO) no longer conducts comprehensive sampling and enumeration programs on spawning grounds (Grant et al. 2014), but escapement estimates to the Fraser River and partial monitoring of the migration to upstream spawning grounds are provided by hydroacoustic and test fishing programs (Hague et al. 2022).

Each even-numbered year, DFO monitors the juvenile out-migration of pink salmon from the Fraser River, mainly through the use of traps near the upstream limit of tidal influence in the lower river (Vernon 1966). These estimates provide a key input for the abundance forecast in the subsequent odd-numbered year. The forecast is also informed by Fraser River discharge, as well as sea surface temperature, and sea surface salinity measurements from coastal waters in the Salish Sea and off the west coast of Vancouver Island (Fisheries and Oceans Canada 2021).

The abundance and timing of adult out-migrating Fraser River pink salmon have fluctuated widely, obscuring simple trends. Trends that have been detected are a considerable decrease in body size from the 1960s to 1990s and increases in up-river habitat use within the Fraser River in recent years (Grant et al. 2014). In coastal areas near the Fraser River, concerns for conservation, and interest in harvest, tend to be low for pink salmon relative to co-migrating salmon species. As a result, detailed studies regarding the detection and especially mechanistic understanding of trends in pink salmon are limited in the published literature relative to encounters in monitoring programs. Importantly, research trawls have been conducted annually in marine areas near the Fraser River since the late 1990s, encountering both odd- and even-year pink salmon, yielding data on juvenile abundance indices, size, diet, parasites, and other information (Chrys Neville, DFO, personal communication). Analysis of the data collected in this program could fill information gaps in the monitoring of Fraser River pink salmon.

In Washington, pink salmon spawn in odd years in many Puget Sound streams and rivers. Spawning in even years is inconsistent and is constrained to a single watershed. Pink salmon escapements are monitored annually using ground-based or aerial surveys. Pink salmon are found in coastal Washington rivers, but spawning has been inconsistent in recent years (Hard et al. 1996) and they are not regularly monitored. Low numbers of pink salmon, thought to be strays, are recorded passing the lower-most Columbia River dam each year (Columbia River Data Access in Real Time; https://www.cbr.washington.edu/dart/query/adult_annual_sum). Finally, Washington Department of Fish and Wildlife and tribal co-managers use traps and visual marine estimates to evaluate juvenile abundance annually.

Canadian Arctic

In the Canadian Arctic, adult pink salmon are rare and those observed are considered to be vagrants or strays from sources outside the area (Dunmall et al. 2013, 2018). Juvenile pink salmon have yet to be reported in the North American Arctic (Nielsen et al. 2013), perhaps due to a potential colonization bottleneck linked to narrow thermal tolerances at early life stages (Dunmall et al. 2016). This lack of reported juvenile pink salmon, however, may also be related to a current lack of directed effort to sample for juvenile pink salmon (Dunmall et al. 2013) or low awareness that they may be present, hindering potentially critical opportunistic observations from other programs (Dunmall et al. 2022).

Occurrences of adult vagrant pink salmon in the Canadian Arctic are monitored through a community-based monitoring program called Arctic Salmon, which has documented the occurrences of unusual fish in subsistence harvests since 2000 (Dunmall and Reist 2018). Harvesters voluntarily contribute the fish (whole or head) to the monitoring program in order to address community-driven questions about fish biodiversity change (Dunmall et al. 2013). Reported occurrences of pink salmon are also provided to Arctic Salmon through other community observation networks and related collaborations, established DFO monitoring programs, and media (social and news) reports (McNicholl et al. 2021) including the Arctic Salmon Facebook page (www.facebook.com/arcticsalmon). All fish received are identified to species using taxonomic keys (e.g., Scott and Crossman 1973) and, when necessary, using genetic analyses (e.g., Dunmall et al. 2022), and multiple tissue types are sampled and archived for analyses following a defined protocol. On occasion, the fish are not provided and high-resolution photographs may be used for species identification when the obvious dorsal “hump” and large black spots on the tail are clearly visible (Dunmall et al. 2013; McNicholl et al. 2021). The use of both scientific and local observations to monitor rare species across a vast geographic area presents an exciting opportunity to connect people and knowledges to better understand the impacts of a rapidly changing Arctic.

Atlantic Canada

In Atlantic Canada, monitoring of aquatic habitats for pink salmon takes several forms. In the north-eastern Canadian provinces of Newfoundland and Labrador, and Quebec, environmental DNA (eDNA, see section 5.3) sampling targeting pink salmon has allowed detection of the species in several rivers. However, monitoring to date has been most commonly conducted through voluntary reporting of bycatch in Indigenous and recreational fisheries (ICES 2022b). Awareness campaigns and tracking networks have been put in place for this specific purpose (e.g., for instance MFFP 2021). Social media have been very effective in publicising these campaigns. The monitoring of adult Atlantic salmon using counting fences also contributes information on pink salmon abundance and distribution (ICES 2022b). Considering the low number of fishermen and monitoring projects relative to the number of rivers, and the fact that pink salmon in freshwater environments have mainly been caught in the fall (ICES 2022b), when many fishing and monitoring activities in this region are ending (Quebec Fishery Regulations 1990 (SOR/90-214), Newfoundland and Labrador Fishery Regulations (SOR/78-443)), the current monitoring scheme is far from comprehensive. Given local concerns regarding the effects of invasive pink salmon on native species, plans for more systematic monitoring programs are being developed. For instance, surveys targeting juveniles would be valuable to verify the presence of self-sustaining populations in this region.

North-eastern Atlantic

In the north-eastern Atlantic there are currently no large-scale national monitoring schemes that specifically target pink salmon. Rather, data on the distribution and abundance of pink salmon come from a range of fishing activities or surveys that target other species such as Atlantic salmon, sea trout, or char. Data on pink salmon can therefore vary substantially in quality. Outside of North-East Russia (White Sea/Kola peninsula), Norway has by far the highest abundance of pink salmon with > 200,000 fish caught in 2021 (Berntsen et al. 2022). Before the major range expansion of naturally reproducing Russian pink salmon in 2017, catches of pink salmon were only sporadically reported, and there are no reliable time series statistics for catches of this species (Sandlund et al. 2019). Since 2017, data on the distribution and abundance of pink salmon in Norway has been reported through multiple fishing activities in rivers and along the coast (see Diaz Pauli et al. 2023; Berntsen et al. 2022; Section 1 of this report). Norway therefore has the most experience in collecting data on pink salmon and this section will mainly summarise this activity.

In Norway, adult pink salmon returning to rivers are captured either in targeted removal fishing with nets or traps, or as bycatch during recreational angling for native salmonids (Diaz Pauli et al. 2023; Berntsen et al. 2022). Drift count surveys are conducted in specific rivers to assess the situation before removal fishing or for counting numbers of fish where removal fishing is not possible (County Governor of Troms and Finnmark 2022). Pink salmon are also caught or observed during surveys monitoring or targeting escaped farmed salmon, or they are observed in camera systems in fish ladders designed for monitoring river migrations of adult Atlantic salmon.

In addition, electrofishing for pink salmon fry or smolts is conducted in some rivers where spawning has been observed (Muladal 2018, 2020; Muladal and Fagard 2022; Kanstad-Hanssen and Monsen 2022; Jensen 2022). Targeted removal fishing, drift count surveys, and electrofishing surveys are primarily organized at a county or municipality level and may vary in spatial coverage and intensity between years.

In coastal waters, pink salmon are either caught during recreational fishing (angling, gillnetting or trolling) or in a licensed salmonid coastal fishery, using bag- or bend-nets inside fjords, targeting Atlantic salmon on their return migration to rivers. Recreational fishing is not strictly regulated except for various restrictions on the gillnet fishery, while the licensed coastal fishery is strictly regulated in terms of fishing locations and periods.

Information on the wider marine distribution of pink salmon comes from bycatch in commercial fisheries targeting other pelagic species reported by the Norwegian Reference Fleet (Clegg and Williams 2020) and in scientific trawl surveys such as the International Ecosystem Survey in Nordic Seas (IESNS) (Diaz Pauli et al. 2023).

Catches and observations of pink salmon from the activities described above are all reported through different channels or reporting systems, either online or in reports. Information on the distribution and abundance of pink salmon is therefore spread out over many data sources but the Norwegian Institute for Nature Research (NINA) collects all available data in a database and analyses are published in annual (odd-years) reports (Berntsen et al. 2018, 2020, 2022).

Catches of adult pink salmon reported from other countries such as Sweden, Ireland, Scotland, Faroe Islands, Iceland and Greenland are low compared to those in Norway (< 400 fish per country per year since 2017) and are mainly reported from recreational angling in rivers (Armstrong et al. 2018; Staveley and Bergendahl 2022; Nielsen et al. 2020; Millane et al. 2019b; Eliasen and Johannesen 2021). Although catches of adults are comparatively low, pink salmon juveniles were present in two rivers in Scotland in March 2022 and within the Botnsá river (Iceland) in May 2022. These fish were caught during targeted electrofishing efforts and net surveys to assess the potential establishment of pink salmon in those areas (Skóra et al., in prep).

3. Competition and Interactions Between Pink Salmon and Other Aquatic Species

Although the effects of pink salmon on freshwater ecosystems in their native range are reasonably well-understood, there is a lack of scientific consensus on the impacts of pink salmon in the marine ecosystem. Interestingly, most publications that support the hypothesis that pink salmon have top-down impacts on other marine species via the food web are from North America and are written in English, while most publications that argue that effects of pink salmon on the marine ecosystem are negligible or minor are from Asia in non-English, primarily Russian, sources. The purpose of this section is to provide a high-level summary that reflects both points of view and to recommend future work that can help resolve this controversy. We start by summarizing key facts about pink salmon that are not in dispute, then provide evidence for and then against the hypothesis that pink salmon effects on other marine species are significant. Lastly, we provide some future direction to better understand and help resolve this debate.

Most scientists agree that:

1. Pink salmon have been the numerically dominant salmon species in the North Pacific Ocean since approximately 1990. In recent years, pink salmon comprised 67% of the total number and 48% of the biomass of all salmon in the North Pacific Ocean (Ruggerone and Irvine 2018).
2. Pink salmon that spawn in odd-numbered years are genetically isolated from those that spawn in even years (Irvine et al. 2014; Radchenko et al. 2018).
3. Data from prior to the mid-1930s indicate even-year spawning pink salmon were more abundant than odd-year in both the Western and Eastern North Pacific Ocean. Since then, odd-year spawning fish have generally been more abundant (Irvine et al. 2014; Radchenko et al. 2018). This is not the case everywhere, however, and there have been interesting switches between even and odd-year dominance in certain areas, primarily the western North Pacific (Nagata et al. 2007; Radchenko et al. 2018).
4. Pink salmon appear to be benefitting from ocean warming, especially in northern regions (Radchenko et al. 2007; Beamish 2012; Irvine et al. 2014). Warming contributes to recent range expansions in Arctic waters of North America (Farley et al. 2020) as well as Asia and Europe where hatchery releases in Russian waters allowed pink salmon to become initially established (Nielsen et al. 2013; Skóra et al. 2022, 2023; Diaz Pauli et al. 2023).
5. Pink salmon diet in the marine phase, of primarily large calanoid copepod zooplankton and euphausiids and increasing amounts of squid and forage fish as they grow (Brodeur 1990; Karpenko et al. 2007; Davis et al. 2009; Graham et al. 2021), overlaps with many other species (Johnson and Schindler 2008).

The following evidence based upon the highly unusual biennial alternation of high (odd years) and low (even years) pink salmon abundance years that serves as a natural "experiment" supports the hypothesis that in years of high pink salmon abundance, zooplankton and other prey populations can be cropped down, impacting many other species in the marine ecosystem:

1. Numerous studies support the hypothesis that pink salmon, when present in high numbers, can exhaust food supplies (e.g., zooplankton biomass), inducing trophic cascades down to the phytoplankton level (Shiomoto et al. 1997; Batten et al. 2018). Specifically, Batten et al. (2018) hypothesized that a trophic cascade, initiated by predation pressures due to abundant maturing eastern Kamchatka pink salmon in the Bering Sea in odd year summers, could explain biennial changes in the abundance levels of large phytoplankton and copepods. In another study, Sugimoto and Tadokoro (1997) found zooplankton biomass anomalies were negatively correlated with Asian pink salmon abundance, as was chlorophyll-a (a proxy for phytoplankton biomass).

2. Studies detail overlapping diet compositions of pink salmon and various non-salmon marine fish species that co-mingle in time and space. Reduced prey availability may directly or indirectly cause reductions in early marine growth and/or enhanced mortality of species competing for zooplankton resources at different stages of their marine life. One example is Atka mackerel—their growth was negatively correlated with the abundance of eastern Kamchatka pink salmon (Matta et al. 2020) except in 2013, a year of unexpectedly low pink salmon returns, highlighted by Batten et al. (2018). Other examples include sand lance in the Salish Sea that were 13 times more abundant in odd than even years (Baker et al. 2020) and Pacific herring (Deriso et al. 2008; Pearson et al. 2012).
3. Numerous studies document biennial fluctuations in various aspects of salmon productivity (Kaeriyama et al. 2000; Ishida et al. 2002; Ruggerone and Irvine 2018; Ruggerone and Nielsen 2004; Cline et al. 2019), including studies that focused on chum (Azumaya and Ishida 2000; Kaga et al. 2013; Litz et al. 2021), sockeye (Bugaev et al. 2001; Ruggerone et al. 2003, 2005, 2007, 2016, 2019; McKinnell & Reichardt 2012; Connors et al. 2020), Chinook salmon (Ruggerone and Goetz 2004; Kendall et al. 2020; Anderson et al. 2021; Claiborne et al. 2021; Buckner et al. 2023) and steelhead (Myers 2018).
4. Results demonstrate effects of zooplankton consumption by pink salmon in years of high abundance on a wide variety of other species ranging from resident and migratory seabirds (Springer and van Vliet 2014; Springer et al. 2018; Toge et al. 2011) to southern resident killer whales (Ruggerone et al. 2019).

Yet the link between the various biennial patterns and pink salmon remains a hypothesis. If pink salmon are not the cause, what might it be?

Opposing views on pink salmon competition with other species have been expressed as criticism of cited research as well as in studies on carrying capacity of the North Pacific marine ecosystems in relation to salmon ranching. These include the following points.

1. North Pacific Ocean zooplankton standing crops are very large and their productivity values are high. Estimates of Pacific salmon consumption represent only a small fraction of potential prey standing stocks and are negligible compared to intake by other fish species. For example, in far-eastern seas, zooplankton biomass in the upper pelagic layer is estimated at 0.8 billion mt with annual production of 28–32 billion mt, while annual zooplankton consumption by fish and squids was estimated to be 274.5 million mt in 1996–2005 (Shuntov et al. 2017).
2. Pacific salmon constitute a small fraction of pelagic nekton biomass, estimated to be a few hundred million mt for the whole Subarctic Pacific Ocean (Shuntov et al. 2017). Estimates of recent average annual adult pink salmon biomass range from 0.6–0.8 million mt (0.6 value from Ruggerone and Irvine 2018 for 1990–2005 and 0.8 value from Radchenko et al. 2018 for 1989–2008). The proportion of food consumed by

Pacific salmon accounts for only a few percent of the total food consumption by nekton and is considered unlikely to significantly impact the trophic web structure.

3. Pacific salmon are very flexible in diet ration composition and their prey include numerous fish and squid species. Copepods chosen as a trigger for trophic cascade effects contribute about 10% to the average pink salmon food ration with euphausiids and hyperiids as preferable items. If pelagic food webs were susceptible to impacts of such magnitude, we could expect much more prominent effects from other ecosystem events like annual variability of biomasses of walleye pollock, Japanese sardine, Pacific saury, mesopelagic fish, etc.
4. Significant overlaps of different salmon species' diet composition may lend credence to the sufficient food resources rather than competition between them. For instance, during the 2022 IYS Expedition, winter foraging areas of Pacific salmon species differed substantially, especially between sockeye and pink salmon, and yet those species demonstrated the largest overlap in prey composition (Radchenko 2022b). In addition, major stocks of pink salmon and sockeye salmon demonstrate the most positive abundance dynamics of all species and have both posted record catches in the current century (NPAFC 2022a).
5. Feeding habits of Pacific salmon species differ even in regions of co-dwelling. Morphological traits of Pacific salmon suggest that mostly planktivorous species (pink, chum, and sockeye salmon) can find their own preferable feeding spots in a mutual food supply (Radchenko et al. 2018). Specifically, chum salmon have a bulkier stomach than pink and sockeye salmon and their esophagus ends with a powerful sphincter, allowing them to consume larger amounts of low-caloric food that can be mechanically accumulated by eddies. Sockeye salmon, with more myoglobin in their muscles and larger eyes, dive for food below the thermocline. Pink salmon, with the largest proportion of caudal fin area to body size, can cover large distances during feeding migrations.
6. Even the most abundant Pacific salmon species, pink and chum, do not follow the principle of competitive exclusion (Gause's Law) during their marine phase. Multi-year (1998–2012) autumn observations of juvenile pink and chum salmon distribution and abundance in the Sea of Okhotsk show that these species behave as a complimentary, rather than competitive, species complex (Radchenko et al. 2013).

In fresh water, pink salmon fry and adults feed less than most other Pacific salmon (Heard 1991) and as a consequence, interactions with other species are limited. At the same time, migrating pink salmon fry can serve as an important food source for many types of fish, birds, and invertebrates in rivers and associated estuaries (Hard et al. 1996; Beamish et al. 2003; Karpenko 2003). As for the adults, nutrients provided by decomposing and frequently abundant pink salmon carcasses often have positive bottom-up effects on the productivity of aquatic and riparian food webs (e.g., Gende and Quinn 2006; Walter et al. 2006). Such cross-ecosystem nutrient subsidies positively affect terrestrial plant growth and reproduction (Dennert et al.

2023). Compared to other, larger Pacific salmon species, spawning pink salmon concentrate primarily in small streams and lower river reaches, diversifying beneficial effects on terrestrial ecosystems. Where suitable conditions are limited, e.g., towards the northern extent of their distribution, pink salmon may compete with other species for limited fresh water spawning habitat (Dunmall et al. 2016).

There have been concerns about the aggressive behaviour of pink salmon to other salmon in fresh water. While pink salmon have been seen attacking other fish on the spawning grounds, the redd-guarding behaviour of females and mate-guarding behaviour of males is typical for all salmon species (Quinn 2018) including coho salmon (Fleming and Gross 1994, Kitano and Shimazaki 1995), Chinook salmon (Anderson et al. 2015), and kokanee (Morbey 2003). It is unlikely that salmon attack each other in the marine phase as extensive analyses of salmon body injuries from at-sea catches do not reveal any wounds inflicted by other salmon (Zolotukhin and Kaplanova 2005).

The topic of competition and interactions between pink salmon and other species in marine ecosystems needs further research. Is it possible that both points of view described above are correct, but for different regions of the northern North Pacific Ocean? For example, higher production of zooplankton in western regions than in central and eastern regions may reduce competition for prey (Batten et al. 2018; Naydenko and Somov 2019). Perhaps pink salmon effects on the marine ecosystem vary between the east and west sides of the Kamchatka Peninsula? Or, more generally, between the western and eastern North Pacific? Alternate hypotheses leading to better understanding of the potential drivers of biennial variability in marine and freshwater ecosystems are important to better understand potential impacts of pink salmon abundance and variability. This is especially true as pink salmon colonize new areas in the Arctic and Atlantic. Continuing collaborative investigations such as documented in this publication will be important going forward.

4. Genetic Stock Delineation

International collaboration efforts are key to advancing our understanding of pink salmon genetic structure and stock delineation across the species' native and expanding range throughout the Northern Hemisphere. To date, pink salmon genetic structure has mostly been studied on a limited, fine-scale level where pink salmon populations of a single region, country, or lineage were examined. However, these fragmented studies across the native Pacific range have consistently observed: (1) greater genetic diversity within the odd-year lineage than the even-year lineage, and (2) greater genetic differentiation between lineages than between geographic areas (Aspinwall 1974; Olsen and Seeb 1998; Beacham et al. 2012; Limborg et al. 2014; Seeb et al. 2014; Tarpey et al. 2018). Broadly, coastwide genetic structure studies improve our understanding of the species' past, present, and future distributions.

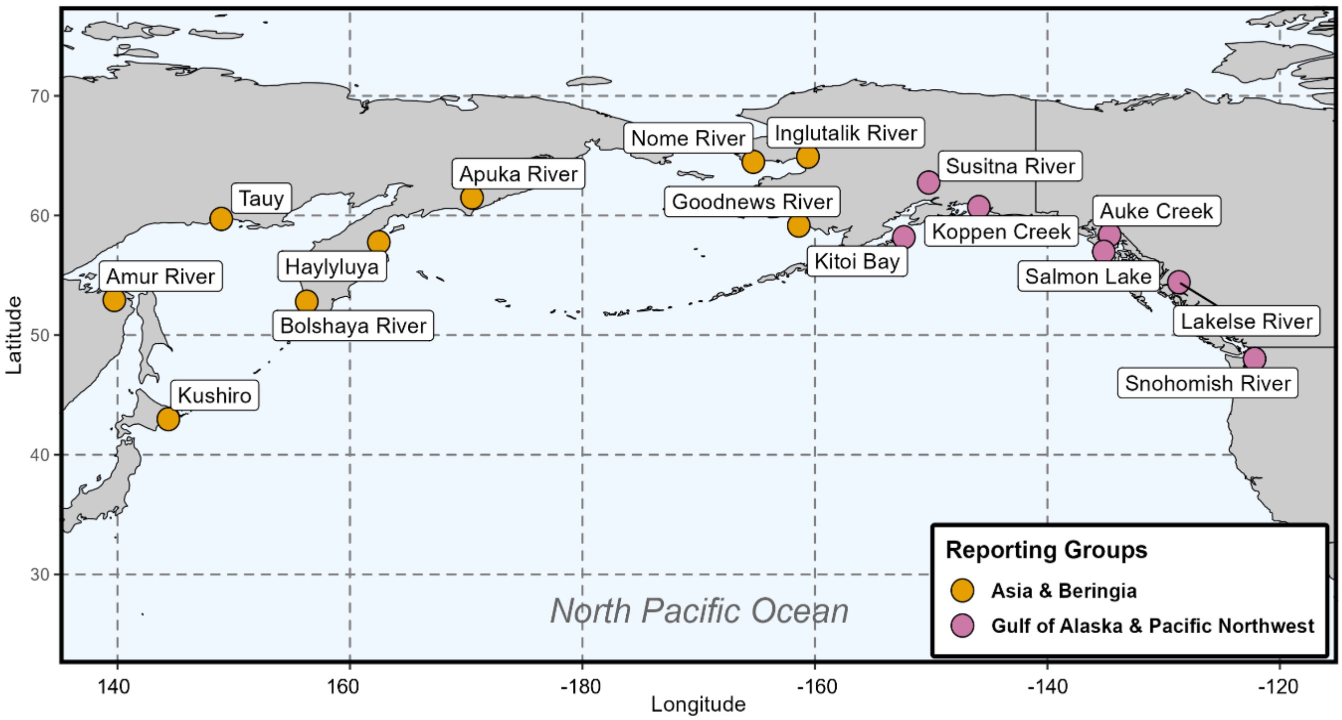

Figure 10. Spawning locations included in the North Pacific coastwide genetic baseline for pink salmon.

As an initial step towards developing a coastwide genetic baseline for the native Pacific range of pink salmon, the ADF&G Gene Conservation Lab built upon a North Pacific pink salmon study by Tarpey et al. (2018) and repurposed a pink salmon genetic marker panel developed for genetic parentage analysis in Prince William Sound, Alaska (Shedd et al. 2016). Alaskan pink salmon genotypic data were combined with genotypic data in Tarpey et al (2018) to establish a baseline of 262 genetic markers genotyped for 15 locations across the Pacific native range with paired odd- and even-year populations. Following guidelines defined by Barclay et al. (2019), the 15 locations were grouped into two reporting groups for each lineage: (1) Asia/Beringia even-year, (2) Asia/Beringia odd-year, (3) Gulf of Alaska/Pacific Northwest even-year, and (4) Gulf of Alaska/Pacific Northwest odd-year (Figure 10). This baseline represents an initial effort to understand genetic stock delineation of pink salmon, however inclusion of additional populations from throughout the species range will expand the potential applications of the baseline for pink salmon studies.

Stocking efforts in the White Sea eventually led to self-sustaining populations of pink salmon in the Atlantic. Genetic studies of White Sea pink salmon provide evidence of a bottleneck effect and genetic divergence of the odd-year population from the original source population, the Magadan region in Russia (Gordeeva and Salmenkova 2011; Gordeeva et al. 2015; Gilbey et al. 2021). However, early generations from the even-year population were still genetically similar to the Russian source population (Gordeeva and Salmenkova 2011; Gordeeva et al. 2015). Pink salmon have been documented in many Northern European rivers west of the

Figure 11. Location of pink salmon samples from Norway, Western Canadian Arctic, and Eastern Canada included in genetic analysis.

White Sea. A collection of pink salmon sampled across 34 Norwegian rivers from 2016 through 2020 (N = 384, Figure 11) were examined for genetic variation with the ADF&G pink salmon genetic marker panel and baseline. Similar to findings by Gordeeva et al. (2015) and Gilbey et al. (2021), the Norwegian odd-year samples genetically diverged from baseline populations representing the original Russian odd-year source population, the Asia/Beringia odd-year reporting group (Figure 12). Whereas, the Norwegian even-year samples were genetically similar to samples representing the Asia/Beringia even-year reporting group (Figure 12). Most of the invading pink salmon from the established populations in the White Sea are found in Northern Norway, with gradually fewer found further south in Europe. It remains to be seen if the invasion leads to the establishment of new self-recruiting populations and a further expansion. To pursue this question, genotypic data from the collection of Norwegian pink salmon samples were analysed in relation to where the fish were caught. These initial studies showed from simulations that full-sibling, half-sibling, and unrelated individuals were 100%, 97.7%, and 99.6% correctly assigned, respectively. A structured pink salmon genetic sampling program will be implemented by the Norwegian Institute for Nature Research (NINA) to study the distribution of full-siblings across Norway and provide information on dispersion, homing, and effective number of breeders. These are examples of genetic methods that could be used by Atlantic countries to monitor the pink salmon invasion and elucidate expansion mechanisms and patterns.

In recent years there have been increased reports of pink salmon observations across Canada, along both the Western Canadian Arctic coast and the Eastern Canadian coast (Dunmall et al. 2021; ICES 2022a). Similar to the analysis of the Norwegian samples, pink salmon samples collected by communities in the Western Canadian Arctic (N = 22) and Eastern Canada (N = 2) (Figure 11) were genotyped with the ADF&G pink salmon genetic marker panel and compared to: (1) the Pacific coastwide baseline samples representing the native range of pink salmon, and (2) the Norwegian pink salmon samples representing secondary colonizations from stocking operations in the White Sea. Both odd- and even-year Western Canadian Arctic samples were genetically similar to baseline populations within the Pacific native range (Figure 12). Odd-year samples from Eastern Canada were genetically similar to the Norwegian samples representing the self-sustaining population of pink salmon in Northern Europe. There were no even-year samples analysed from Eastern Canada. These genetic findings suggest that the expansion of pink salmon in the Western Canadian Arctic originates from the Pacific native distribution of pink salmon, whereas the pink salmon in Eastern Canada are a part of the invasion from Northern Europe. This example illustrates how genetic methods can improve our understanding of the origin of expanding pink salmon populations and benefit research, monitoring, and management of the species.

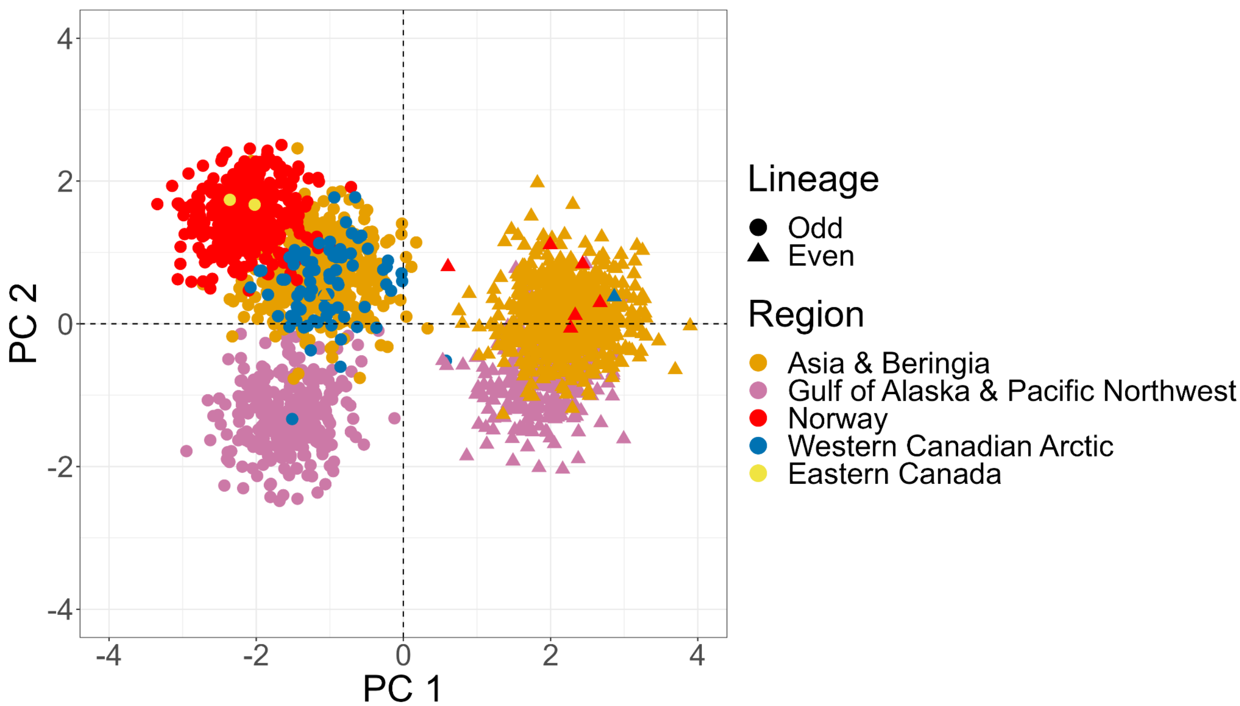

Figure 12. Principal component analysis (PCA) results of genotyped pink salmon samples from the North Pacific coastwide genetic baseline (Asia and Beringia reporting group and Gulf of Alaska and Pacific Northwest reporting group), Norway, Western Canadian Arctic, and Eastern Canada.

5. Approaches to Assessing Current and Predicting Future Distribution Changes

Pink salmon are encountered in a variety of surveys conducted on continental shelves around the Pacific Rim. However, regular sampling of areas of the North Pacific high seas large enough to support monitoring of salmon distribution changes is not logistically possible. Instead, inferences regarding current and future ocean distribution patterns of pink salmon must be made through analysis of historic data. The NPAFC, formerly the International North Pacific Fisheries

Commission, has supported research on salmon in the high seas since the 1950s. To date, these efforts, focused primarily on the spring and summer months, have resulted in the collection of more than 30,000 salmon catch records from across the basin.

Research is being conducted by Langan et al. (in prep.) to develop distribution models from these historic catch data. In order to investigate potential distribution differences between the brood lines of pink salmon, the data from even- and odd-years were modelled separately. Although this approach will not fully separate the brood lines of pink salmon in the catch records, limited available biological information suggests that even- and odd-year data will primarily represent the even- and odd-year brood-lines, respectively. Preliminary results suggest that the pink salmon brood-lines occupy similar habitats in the high seas and have similar temperature preferences. Positive catches of even-year pink salmon were observed between 1.0–19.4°C, while odd-year pink salmon were caught between 1.0–17.8°C. Preliminary estimates of the spring-summer mean preferred temperature range of even- and odd-year pink salmon derived from distribution model fits, meanwhile, suggest that most individuals of each brood-line will be observed between approximately 3–12°C , in general agreement with past research (Takagi et al. 1981; Abdul-Aziz et al. 2011).

Such estimates of pink salmon thermal preferences help to understand current and future potential shifts in ocean distribution patterns. Langan et al. (in prep.) compared past thermal conditions to recent warm periods in the North Pacific to suggest that optimal thermal habitats may move northward and toward the center of the basin under continued climate change. Similarly, these preferred temperature ranges are being used to investigate the growing presence of pink salmon in the western Canadian Arctic (Dunmall et al. 2018). Given that continued and rapid Arctic warming may increase the suitability of the region for pink salmon, anticipation of such changes will rely upon inferences gained studying historic data from the North Pacific.

6. Selective Methods and Removals, Opportunities for New Fisheries

Norway

Pink salmon is on the Norwegian Biodiversity Information Centre's Black List of alien species, in the "high risk" category. The strategy of the Norwegian Government is to eradicate pink salmon by targeted removal in rivers, and the Norwegian Environment Agency is responsible for the action plan. The rapid increase in numbers of pink salmon entering Norwegian rivers from 2017 somewhat surprised the managers and there was no national strategy on how to handle the river invasion even in 2021. In at least 46 rivers, local organisations voluntarily organized removal of pink salmon from the rivers in 2021. In at least 19 rivers, these organisations installed improvised traps to hinder pink salmon from entering the river (mainly relatively small rivers). The upstream migrating salmonids were trapped and most of the pink salmon were removed while letting native anadromous fish enter the river. Successful installation and maintenance of such traps depends on local knowledge and financial support, and are practically limited to rivers with shallower depths and installations during periods of low flows. The experiences with *ad-hoc* traps in Norway in 2021 were mixed, some functioned well while others did not work as planned, but these will be valuable for further efforts in future years. In some of the largest rivers, including the Tana/Teno River, a proper eradication program with traps or gillnets was not possible in 2021.

Removal of pink salmon in rivers without functional traps was limited to gillnets, seine nets or spearfishing. Gillnets were avoided in river areas and periods when native anadromous fish were observed to mix with pink salmon. In general, the managers in northern Norwegian counties accepted the use of gillnets and trusted local organisations to operate these in a way that had minimal effect on native anadromous fish. However, in rivers where gillnets, seine nets and spearfishing were used as the main effort for removing pink salmon, it was estimated that hundreds or thousands of pink salmon remained to spawn in each river. In rivers with salmon ladders, these could be closed off and native anadromous fish could be sorted out and released above the ladder. A land seine was applied in some rivers although this gear could only be operated in slow-running rivers. In total, more than 100,000 pink salmon were removed from rivers (Diaz Pauli et al. 2023). However, the heavy involvement of volunteers in 2021 is not sustainable.

National mitigation measures are in place for 2023 with ~2.5 million Euro allocated to install traps in the rivers most impacted by pink salmon. The work to improve existing traps and install new traps was organized during the winter of 2022, before the expected invasion of pink salmon in 2023. The work benefitted from experiences in 2021. The main focus areas for the 2023 program were to: (1) maintain animal welfare for the native anadromous fish while removing pink salmon; (2) ensure the correct quality and dimension of the part of the trap closing the rivers, the appropriate dimensions of the catch chamber where fish are trapped, and the correct angle and placement of the parts used to guide fish to catch chambers; and (3) ensuing sufficient personnel to monitor and clean the traps. Resistance board weir traps were installed in some of the largest Norwegian rivers, as the ability of resistance board weirs to avoid collapse under high flow/debris levels allows them to resist ‘blow-out,’ which is normally when rigid weir structures get lost.

There is a growing interest among fishers to target pink salmon at sea. This potentially new fishery does not affect the present strategy of removing pink salmon in the rivers. To date, however, no targeted fishery using commercial gear for pink salmon at sea has been allowed due to the risk of bycatch (VRL 2022, 2023) and increased mortality of native anadromous fish. There will most likely be a minor research test-fishery in northern Norway targeting pink salmon at sea in 2023 to gain experience of catch efficiency and bycatch of both marine and anadromous species.

Other Countries

While Norway might be the first country to implement an official strategy to eradicate pink salmon, this approach is considered in other countries where this fish is non-native and represents a threat to native species. To begin with, some governments removed any catch limit for pink salmon (for instance Quebec: MFFP 2021) and asked that all caught pink salmon must be killed immediately (for instance Sweden: Staveley and Bergendahl 2022). In Ireland, the state agency responsible for inland fisheries advises anglers to remove and report any pink salmon encountered and retain these for verification and scientific purposes (Millane et al. 2019b). There are also local initiatives developed by river organizations, and supported by relevant government agencies, to monitor and potentially remove pink salmon in some rivers in Scotland. However, apart from Norway, the approaches taken and the planned effort in 2023 are not well described at this time. Approaches based on the disruption of pink salmon nests have been judged too resource intensive and to be associated with too high human health and safety risks to be a viable option for widespread application (Armstrong et al. 2018). The attempts conducted in Norway will therefore benefit and guide others.

One key question for countries bordering the Atlantic Ocean is the likelihood of successful eradication of pink salmon. Indeed, there are cases of success and failure involving other species worldwide (Myers et al. 2000; Simberloff 2021). If the general tendencies of increased abundance and distribution observed between 2017 and 2021 remain unchanged, it is difficult to imagine how countries with thousands of remote rivers with potential spawning grounds can totally eradicate pink salmon when facing sustained propagule pressure from other source countries. Nevertheless, it might be possible to keep prioritized watersheds free of this exotic species, or at least prevent or limit the establishment of self-sustaining populations in ‘new’ rivers. The amount of investment in eradication by the different countries dealing with invasive pink salmon will likely be proportional to the perceived or demonstrated negative impacts, which remain to be investigated in more detail. The lack of knowledge of the scale of any impact is highlighted in the risk assessments for this species in the UK, Ireland, and Norway (Bean 2022). As such, ongoing surveillance through direct monitoring, as well as using indirect techniques such as eDNA, are key to quantifying the level of incursion and establishment in order to better inform appropriate management responses and appraise likelihood and effectiveness. Considering, for instance, that the economic benefit of some renowned Atlantic salmon rivers is estimated at more than one million Euros or American dollars annually (Atlantic Salmon Federation 2011; Myrvold et al. 2019), even without considering the additional intrinsic value of biodiversity, investing a fraction of this amount for their protection from non-native pink salmon can likely be justified.

7. New Tools: Using eDNA for Monitoring the Pink Salmon Invasion

eDNA: A Cost-effective Monitoring Tool

Monitoring the occurrence and distribution of pink salmon is crucial for understanding the dynamics of the invasion process. Analysis of eDNA is a new and cost-efficient method for detecting rare species, as it makes it possible to monitor more localities than using conventional methods. eDNA is the suspended DNA-remains in water, soil and air shed by most living organisms, consisting of saliva, scales, hair, slime and mucous, and that can be collected and used with genetic analyses for identifying the species living in the sampled ecosystem (Taberlet et al. 2018). Comparisons with conventional methods also show that analyses of eDNA often are more sensitive in detecting rare species, and are very effective for detecting invasive species (Valentini et al. 2016; Fossøy et al. 2019; Sepulveda et al. 2020; Taugbøl et al. 2021). Collection of eDNA from water is usually done by filtering water through a fine-meshed filter, and the procedure is relatively simple and well suited for citizen-science projects (Biggs et al. 2015; Agersnap et al. 2022). The filters can be stored in ethanol or conservation buffers for some months, before being analysed.

For identification of single species, eDNA-samples are usually analysed using species-specific markers to screen many samples for the presence of a target species, e.g., pink salmon (Gargan et al. 2021; Fossøy et al. 2022). However, eDNA-samples can also be analysed using DNA-metabarcoding, where a more general DNA-assay is used to detect multiple species (Miya et al. 2015; Valentini et al. 2016). The former method is relatively simple and can be done in most genetic laboratories within a few days, whereas the latter method requires modern sequencing technology and advanced bioinformatic analyses (Taberlet et al. 2018).

While eDNA-analyses can detect and monitor occurrence, it cannot provide information on the absolute number of individuals, or biological characteristics such as the sex-ratio, age- or size class structures for the target species. However, relative differences in eDNA concentration can imply changes in relative abundance over time, and a recent review concludes that eDNA can be used for assessing fish population abundance and/or biomass (Rourke et al. 2021). For the monitoring of pink salmon, eDNA offers a cost-effective method for detecting possible increases in numbers of pink salmon and potential decreases in local fish species over time. This method makes it possible to monitor many rivers at a relatively low cost, although studies must carefully consider the temporal and spatial aspects of survey design if this approach is to be deployed effectively. The next two subsections describe two examples of applications in greater detail, before we conclude with considerations about future prospects.

Monitoring the Pink Salmon Invasion in the Tana/Teno River Using Species-specific eDNA Analyses

The large river Tana/Teno forms the border between northernmost Finland and Norway and supports the largest Atlantic salmon population among all Norwegian salmon rivers, so large in fact that salmon from several tributaries are considered separate stocks for management purposes (VRL 2022). Recently, the Atlantic salmon stocks have strongly declined (Anon. 2021) and salmon fishing has ceased. At the same time, numbers of non-native pink salmon have increased substantially. The estimated numbers of pink salmon entering the river system in 2000–2010 were only a few tens or hundreds (Sandlund et al. 2019). However, in 2017 and 2019 close to 5,000 pink salmon were estimated entering the river in each of those years. In 2021, the estimated pink salmon abundance had increased ten-fold and exceeded 50,000 individuals (Anon. 2021).

Until 2021, the monitoring programmes recorded the presence of pink salmon in the mainstem of the river, large headwater branches and some other large or mid-size tributaries of the Tana/Teno system. To further increase the understanding of pink salmon distribution, eDNA samples were collected from 19 tributaries in 2019 and from 24 tributaries in 2021 (Fossøy et al. 2022). The eDNA water samples were analysed using a species-specific genetic primer for pink salmon (Gargan et al. 2021), and another primer for Atlantic salmon (Fossøy et al. 2019). The eDNA analyses detected Atlantic salmon in almost all tributaries in both years, with a pronounced higher DNA-concentration in the middle of the watercourse. Pink salmon were detected in five localities in 2019 and in 15 localities in 2021, reflecting the large observed increase in the number of pink salmon entering the river between the two odd-years. These detections were distributed across all parts of the Tana watercourse and showed the large-scale geographical span of pink salmon in this river. The upper part of Inarijoki represents the most upstream detection of pink salmon recorded in Tana/Teno River so far.

The DNA-quantities of Atlantic salmon appeared to be much higher than those of pink salmon (Fossøy et al. 2019), despite the fact that the numbers of pink salmon entering the river was approximately twice that of Atlantic salmon (Anon. 2021). There are likely to be species-specific differences in shedding and excretion of DNA that could affect these estimates. However, there was only one age class of pink salmon in the river at the time of sampling, compared to up to six different age classes of juvenile Atlantic salmon plus the adults returning from the sea. The continued presence of the juvenile Atlantic salmon makes it hard to assess the relative abundance of pink vs. Atlantic salmon using eDNA.

The first even-year study of eDNA in the Tana/Teno River was conducted in 2022. This should increase knowledge of the pink salmon juveniles from the 2021 spawning run, alongside adults from the spawning run of 2022. The results of this study have not been reported at the time of writing, but the goal for the project is to secure funding for sampling the same 24 tributaries every year in order to monitor eDNA-concentrations for both the native Atlantic salmon and the invasive pink salmon populations in the years to come.

Monitoring Pink Salmon Distribution and Fish Diversity in North-eastern Canada Using eDNA-metabarcoding

eDNA-metabarcoding analyses have been used in north-eastern Canada to study the early invasion of pink salmon (e.g., Côté et al., in prep.). Few people inhabit this region, and most rivers are difficult to access since they are not accessible by any roads, making it logistically challenging to assess the distribution of pink salmon and any other species. Monitoring pink salmon nevertheless remains extremely important since Inuit people rely heavily on aquatic resources. The main objective of this project was to improve knowledge on the occurrence of pink salmon in the northernmost part of the Atlantic salmon distribution and to compare the distribution based on the few pink salmon records (4) from Inuit fishermen that were suggested by eDNA detection (Coté et al., in prep.). A secondary objective was to compare the fish community assessed with traditional methods with the one assessed using eDNA-metabarcoding.

A helicopter was used in 2021 to obtain 43 samples from 39 rivers distributed across nearly 1,500 km of coastline in Quebec, from Hudson Bay to Ungava Bay. Those samples were mainly collected near the river mouth, assuming that pink salmon abundance would be greatest in the lower reaches and considering that eDNA should be detectable a few km downstream from its source (Laporte et al. 2020; Jo and Yamanaka 2022). Five replicate samples were amplified using the primers from Miya et al. (2015). Bidirectional sequencing was conducted using the Illumina MiSeq sequencer (reactive V3, Illumina, San Diego, USA). Negative controls were included at each step of the procedure (filtration in the field, extraction and amplification in the lab).

Pink salmon were detected only at a single sampling site. This site is located in Ungava Bay within a 70 km radius of where three out of the four pink salmon have been caught in Northern Quebec. The fourth pink salmon was caught outside of the study area of this eDNA project, on the east side of the Ungava Bay. While results from eDNA must be interpreted with caution, this study suggests that pink salmon were not widely distributed nor abundant in Northern Quebec outside the Ungava Bay in 2021. It further confirms that Ungava Bay is a hot spot for pink salmon invasion in the northernmost distribution range of Atlantic salmon in North America.

Future Prospects for the Use of eDNA in Pink Salmon Management and Research

Methodological advances and improved knowledge of eDNA ecology should rapidly offer new opportunities to study pink salmon. For instance, increased understanding of the biotic and abiotic factors affecting the production and degradation of eDNA (Caza-Allard et al. 2022), as well as of the multidimensional dispersion of eDNA in fluvial environments (Laporte et al. 2020; Berger et al. 2020), will allow a stronger interpretation of eDNA results. However, the sensitivity of the tool is not without drawbacks, for instance regarding the risks of contamination and of eDNA movement issues. Combined with the analyses of eRNA, it appears possible to evaluate the age of eDNA material and therefore the time since its release into the water (Marshall et al. 2021). New methodological development, such as CRISPR-Cas (Williams et al. 2021), opens the door to real-time on-site detection. It is also possible to use eDNA for population structure studies (Adams et al. 2019). Thus, it is likely that eDNA will play an increasingly important role in fishery management in general, and specifically in the study of non-native species like pink salmon.

While eDNA samples in this context mainly are collected for analysing the presence of pink salmon and local fish species, these samples can also provide information on other taxa using different genetic assays. DNA-extracts from eDNA water samples represent most of the living organisms in the river, and hence they can also be used for assessing diversity of e.g. macroinvertebrates (Elbrecht et al. 2017), molluscs (Klymus et al. 2021) and amphibians (Valentini et al. 2016). DNA-extracts can be stored in ultra-freezers and reanalysed many years after collection, representing time-capsules of biodiversity for the sampled localities. This means that in addition to monitoring the invasion of pink salmon, the eDNA samples can also be used to assess the consequences of the invasion, where potential changes in diversity of local species across many taxa can be investigated in relation to changes in pink salmon abundance.

An effort of joining forces across nations for eDNA-monitoring of pink salmon was attempted already in 2019 and samples were collected across many countries (www.1000rivers.net). There was, however, a more northerly distribution of pink salmon that year, and there were basically mostly negative results with the exception of northern Norway. In 2022, a new attempt was initiated with support from the North Atlantic Salmon Conservation Organization (NASCO) and potential start funding from the EU. Discussions are ongoing regarding choices and standardization of sampling equipment and analysis. Time will show if this initiative can provide a standardized monitoring of the pink salmon invasion across borders.

8. Information Exchange and Future Collaborations

Knowledge on pink salmon biology is not equally distributed throughout its natural and new range. Salmon scientists working in the North Pacific have a wealth of knowledge of pink salmon biology as the native species is the focus of extensive research and monitoring efforts. In north-western Russia, where the species was introduced in the 1950s, there is also a history of scientific research of pink salmon biology but it is not easily accessible for researchers without knowledge of the Russian language. In the Atlantic area, the northern parts of Norway and Finland had limited presence of pink salmon for many years prior to the large increase in abundance and distribution range from 2017 onwards, some scientific work has been conducted on this species over this extended time period. In the rest of the Atlantic area, however, research into pink salmon only started in earnest after 2017. Indeed, it was quickly recognised by many salmonid scientists from the Atlantic area that their knowledge on pink salmon biology was lacking when confronted with questions about pink salmon from policy makers and fisheries managers after the rapid expansion in 2017 (e.g., Bean 2022). This highlighted the importance of sharing knowledge of the potential impacts on ecosystems and implications for fisheries management.

At the October 2022 Northern Hemisphere Pink Salmon Expert Meeting in Vancouver, Canada, this important exchange of information on pink salmon led to discussions on future collaborations by scientists working across the Pacific, Atlantic, and Arctic Ocean basins. However, this knowledge sharing should not be limited to pink salmon, as pink salmon range expansion is far from being the only current issue in global salmon conservation and management. Therefore, the creation of a Northern Hemisphere Salmon Expert Group (NHSEG) is recommended to oversee and facilitate knowledge exchange throughout the three oceanic basins. This NHSEG should then form specialist sub-groups to address specific issues, such as the Northern Hemisphere Pink Salmon Expert Group (NHPSEG).

The NPAFC and ICES have expressed an interest in setting up the NHSEG. ICES Expert Groups like WGNAS, WGDIAD, and the Baltic Salmon and Trout Assessment Working Group (WGBAST) could link into this, and we would recommend other interested organisations be approached to join this group, for example The North Pacific Marine Science Organization (PICES).

At the same time, NASCO is creating a pink salmon working group. The Terms of Reference for this group are under development but we understand that the focus will be on management, and therefore this would be complementary to, rather than duplicating the sciencefocussed Northern Hemisphere Pink Salmon Expert Group, though the two groups would undoubtedly share, cooperate, and collaborate whenever appropriate.

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Appendix

Appendix A: List of Meeting Participants

Name	Affiliation
Alan Walker	Centre for Environment, Fisheries and Aquaculture Science (Cefas)
Alan Wells	Fisheries Management Scotland (FMS)
Andrew Munro	Alaska Department of Fish and Game (ADFG)
Annie Cooper	International Council for the Exploration of the Seas (ICES)
Chris Habicht (virtual)	Alaska Department of Fish and Game (ADFG)
Dennis Ensing	Agri- Food Biosciences Institute (AFBI)
David Meerburg	Atlantic Salmon Federation
Dion Oxman (virtual)	Alaska Department of Fish and Game (ADFG)
Ed Farley	National Oceanic and Atmospheric Administration (NOAA)
Elizabeth Lee	Alaska Department of Fish and Game (ADFG)
Emma Hatfield	North Atlantic Salmon Conservation Organization (NASCO)
Henrik Berntsen (virtual)	Norwegian Institute for Nature Research (NINA)
Jaakko Erkinaro	Natural Resources Institute Finland
Jim Irvine	Fisheries and Oceans Canada (DFO)
Julien April	Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs du Québec (MELCCFP)
Karen Dunmall	Fisheries and Oceans Canada (DFO)
Katie Howard (virtual)	Alaska Department of Fish and Game (ADFG)
Kjell Utne (virtual)	Institute of Marine Research, Bergen, Norway
Michael Millane (virtual)	Inland Fisheries Ireland
Polina Orlov	North Pacific Anadromous Fish Commission (NPAFC)
Sten Karlsson	Norwegian Institute for Nature Research (NINA)
Steve Latham	Pacific Salmon Commission (PSC)
Tor Kitching	North Pacific Anadromous Fish Commission
Vladimir Radchenko	North Pacific Anadromous Fish Commission (NPAFC)
Wendy Kenyon	North Atlantic Salmon Conservation Organization (NASCO)
William Templin	Alaska Department of Fish and Game (ADFG)