



Atlantic Salmon Trust

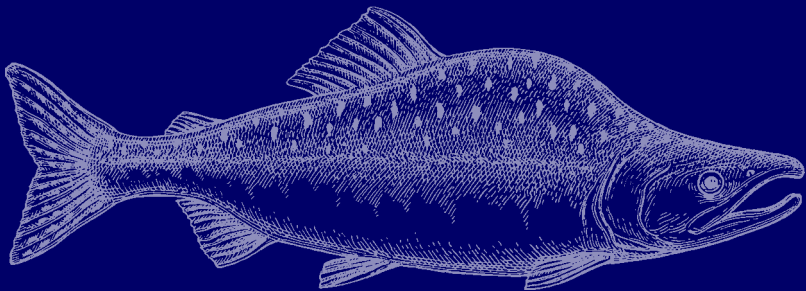


Norwegian Institute for Nature Research

Pink Salmon and Red Skin Disease: Emerging Threats for Atlantic Salmon

Edited by Ken Whelan and Tor Atle Mo

Based on a workshop organised by the Atlantic Salmon Trust, in cooperation with the Norwegian Institute for Nature Research, at the Royal Botanic Gardens, Edinburgh, on the 28th and 29th June 2022.



www.atlanticsalmontrust.org

December 2022



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**To be cited as : Whelan, K. and Mo, T.A. (Eds) (2022) Pink Salmon and Red Skin Disease Emerging Threats for Atlantic Salmon. Atlantic Salmon Trust, Blue Book Series, no. 40.
Published by: AST, Battleby, Perth, Scotland. 58pp.**

Contents

Foreword

Mark Bilsby, CEO Atlantic Salmon Trust	3
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Part 1:

The Pink Salmon Invasion – what we know to date	5
Pink Salmon in the Northernmost Atlantic Area – with special emphasis on the River Teno/Tana, Finland/Norway	8
Pink Salmon in Norway 1	11
Using Stable Isotopes to Evaluate Potential Impacts of Pink Salmon - PinkSIES Project	14
Assessing the Risks Posed by Pink Salmon to UK Waters	17
Pink Salmon in Norway 2	24
Pink Salmon – Lessons Learned and Planning for the Future	26

Part 2:

Red Skin Disease – Research and Monitoring Efforts to Date	28
Red Skin Disease – The Search for a Cause and a Potential Breakthrough	30
Red Skin Disease – The Situation Within Scotland, Reports, and Diagnostic Findings	34
Red Skin Disease, Saprolegniosis and their Potential Impacts on Salmon Populations.	40
Managing Red Skin Disease in Ireland	46
Is There a Link Between Red Skin Disease and Red Vent Syndrome?	49
Red Skin Disease – Unravelling the Mystery and Planning for the Future	51

Appendix 1

Summary of Work of the Atlantic Salmon Trust	57
Summary of Work of the Norwegian Institute for Nature Research	58

Foreword

The dramatic and unprecedented decline in Atlantic salmon abundance has been well documented over the past three decades. In recent years, a great deal of resources have been devoted to identifying the causes of this steep drop in overall salmon population abundance. However, in addition to the obvious threats to the long-term viability of Atlantic salmon, there are also a number of emerging threats, which could well add additional pressure to the survival of wild Atlantic salmon populations.

Conscious of the need to highlight these emerging threats, the Atlantic Salmon Trust organised a workshop in the Royal Botanic Gardens, Edinburgh, in June 2022, where invited experts offered their perspectives on the threats posed by the recent southerly spread of invading pink salmon populations and the potential impacts and long-term significance of the recently described 'Red Skin Disease'. We were delighted that those invited to speak at the event readily accepted our invitation to attend the workshop. This has enabled us to capture both on video (AST YouTube channel) and in this Blue Book, a summary of the current position with regard to these emerging threats. The workshop was very well attended and we have summarised the key points from the discussion periods of the workshop in the final chapters of our Blue Book.

Pink Salmon

Pink salmon have been reported in Norwegian rivers, in varying numbers, since transplantation and stocking of this species began in Russia, in 1956. Self-reproducing stocks were established in Russia from 1985 onwards, as this transplantation programme proved more effective. Norwegian rivers contained low and relatively stable numbers of reproducing pink salmon until 2017 when a significant movement of these fish, in a southerly direction, was recorded across Europe and indeed across the Atlantic, to Greenland, Iceland and North America. The recent intensity of these invasions and the numbers of fish involved, particularly the exponential increase in the populations of pink salmon invading waters in Northern Norway and Finland, has caused major concern for those involved with the conservation and management of Atlantic salmon. Closer to home, significant numbers of pink salmon have appeared in some rivers in northern and eastern Scotland and pink salmon have spawned successfully in both the Rivers Ness and Thurso.

Our Blue Book, and the accompanying videos, contain not only a detailed description of the events which have taken place over the past five years, but also the experience and the expertise of those managing the problem on the ground in Norway and Finland. Our contributors clearly lay out the management approaches which have worked and the refinements which are planned for the years to come.

The threat which pink salmon may pose to our migratory salmonids is at this stage unknown, but it was encouraging to learn, over the course of the workshop, that a formal risk assessment has been carried out in both the UK and Ireland and that this assessment will be updated on a regular basis as more information becomes available.

Hopefully, through continuing close cooperation with our colleagues in Norway and Finland, we can build on the information they have provided to date and take a proactive approach to the management of this threat, thus minimising the impact of the pink salmon on our Atlantic salmon populations in southern Europe.

Red Skin Disease

As outlined later in this publication, skin anomalies/diseases in adult Atlantic salmon returning from the ocean have been known for more than 150 years. In the 1860s, 1870s and 1880s a condition named The Salmon Disease caused severe disease on salmon in numerous rivers in Britain and Ireland. Over the period, thousands of adult salmon died from this skin disease. About 100 years later, in the mid-60s to the 80s, a severe outbreak of a skin disease, later known as Ulcerative Dermal Necrosis (UDN), again hit returning adult salmon, predominantly multi-sea winter fish. This time the skin disease affected salmon populations in a larger geographical area in the southern Atlantic Ocean including Great Britain, Ireland, France, southeastern Norway, the west coast of Sweden, and the Baltic Sea.

From the available literature, there is very little clear advice in terms of what constitutes UDN and how it might be diagnosed. One of the editors of this Blue Book, Tor Atle Mo, an expert in wild salmon diseases, has provided us with a clear outline of what is known about UDN and how the symptoms can be separated out from other skin diseases. This clarification is important, as when Red Skin Disease (RSD) first impacted returning Baltic and subsequently Atlantic salmon, there was serious concern that RSD might signal the return of UDN.

To date, outbreaks of Red Skin Disease have been highly variable. Salmon with RSD have been noted on several occasions in some rivers, rarely in others, and in the majority of rivers not at all. In some, apparently isolated incidences, RSD-like symptoms have caused serious losses in terms of adult salmon and put enormous pressure on small streams, where juvenile parr numbers have dropped to very low levels.

Over the course of the workshop, we learned about the highly detailed research which is being carried out, particularly in Sweden and Norway, in an attempt to identify the actual cause or causes of RSD. We are very fortunate to have captured, over the course of the workshop, detailed knowledge of the research carried out to date, what has been learned from this research and what work is planned in the near future. What emerged at the workshop was an excellent and highly informative discussion on the links between what is now described as Red Skin Disease and the closely associated condition of Saprolegniosis.

It is clear that in the context of increasing stress factors associated with climate change and other human-made impacts, that the skin of salmon is particularly sensitive to major changes in its environment. This can lead to complex and damaging effects. Given the speed of change we are witnessing in our environment, we must be far more vigilant in terms of watching for the appearance of new and emerging threats. It is equally important to ensure that appropriate samples are collected and are professionally examined in a timely fashion. Additional resources should be allocated to rebuild the diagnostic expertise we once had in our laboratories to monitor and assess wild fish diseases. Our fish pathology units are currently largely focused on assessing and monitoring fish diseases arising in the aquaculture industry. Important as this work is, timely and accurate diagnosis of wild fish diseases may well prove to be an important tool in stemming aquatic biodiversity loss.

Our aquatic environment is changing and changing fast. Increasing pressures are impacting on wild Atlantic salmon and we must use all modern means of communication to make sure that we stay on top of this fast-moving tapestry of events. The Atlantic Salmon Trust is intent on providing a platform through which we can identify and seek to manage such emerging threats over the years to come.

Mark Bilsby, CEO, Atlantic Salmon Trust

Part 1: The Pink Salmon Invasion

– what we know to date

Life history and colonization capacity of pink salmon: so simple, and yet so complex

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Pink salmon, *Oncorhynchus gorbuscha*, is one of five species of anadromous (sea-run), semelparous (dying after the first season of spawning) salmonids native to the Asian and North American sides of the Pacific Rim. It is joined in the genus by *O. masou*, native to only the Asian side, and several species of trout in the same genus that may be anadromous or not, but do not die after spawning (i.e., are iteroparous). In some respects, pink salmon has the simplest life history. Specifically, these fish enter rivers in the early fall, spawn shortly thereafter, and soon die. Spawning tends to occur in small streams near the coast, but some longer migrations of 10s to 100s of kilometers occur. Embryos incubate over the winter in stream gravels, as is typical of salmonids, and fry emerge in the spring. They are already tolerant of seawater and migrate downstream immediately, with less time spent feeding in the river than any other salmonid. Entering the ocean, they migrate to offshore waters, feed in the near-surface waters that summer, through the following spring and early summer, and then migrate to their natal stream to spawn and die the next fall. Thus, all pink salmon in their native range are age-2 at maturity. During their time at sea they grow rapidly, from ca. 0.2 g newly emerged fry (ca. 30 mm long) to ca. 2 kg in about 18 months, thus about a 10,000-fold increase in mass. They are generalists in their diets, eating a variety of small fishes, crustaceans, and other invertebrates.

Their minimal use of streams for feeding results in high densities of spawning adults in many cases, as the carrying capacity is set by the spawning habitat rather than the stream's capacity to produce food for the offspring, and most streams can support more incubating embryos than they can support the food demands of the resulting juveniles. Consequently, small streams may have densities of pink salmon that seem incredible to anglers, biologists, and others who are used to the much lower densities of other Pacific salmon species and especially Atlantic salmon. Moreover, because they all die after spawning, their abundance is especially evident. The carcasses are fed upon by a variety of consumers and decomposing organisms, and thus the nutrients obtained by the salmon at sea fertilize the stream and riparian zones.

Like all salmonids, pink salmon have a strong tendency to return to their natal stream for reproduction. However, as with all species, some fraction strays and spawns in a non-natal stream. It is often said that this straying is more prevalent in pink salmon than the other species. This is inferred from 1) the rapidity with which they have colonized new habitat in their native range (e.g., in Glacier Bay, Alaska, as receding glaciers create suitable new habitat), 2) the rapidity with which they re-colonized formerly occupied habitat after extirpation from blockages (e.g., the expansion into the upper Fraser and Thompson rivers in British Columbia after passage was improved at Hell's Gate after a rock slide), 3) documented straying from hatcheries that mark juveniles, 4) their rapid expansion after accidental introduction into the Great Lakes of North America, and 5) the generally shallow

genetic population structure compared to other Pacific salmon species. That is, populations are more genetically similar to each other, for a given geographical distance, than other species, indicating more gene flow between populations. Moreover, in parts of their range, pink salmon spawn in virtually every accessible stream, even in inter-tidal reaches, and give the impression of being not only ubiquitous but not specialized for particular attributes of streams, as are other salmon species. This lack of specialization is thought to be linked to the absence of extended holding by adults and absence of extended rearing by juveniles in the stream, relative to other salmonids.

These attributes (lack of variation in age at maturity and less reliance on streams than other salmonids) belie some complex aspects of the life history of pink salmon. First, because the adults spawn two years after they themselves were spawned, a stream can have runs on even and odd numbered years that are entirely independent of each other, without interbreeding. At the southern end of their range (Puget Sound, Washington, in North America) most rivers will have exclusively odd-year runs (i.e., adults in 2015, 2017, 2019, etc.) but be entirely devoid of pink salmon on the even-numbered years or orders of magnitude fewer. The fact that a given stream can support hundreds of thousands of spawning adults but only every other year is most striking indeed. Many efforts were made to transplant even-year runs to Puget Sound but they were entirely unsuccessful, as were many efforts to establish runs on the off-cycle in British Columbia. Well-planned efforts to transplant them outside their native range, to Newfoundland, Canada also failed conspicuously. As one moves to the middle of the species' North American range, in northern British Columbia and southeastern Alaska, both even and odd year runs are common, and in some cases the relative abundance changes between lines. Farther north in Alaska, even-year runs tend to be more abundant.

In addition to the variation among populations and the decline with latitude in relative dominance of even and odd year lines, the patterns of spawning habitat and overlap with other species also vary. In Puget Sound, for example, pink salmon spawn early in the fall in large rivers and are absent from the smaller streams that are used later in the fall by chum salmon, *O. keta*. However, in southeastern Alaska, pink and chum salmon co-occur in many such small streams and overlap in spawning timing. Then, in the north, they tend to segregate again. These patterns have not been explained, and are seldom even commented on, though they are quite clear.

In their native range, pink salmon are more abundant (in both biomass and numbers of adults) than any other salmon species, and their relative abundance seems to be increasing over the past decades. Despite losses of salmon in the southern and middle parts of their range (e.g. California, the Columbia River, and southern British Columbia), salmon are still very abundant in Alaska, where they were always more numerous than farther south. In addition to strong wild populations, there are also very extensive hatchery programs in southeastern and central Alaska.

Pink salmon are highly abundant but have proven very difficult to forecast from a fishery management standpoint, for two reasons. First, because they all return at the same age, managers cannot use the abundance of the younger members of the cohort returning in one year to forecast next year's return of older salmon that went to sea in the same year (a so-called sibling relationship approach). Second, because they are smaller as adults, the eggs are not buried as deeply as are the eggs of other salmon, and so may be more

vulnerable to scouring flows from floods during incubation. Third, because they enter the ocean at a smaller size than the juveniles of other species, they may be more vulnerable to variable ocean conditions, and thus their survival at sea may vary greatly. As a result of these factors, pink salmon often display large changes in abundance and are very difficult for managers to forecast.

Thus, pink salmon present a series of paradoxes that perplex biologists in their native range, and challenge those in the regions of Western Europe, where non-native populations are currently expanding. The odd and even year lines are highly divergent lineages, and both are capable of exceptional levels of abundance and fluctuation. They seem to readily colonize new habitat when it is available, within their native range and outside it, yet can resist even concerted efforts to establish new populations within their range in habitat used by the species on alternating years. The progress of their expansion in Europe is obviously of great importance to biologists and managers in this region, and is also of great interest to those studying the species and other salmonids in their native range.

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Pink Salmon (*Oncorhynchus gorbuscha*) in the Northernmost Atlantic area – with special emphasis on the River Teno/Tana, Finland/Norway

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Pink salmon (*Oncorhynchus gorbuscha*) was introduced to the Atlantic area, in the Russian White Sea basin, in the late 1950s (Alekseev et al., 2019). The new species gradually established naturally spawning populations in the White and Barents Sea rivers of Russia and also in northeastern Norway (Sandlund et al., 2019). The current pink salmon population in the north-east Atlantic area originates from a second introduction in 1985 from the Ola River, a North Okhotsk Sea drainage in the Magadan oblast. This has resulted in a self-reproducing, odd-year population (Gordeeva et al., 2015), now spanning over 18 successive generations. The even-year population in the North Atlantic area has, to date, proven far weaker than the odd-year population.

After some 30 years of slow development, since the second introduction to Russia in 1985, a sudden, rapid, and widespread increase in the distribution and abundance of pink salmon in the North Atlantic area started in 2017. This population explosion was characterised by the appearance of high salmon abundances in the Barents Sea area in 2019, followed by even higher runs of fish in 2021 (Sandlund et al. 2019; Berntsen et al. 2020; VKM 2020; Anon, 2021). A rough, overall estimate of pink salmon abundance across large areas in northern Norway and Finland suggests a 10-fold increase in abundance between 2019 and 2021 (NINA, Norway, unpublished; Anon, 2021). In the northernmost Norwegian county, Finnmark, some 70,000 pink salmon were removed from the rivers in 2021. Between 10,000 and 20,000 individuals were removed from some surprisingly small northeastern rivers (NINA unpublished). In 2021, the nominal catch of pink salmon in the Murmansk region in Russia was approximately 600t (Prusov & Zubchenko 2021), and in the White Sea basin, approximately 300t were caught in the River Varzuga alone (Prusov, unpublished).

In the large River Teno (River Tana, Norway), which forms the border between the far north of Finland and Norway (70°N), occasional pink salmon have been caught since the 1960s. Catches have been higher in some years, following the release of large numbers of pink salmon juveniles in Russian waters (Sandlund et al. 2019). The estimated numbers of pink salmon entering the river system in the 2000s has been some tens or hundreds, based on catch estimates and counts in tributaries (Figure 1). In 2017, close to 5,000 pink salmon were estimated entering the river and at least the same number of fish were detected by sonar in 2019. In 2021, the estimated pink salmon run was c. 50,000 individuals (Figure 1). The sonar figures are underestimates, since significant spawning areas of pink salmon were found in the main stem and in one major tributary downstream from the sonar site in 2021 (Muladal & Fagard 2021). Based on the Atlantic salmon monitoring programme, which extends to multiple tributaries of the large Teno system, expansion and distribution of pink salmon in the tributaries have been observed by video arrays, snorkelling and sonar. Until 2021, the only tributaries occupied by pink salmon were the large headwater branches and some other large or mid-sized tributaries in the mid- and lower parts of the catchment. No

evidence of pink salmon was detected to date in the smaller tributaries, despite intensive monitoring by snorkelling, electrofishing etc. However, preliminary eDNA analysis has suggested a somewhat wider distribution of pink salmon in the Teno system (Fossøy et al., in prep).

Spawning of pink salmon in the River Teno was observed both during and after an unprecedented run of the alien species in 2021 (Anon, 2021). Observations of spawning fish and their aggregations were made in multiple areas of the middle reaches of the Teno main stem by snorkelling and visual observations from the riverbank (Erkinaro et al. 2022). The largest aggregations of spawning pink salmon, in the sampled areas of the large Teno main stem, were located very close to the shoreline (c. 1–30 m). Here, the total channel width varied between 150m and 250m. The majority of the redds were in shallow water (30–60 cm), with relatively high flow velocities (c.0,3–1 m/s) and gravel-cobble substrate (Erkinaro et al. 2022). The spawning period started in late July/early August and egg development was rapid: all eggs were eyed by mid-September. The first juveniles hatched in late September and, by early October, most of the eggs had hatched (Erkinaro et al. 2022). Electrofishing, excavating of redds and beach seining in the estuary of the river in April–May 2022, confirmed successful juvenile production. Large numbers of pink salmon smolts were present and apparently ready for their feeding migration to sea (unpublished data).

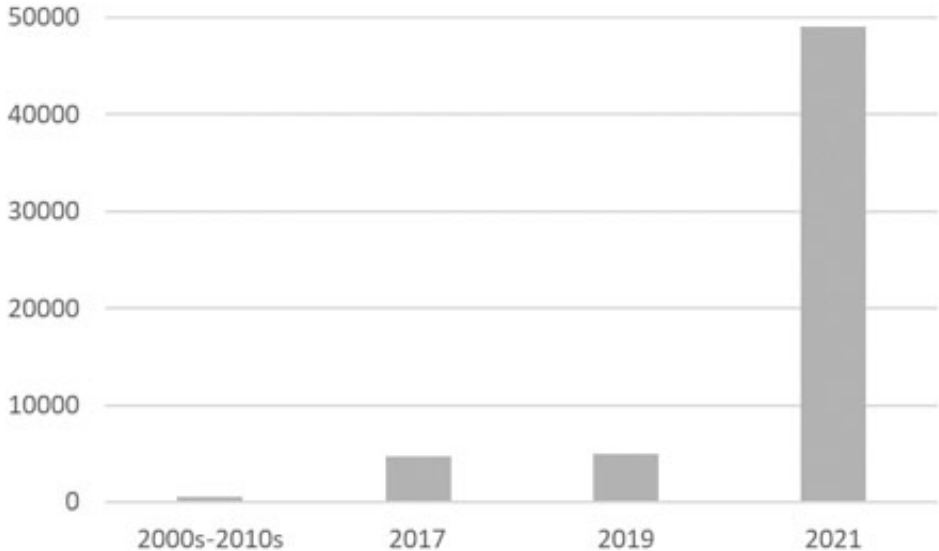


Figure 1. Estimated numbers of pink salmon entering the River Teno/Tana. Figures for 2019 and 2021 are based on sonar counts, those in 2017 and earlier odd years are estimated from catches.

While Norway has defined pink salmon as a high-risk invasive species and is investing very significant resources into their removal from multiple river systems, no such management plans have been reported from Russia. For this reason, the spread of pink salmon may continue unabated from the large production areas in Russia. Increasing numbers of pink salmon may continue to invade Norwegian and other river systems in the North Atlantic, despite the strong preventive measures underway or planned in a number of countries. The efficacy of the Norwegian mass removals programme and information on the interactions between pink salmon and native salmonid fishes, should be reviewed and summarised on an ongoing basis. Such detailed information from the most severely affected areas in the far north would facilitate the preparation of exclusion/clearly focused eradication plans for areas at risk elsewhere in the North Atlantic area.

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Pink Salmon in Norway 1

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The Situation in Norway

Pink salmon is an introduced species in Norway. The origin of the invasion in Norway is the transplantation of pink salmon in Russia, from rivers of the Pacific coast to rivers in the Barents Region. Pink salmon have been reported in Norwegian rivers in varying numbers, since stocking of this species began in 1956. Self-reproducing stocks were established in Russia from 1985 onwards, as broodstock were collected further north in the Pacific region and the transplantation programme proved more effective. Norwegian rivers contained low and relatively stable numbers of reproducing pink salmon until 2017. Over this period the regular occurrence of these fish was largely restricted to the northeastern part of Norway.

In 2017, adult pink salmon were found throughout Norway, but the numbers encountered were clearly related to proximity to the Russian border. In 2019 there was a further increase in the northernmost counties of the country, but not across the country as a whole. In 2021 there was an estimated ten-fold increase in the numbers of pink salmon running rivers in the northeast. Alarming, over the summer period, pink salmon became by far the most abundant fish species in many rivers in this area.

The river with the highest run of pink salmon was, most probably, the very large border river, the Tana (named the Teno River in Finland), with an estimated run of 50,000 pink salmon, based on sonar and video surveillance. Some smaller rivers also witnessed massive runs of pink salmon. For example the River Vesterelva had an estimated run of 25,000 to 30,000 individuals. As before, the abundance of salmon in an area remains strongly correlated with proximity to the Russian border. However an increasing number of rivers in areas further west and south have pink salmon runs which the Norwegian Environment Agency regards as potentially harmful to native fish species, to other parts of the ecosystem and to water quality. As the carcasses decompose they release significant quantities of marine-derived nutrients into the receiving waters.

Methods Used to Control the Spawning of Pink Salmon

To date, the removal of pink salmon has largely been carried out by volunteers from local angling and fisheries organisations. Some of the work has been financed by the State of Norway, through the County Governor's Office or through the Norwegian Environment Agency. The volunteers applied to the County Governor's Office to have a permit granted for their choice of eradication measures. Thus, the removal methods used were licensed by the regional environment authority, and contained specific protocols to avoid potential harm to other native species. The methods used included: trapping in fish ladders, spearfishing, gillnetting, beach seines and the construction of interceptory weirs.

Removal of pink salmon from fish ladders, which permit full upstream passage of all species of fish, have, in many situations, been refined to ensure that the water flow is constrained through a narrower slot. This can be effective, but fish ladders are seldom

located close to the sea. Such passes are generally built to enable fish to ascend waterfalls, and in many locations the landscape is flat and displays a low gradient. It has been found that fish ladders can be manipulated to stop the upstream movement of all of the pink salmon entering the fish pass chamber but other eradication measures are needed below the location of the weir or the fish pass structure.

Spearfishing is a method with low risk of damage to fish other than the target species. Given good visibility, it is possible to remove a large number of pink salmon in a very safe manner. However, where there are thousands of individuals present, spread over large parts of the river, with new pods of fish running each day, the efficacy of spearfishing is limited. It is regarded as a supplement to other methods and is most suited to rivers with a low and concentrated occurrence of pink salmon. It is also useful in confined areas, for instance pools with large rocks and boulders, where the use of other removal methods has proven ineffective.

Gillnets have a high risk of harming fish other than the target species. Once a fish is entangled in a gillnet, it is generally not possible to release a fish without significant damage. This trapping method should only be used with great caution in an Atlantic salmon river. However, in cases where there are very high numbers of pink salmon, with little or no mixing with other species in the pool, gillnets can be used to remove very significant numbers of fish, with negligible bycatch. When using gillnets to remove pink salmon, the pool where shoals of pink salmon are present should always be checked by divers and the removal attempt aborted if native fish are mixed amongst the shoals of the pink salmon. Depending on the speed of the current, it is often necessary to use an extended lead rope and extra flotation on the gillnets. One gillnet is placed in a fixed position at the lower end of the pool, and another is drifted toward this from the upper end of the pool. Often the pink salmon will be caught just when the driftnet is about to reach the fixed net. Pink salmon can easily find a way to escape under the nets. For this reason, it is normal to have a lot of extra helpers involved, to hold the nets in position, ensuring that the nets are not rising from the bottom or collapsing as fish become entangled in the mesh. Gillnets will not work when there are large rocks or other structures on the river bottom, or in deep pools. Although gill netting has proven very effective, experience has shown that in many rivers where the method was used, thousands of pink salmon had to be left to spawn because mixed populations of native species were present or due to the morphology or hydrology of the river.

A beach seine is designed to catch fish alive, hence it has a far thicker netting and smaller mesh size compared to a gillnet. This results in more drag when a seine is used in a flowing river. Only in specific, slow flowing locations has this method proven to be effective. There are different techniques used when seine netting, but the general goal is to surround a shoal of fish with the seine and haul them ashore. The volunteers reported that often a shoal of pink salmon can be almost surrounded, but manage to escape the bag of the net at the last second, as maneuvering a large beach seine in the current is difficult and slow. The greatest benefit of this method is that, when it works, any bycatch can, in most cases, be released undamaged.

Some rivers have used temporary weirs in the lower parts, catching all ascending fish alive in a trap box. The fish are manually sorted by species, removing pink salmon and gently releasing other species. These light structures can be completely removed once the run has ceased.

The conclusion reached following the 2021-season is that the methods outlined above all have their limitations, and that the overall efficiency of the methods used to date is not sufficient to gain control over the fast-growing populations of pink salmon.

The main future strategy will be the construction of purpose-built fish fences. Two different fish fence designs have been identified: rigid weirs made from steel and aluminium and floating weirs of the resistance board weir design* . (<https://fishbio.com/fish-counters-weir-resistance-weir-panels>)

* One of the advantages of a Resistance Board Weir over a rigid weir, is the ability to withstand higher flows. Rigid weirs have a tendency to get blown-out when increased velocity and debris put excessive force against the weir, whereas resistance board weirs have flexibility and can shed debris over the top. This type of weir is made up of an array of resistance panels that span the majority of the river channel. Each panel consists of evenly spaced PVC conduit pickets held together by UHMW polyethylene (high density plastic) stringers. The upstream end of the panel is attached to a cable and rail system (i.e. substrate rail) that is anchored to the channel bottom, and the downstream end is lifted above the water surface by a 2 ft. x 3 ft. (60 cm X 92 cm) resistance board that planes upward in flowing water.

Expected Development of Pink Salmon Populations

Based on drift-counting in August 2021, it is assumed that the overall number of pink salmon spawners was higher in 2021 than 2019, despite the intensive eradication efforts outlined above. The environment authorities in Norway monitored the development of the pink salmon eggs, and based on the evidence collected, it is postulated that there was a high survival rate from egg to smolt over the winter 2021/2022. Norway will continue in its efforts to gain control over the ongoing invasion of pink salmon. More state funding has been made available to establish weirs and to fund their operation over the years to come. If Norway fails to stem the spread of this invasive species, the result will be the further spread of reproducing populations to neighboring countries in the North. If conditions for colonisation are suitable for the species, it may well spread to countries lying far further to the west and south of Norway and potentially to other countries across the North Atlantic.

Using Stable Isotopes to evaluate potential impacts of pink salmon – PinkSIES project

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Pink salmon are native to the North Pacific, inhabiting a large range where they reproduce in tributaries on both sides of the ocean. Among the Pacific salmon species, pink salmon is the smallest but the most abundant. They have one of the fastest oceanic growth rates and display a two-year life cycle. Their freshwater phase is short, and the juveniles leave the natal river at c. 3.5 cm in length (Heard, 1991).

In 2017, an unexpectedly large number of pink salmon records were reported from countries around the North Atlantic. Mature specimens were caught in tributaries outside Scandinavia and Russia, as far as Canada, Greenland and France (ICES, 2022). Spawning of pink salmon was observed in Scottish rivers, including the Spey, Ness and Dee (Armstrong et al., 2018). Between 2017 and 2021, the number of returning adult fish recorded increased further (Diaz Pauli et al., 2022; Skóra et al. 2023). The dramatic increase in the numbers of this non-native salmon species has generated much concern, particularly regarding impacts on native Atlantic salmon populations. To date, there are unanswered questions regarding the implications of this invasion, particularly the regarding competition with native salmonids at sea and in freshwater.

The PinkSIES project (Pink Salmon Invasion of the North Atlantic: Evaluation of Stable isotopes as a method to detect potential impacts) is supported by collaborators from many countries around the North Atlantic. The aim of the project is to determine the impact of pink salmon on native salmonids at sea and in recently invaded rivers. The objectives of the programme focus on the marine phase of pink salmon in the NE Atlantic and include, i) an assessment of the distribution of feeding grounds, co-occurrence and potential competition between pink and Atlantic salmon, ii) to establish field metabolic rates (FMR) and the thermal sensitivity of FMR of pink and Atlantic salmon, and iii) to model the impact of climate warming on the future distribution of pink salmon. The project will also investigate the freshwater phase in recently invaded rivers, aiming to determine the duration of this phase, the extent of feeding of pink salmon fry whilst in freshwater, and predation on pink salmon fry by native fish species.

To date, biological samples from pink salmon (otoliths, scales, muscle tissue) have been collected from approximately 500 specimens. These fish were caught offshore, inshore and in rivers in Norway, Iceland, Faroe Islands, Ireland, the UK, Greenland, Sweden, Denmark, and Germany. Analysis of stable isotopes of nitrogen and carbon of these samples will be used to determine the oceanic conditions where the pink salmon have been feeding. The same isotopic technique will be used with tissue from pink salmon juveniles to assess their ecological role as both predators and prey.

In spring 2022, surveys were undertaken to capture pink salmon smolts in Scotland and Iceland. This study confirmed that pink salmon had successfully reproduced in both countries (Scotland: Skora et al. 2023, Iceland: in prep.). Our field observations also indicated that pink salmon fry were feeding in freshwater prior to migration, and were consumed by sea trout parr (unpublished).

The projects will provide details of the distribution of pink salmon feeding grounds in the NE Atlantic, enabling an assessment of the co-occurrence and potential competition with Atlantic salmon at sea, and how climate warming may modify the future distribution of pink salmon. Regarding the freshwater phase of the pink salmon's life cycle, we have confirmed successful recruitment of pink salmon in Scottish and Icelandic rivers, established important details of their life-cycle and detected opportunistic predation of sea trout parr on pink salmon fry (unpublish).

We thank colleagues who helped with sampling of pink salmon smolts in Scotland and Iceland: Alan Youngson, Sean Robertson and Gudni Gudbergsson, the project partners and all collaborators who have donated samples of pink salmon.

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme, under the Marie Skłodowska-Curie grant agreement No 101026030.

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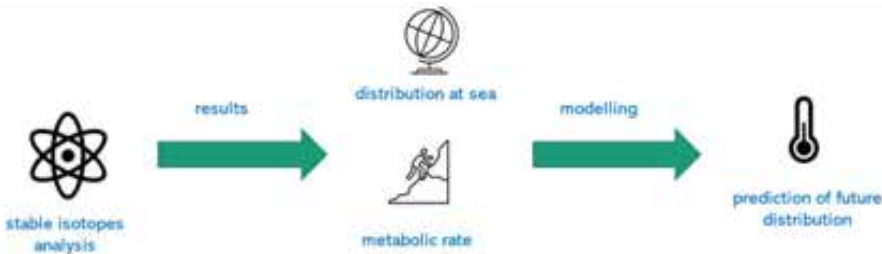
PinkSIES

PINK SALMON INVASION OF THE NORTH ATLANTIC
EVALUATION OF STABLE ISOTOPES AS A METHOD
TO DETECT POTENTIAL IMPACTS



H2020-MSCA-IF-2920

IMPACT OF PINK SALMON ON NATIVE SALMONIDS AT SEA



FIRST PINK SALMON SMOLTS CAUGHT IN SCOTLAND



The first pink salmon smolt caught in the R. Thurso



Pink Salmon smolts caught in the R. Oykel

FISHING IN ICELAND~ THE RIVERS BOTSNA, GRIMSÁ, LANGÁ



Assessing the Risks Posed by Pink Salmon to UK Waters

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Introduction

Pink salmon were first introduced into rivers entering the White Sea basin in the 1950s (Alekseev et al., 2019) and they have quickly established self-sustaining populations in northern Russia, Norway and Finland (e.g. Sandlund et al., 2019; Erkinaro et al., 2022). They were first recorded in Great Britain in 1960. In the 56 years between 1960-2016 only 17 pink salmon had been recorded in Scotland. Over the same period an additional 11 confirmed captures were recorded from English rivers and coastal nets, and a single individual was captured near the mouth of the River Wye which forms the border between England and Wales. Almost all of these fish (89%) were captured in 'odd' years and catches were most prevalent (74%) in east coast river catchments and coastal areas. The sudden, and unexpected, increase in pink salmon records throughout Great Britain, and particularly Scotland (see Armstrong et al., 2018), resulted in increased concern from fisheries managers and government agencies (see: Bean, 2017).

The unexpected appearance of large numbers of pink salmon in Scotland was matched by an increase in the number of records reported from other parts of Europe (ICES, 2022), and several countries reported the occurrence of this species for the first time (Bean, 2017). Whilst the species has been present in large numbers in Finland (Erkinaro et al., 2022, Sandlund et al., 2019) and northern Norway for some time, their abundance and southern distribution in Norway also increased significantly during 2017 (Mo et al., 2018; Sandlund et al., 2019). Increased numbers of fish were also recorded in Ireland (Millane et al., 2019a), Sweden (Staveley & Bergendahl, 2022), Greenland (Nielsen et al., 2020), the Faroes (Eliassen & Johnjansen, 2021), Iceland, Germany, France, Netherlands and Denmark (Bean, 2017; ICES, 2022).

The Risk Assessment Framework

Horizon Scanning

Despite their long-term, but still occasional, presence in UK waters, horizon-scanning assessments of the highest-risk future alien invasive alien species (IAS) in Great Britain (based on their likelihood of arrival, establishment and impact on native biodiversity over the next 10 years) (e.g. Roy et al., 2014) did not identify pink salmon as a significant threat. Subsequent assessments of risk by invasive species, such as that carried out by the Water Framework Directive UK Technical Advisory Group on Alien Species (WFD UKTAG, 2015) also failed to identify pink salmon as a risk to waterbody status. Identifying IAS as one of the major causes of biodiversity loss, EU Regulation 1143/2014 introduced the first comprehensive EU-wide approach to tackling this issue. This regulation requires member states to take action on pathways of unintentional introduction, and to take measures for the early detection and early eradication of IAS. Additionally, member states are also required to manage IAS, which are already widely spread within their territory. A core

provision of this regulation was the development of a list on IAS of union concern. These are IAS which have the potential to establish and cause significant adverse impact, and for which concerted action across the EU is necessary if management is to be successful. The regulation also has a strong focus on the potential arrival of future invaders. Publication of the 'The Union List' took place in 2016 via EU Regulation 2016/114 and it identified the need for action on 14 plant and 23 animal IAS. An additional 17 species were added in 2019. Whilst many aquatic species are included on the list, only one fish, the Pumpkinseed *Lepomis gibbosus*, was included. Pink salmon have not, therefore, been identified as a species of 'Union Concern', possibly reflecting its limited distribution throughout the EU and its relatively recent, post-2017, expansion in range.

Commissioning Risk Analysis and Risk Assessments

Risk assessments are only one component of a process called 'risk analysis'. This is a structured process that provides a framework for the implementation of IAS management measures, and is comprised of three component parts: risk assessment, risk management and risk communication (Booy et al. 2020). In reality, all three components are often contained within the risk assessment.

Risk assessment is a valuable tool to determine the risk caused by IAS to native biodiversity, the economy, or livelihoods. It also aids effective decision-making when dealing with invasive alien species and is used globally as a mechanism to both prioritise action and allocate, often limited, financial resources. Within Great Britain, the framework for risk assessments in the context of dealing with IAS was set out within Defra's review of non-native species policy (Defra, 2003). This framework set out the need to involve scientific experts in the development of risk assessments, for these to be rigorously peer reviewed, and for public consultation.

The GB Non-Native Species Secretariat (GB NNSS) is responsible for coordinating the national approach to IAS within Great Britain. The GBNNSS reports directly to a Programme Board, which contains representation from the devolved governments of Scotland and Wales and their relevant agencies. Risk assessment in Northern Ireland is assessed separately (and along with the Republic of Ireland, on an island-wide basis) because it is located in a different biogeographical region to Great Britain. The GB NNSS facilitates the work of a Non-Native Species Risk Analysis Forum (NNRAF), and it is the role of this forum to provide the Programme Board with robust, independent, risk-based evidence to underpin decision making on non-native species and the application of the retained EU Invasive Alien Species Regulation. It also provides a risk analysis function and scientific advice to the UK Programme Board in relation to the GB invasive species strategy.

Within Great Britain, Defra's review of non-native species policy (Defra, 2003) promoted the use of risk assessments to use best available evidence to determine the likelihood of invasion, the risk of establishment and the impact of this occurring. Following this review, a national risk assessment mechanism was established to provide assessments of the risk posed by any non-native species in Great Britain (see Baker et al., 2008; Defra, 2008, 2015). This ensures that risk assessments are carried out by independent experts, are peer reviewed and placed on the GB NNSS website for public comment before being finalised. The entire process is overseen by an independent panel of risk analysis experts (NNRAP) on behalf of the GB Programme Board which approves the assessments once they are completed. All completed risk assessments are reviewed when appropriate and there is no set timescale, or dedicated funding, available for this.

Applying the Risk Assessment Framework to Pink salmon

The arrival of large numbers of Pink salmon in UK waters in 2017 prompted the GB NNSS to commission a Rapid Risk Assessment (RRA) and then full Risk Assessment (RA) for this species. The RRA is used to provide a quick assessment of the potential impact of a newly arrived, or imminently arriving, IAS. It follows the same basic structure of a full risk assessment, but may not be as detailed and is not peer-reviewed. The pink salmon RRA (Copp, 2017) concluded that there was potential for rapid spread, but that environmental, economic and social impact may be moderate, but with low confidence. The GB NNSS then commissioned a full risk assessment (Cowx, 2018), which was informed by the data collected over 2017 from within the UK, Ireland and mainland Europe.

This assessment included an evaluation of the available published literature and an appraisal of the pink salmon data available up to, and including, 2017. Providing some context on the known biology of the species, along with a description of the global and national distribution of this species, the risk assessment then considered: 1) the probability of future entry into Great Britain, 2) the likelihood of establishment, 3) the potential for spread, and 4) the environmental, economic and social impact that this species may have on receiving systems. Additionally, the risk assessment also identified key knowledge and research gaps that existed at that time.

A summary of the key risk factors for pink salmon and their evaluation is provided in Table 1 below. This sets out ratings for the levels of risk and confidence associated with each element of the assessment.

Risk Assessment Criteria	Risk Assessment	Confidence
Entry	Very Likely	High
Establishment	Very Likely	High
Spread	Rapid	High
Impact	Moderate	Low

Table 1. Summary Risk Analysis scores for each component of the 2018 GBNNSS Pink salmon risk assessment.

Separate pink salmon risk assessments have been developed by Irish (Millane et al, 2019b) and Norwegian (VKM, 2022) agencies. Whilst both address many of the same issues as those covered within the GBNNSS pink salmon risk assessment, all three differed in the level of complexity allocated to each of the key criteria. The Norwegian risk assessment, which was based on a significantly higher level of past experience with pink salmon, included a modelling approach, which was absent from those risk assessments produced by GB and Ireland. In addition to a comprehensive review of existing literature and consultation with relevant agencies, the Norwegian risk assessment also investigated whether changing sea surface temperature (SST) scenarios had any effect on pink salmon recruitment and the number of returning adults.

Knowledge and data gaps identified within both the GB and Norwegian risk assessments have helped to focus attention on key aspects of pink salmon invasion ecology and the potential for wider societal and economic impacts. These are summarised in Table 2.

Table 2. Summary of key knowledge and research gaps identified within the GB and Norwegian pink salmon risk assessments.

Surveillance
<i>A need to assess the abundance of Pink salmon</i> – development of systematic (national) recording; use of novel approaches such as environmental DNA (eDNA)
<i>Habitat availability and projected numbers</i> – how much Pink salmon habitat is available and what is the expected timeframe for full occupancy
<i>Requirement to determine the genetic origin of fish</i> – are fish in the GB progeny of fish spawned in Norway or Russia
Ecology
<i>Knowledge relating of their spawning ecology</i> – spawning habitat, location within catchments, temperature requirements, hatching times, recruitment. Temporal and spatial overlap of spawning sites with native salmonids and Sea lamprey
<i>Ecology of juvenile Pink salmon</i> – interactions with native salmonids through competition for food and space, predation by other fish.
<i>Agonistic interactions</i> – aggressive behaviours (including crowding and displacement) by adult Pink salmon on native salmonids
Environmental impacts
<i>Effects of replacement of native salmonids on ecosystem functioning</i> – role of Pink salmon as an alternative host for Freshwater Pearl Mussel or by impacting native salmonid FWPM hosts, impact on fish, bird and mammal predators, impact of marine derived nutrients (eggs, juveniles and carcasses) on nutrient cycling and overall productivity
<i>Effects on invertebrate populations</i> – predation by juvenile Pink salmon, impact of marine derived nutrients on invertebrate production.
<i>Effects in water quality and terrestrial ecosystems</i> – deterioration of water quality in nutrient poor river systems, impacts of increased phosphorus levels on Freshwater Pearl Mussel, transport of fish borne nutrients to terrestrial environments by scavengers
<i>Transport of marine contaminants to rivers</i> – unknown risk of bioaccumulation and transport of contaminants from the Atlantic and Bering Sea
Fish health
<i>Introduction of parasites and pathogens</i> – clarify the risk to native salmonids from those which may be carried by Pink salmon
<i>Identify risks of parasite and disease introductions to the farmed Atlantic salmon sector</i>

Marine impacts
<i>Behaviour in the sea – distribution and resource use</i>
<i>Assessment of potential for ecological interactions between Pink salmon and Atlantic salmon/sea trout at sea – competition for prey items, predation of post-smolts</i>
<i>Potential impact on birds and other animals in estuaries and in the sea – competition for food at sea, impact of carcasses flushed into estuaries from rivers</i>
Climate change
<i>Assess the impact of climate change on abundance, spread, establishment and on ecological interactions</i>
Social and Economic impacts
<i>Impacts on ecosystem services – water quality, angling and tourism income, biodiversity value</i>
<i>Assessment of social and economic impacts of loss or substitution – loss of employment within fisheries, reputational issues for fisheries through loss of the 'angling experience', potential opportunities for harvesting</i>
Management
<i>Review potential control and containment measures – use of barriers, targeted removal (using rods, nets, traps, harpoons), redd disruption</i>
<i>Costs of management – now and in the future, who pays?</i>

Conclusion

Risk assessments are an invaluable resource for identifying the range and potential scale of impacts related to the extended distribution and invasion by pink salmon. However, confidence in scoring these impacts is limited by a lack of knowledge in key areas.

Whilst the current risk assessments highlight the many areas in which data or knowledge is lacking they do not identify who is responsible for filling identified gaps, nor do they provide an allocated resource for doing so. Moreover, there is no timescale for the review of existing risk assessments.

Reviewing risk assessments is however an essential process, particularly when, as in the case of pink salmon, a significant volume of new knowledge has become available since 2017. Increased interest in the potential impact of pink salmon on Atlantic salmon by NASCO and ICES is welcome and may be useful in encouraging the need for a structured surveillance and reporting programme for this species, and for leveraging resources for future work.

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Pink Salmon in Norway 2

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The first introduction of pink salmon (*Oncorhynchus gorbuscha*) in the Russian Barents region occurred in the late 1950s. Between 1956 and 1979, more than 220 million pink salmon eggs and fry from the southern part of Sakhalin Island in the Pacific Ocean were transported to rivers and local hatcheries in the White Sea drainage, in north-western Russia. These introductions resulted in relatively abundant but variable returns of adult fish. The catches of returning adult fish did however rely on stocking activity and the aim of establishing permanent self-sustaining populations was not reached, perhaps because these pink salmon were not adapted to the local climatic conditions and timing of spawning.

The stocking programme with eggs and fry from Sakhalin was therefore terminated in 1979. In 1985, the stocking programme of pink salmon around the White Sea was resumed but, on this occasion, with eggs and fry from a more northern locality on the Pacific, specifically from the River Ola, in the Magadan oblast. These new introductions proved more successful and resulted in local self-reproducing populations in the White Sea area, with odd-year stocks being more abundant than even-year stocks. The stocking programme of pink salmon in north-western Russia was discontinued in the year 2000 and consequently, all pink salmon caught since 2001 in the northeast Atlantic, the Arctic Sea and the Barents Sea, and in rivers draining into these seas, are the result of reproduction in the wild.

The first records of pink salmon in Norway occurred in 1960, as a result of the Russian stocking in 1959. During 1960–1975, abundant returns to Russian waters were accompanied by relatively large catches and numerous observations in Norwegian waters. However, apart from individual years with larger catches of pink salmon, catches of this species in Norway were relatively low. During 1976–2016, on average 200 and 50 pink salmon were captured in odd and even years respectively, in less than 50 rivers. However, since 2017 there has been a dramatic increase in the number of pink salmon (odd-year fish) in Norwegian waters. In 2017, more than 11,000 fish were captured or observed in a total of 263 rivers, spanning the entire country. A total of 25,000 pink salmon were captured in 2019, of which 19,000 were caught in rivers and about 6,000 in coastal bag-net fisheries. In 2021, more than 200,000 pink salmon were captured or observed, >160,000 in 271 rivers and 40,000 in coastal fisheries. The number of pink salmon registered in Norway in 2021 was 9 times higher than in 2019 and 17 times higher than in 2017.

The majority of pink salmon in Norway are captured in the northernmost county of Finnmark, close to Russia. In 2017, 2019 and 2021 the catches, both in rivers and at sea, constituted some 90% of the total recorded catch in the country. Particularly large numbers of pink salmon were in evidence along the eastern region of Finnmark, from the North Cape to the Russian border. These catches accounted for approximately 80% of the total pink salmon catch in Norway. In 2021, five rivers in this region received more than 10,000 pink salmon each (range: 10,000 – 47,000 fish). Although the largest catches of pink salmon are found in eastern Finnmark, the largest increase in numbers since the first major invasion in 2017 has occurred in the western part of Finnmark and further south in the county of Troms. Hence, the pink salmon population in Norway shows indications of slowly spreading further west and south. In southern Norway catches remain low, although the catches in 2021 were the highest yet recorded.

Pink salmon are captured along the coast and in the fjords (coastal fishery) of northern Norway between early June and August, with the majority of fish being captured in late June-early July. In- river catches are highest in late July/early August, some three weeks later than in the coastal fishery. Spawning in rivers takes place from mid- to late August.

Little is known about the potential negative effects of pink salmon on native salmonid species and Norwegian river ecosystems. Pink salmon have been shown to have a similar marine diet to Atlantic salmon and sea trout, and use the same spawning grounds as Atlantic salmon, sea trout and sea-run char, although earlier in the year. In a future scenario where numbers of pink salmon continue to rise, competition for food or space with other salmonid species cannot be ruled out.

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Pink Salmon – Lessons Learned and Planning for the Future

Across the pink salmon's native range their minimal use of streams for feeding results in high densities of spawning adults, as the carrying capacity is set by the spawning habitat rather than the stream's capacity to produce food for the offspring, and most streams can support more incubating embryos than they can support the food demands of the resulting juveniles. Consequently, small streams may have densities of pink salmon that seem incredible to anglers, biologists, and others who are used to the much lower densities of other Pacific salmon species and especially Atlantic salmon. Moreover, because they all die after spawning, their abundance is especially evident. The carcasses are fed upon by a variety of consumers and decomposing organisms, and thus the nutrients obtained by the salmon at sea fertilise the stream and riparian zones.

Over the millennia, the pink salmon's native systems have adapted to greatly benefit from this annual injection of welcome additional nutrients. However, in areas inhabited by Atlantic salmon the appearance, over the past few years, of hundreds, thousands and more recently hundreds of thousands of additional non-native salmon has caused dismay, disbelief and increasing levels of alarm.

Presentations at the workshop have shown that in northern Norway and Finland the unprecedented runs of pink salmon recorded in 2021 were orders of magnitude higher than those present only two years earlier. On the large Teno / Tana River system (the largest Atlantic salmon river catchment in the world), the estimated pink salmon run was c. 50,000 individuals in 2021. These sonar figures are known to be underestimates, as significant spawning areas of pink salmon were found in the main stem and in one major tributary downstream from the sonar site.

In northern Norway, even greater increases in pink salmon runs were recorded. The number of pink salmon documented in Norway, in 2021, was 9 times higher than in 2019 and 17 times higher than in 2017! The majority of pink salmon in Norway are captured in the northernmost county of Finnmark, close to Russia. In 2021, five rivers in this region received more than 10,000 pink salmon each (range: 10,000 – 47,000 fish). Although the largest catches of pink salmon were found in eastern Finnmark, the largest increase in numbers since the first major invasion of pink salmon in 2017 occurred in the western part of Finnmark and further south in the county of Troms. Hence, the pink salmon population in Norway shows indications of slowly spreading further west and south. In southern Norway catches remain low, although the catches in 2021 were the highest yet recorded.

To date, such increases in numbers have not appeared in rivers further south in Europe but, worryingly, spawning pink salmon have been recorded from several rivers in Scotland, including the Rivers Ness and Thurso, and also from rivers in Iceland. Not only have pink salmon successfully spawned in these locations, but viable pink salmon smolts have also been recorded from these systems.

In addition to concerns regarding the potential significant biodiversity impacts from invading pink salmon, they may also pose serious health risks for Atlantic salmon and other native salmonids. As was seen from the devastating impacts of *G.salaris* on many major Norwegian salmon populations, parasites and diseases which are benign for one population may prove catastrophic for a closely related stock of fish.

Countries directly at risk from the spread of pink salmon moved quickly to establish surveillance and monitoring programmes. For example, Scotland's response to pink salmon is coordinated through the Pink Salmon Task Group, with a membership of Scottish Environment Protection Agency (SEPA), NatureScot, Marine Scotland, Fisheries Management Scotland and the Dee and Ness District Salmon Fishery Boards. The group developed detailed guidance for managers and anglers. Fisheries Management Scotland also designed a national online recording tool to gather, store and map information on captures and sightings of pink salmon. (<https://fms.scot/wp-content/uploads/2022/01/211006-Pink-Salmon-Licensed-activity-report.pdf>).

In addition to surveillance, a key priority for the fisheries management groups in these countries is to identify appropriate and effective management measures, with a particular focus on having well-honed plans in place for the expected runs of pink salmon in 2023.

We are very grateful to our Norwegian colleagues for sharing with us in such detail at the workshop their experiences in managing a large influx of pink salmon. NASCO has also expressed serious concerns regarding the rapid spread of pink salmon and urged all parties to work closely together to stem the further spread on this species.

Little is known about the potential negative effects of pink salmon on native salmonid species. However, pink salmon have a similar marine diet as Atlantic salmon and sea trout and use the same spawning grounds as Atlantic salmon, sea trout and sea char, although earlier in the year. In a future scenario, where numbers of pink salmon continue to rise, competition for food or space with other salmonid species cannot be ruled out.

While many countries have defined pink salmon as a high-risk invasive species and are investing very significant resources into their removal from multiple river systems, no such management plans have been reported from Russia. For this reason, the spread of pink salmon may continue unabated from the large production areas in Russia. Increasing numbers of pink salmon may continue to invade Norwegian, Finnish and other river systems in the North Atlantic, despite the strong preventive measures underway or planned in a number of countries.

Part 2: Red Skin Disease – Research and Monitoring Efforts to Date

A Brief History of Red Skin Disease – what do we know?

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When The Alarm Went Off

In the second half of May 2019, a number of diseased adult salmon, recently arrived from the ocean, could be observed in many places in the River Enningdalselva, southeast Norway. The salmon were bleeding and/or had large, white spots on their skin. The fish were located near the surface of the water, in stagnant parts of the river and several dead salmon were present. A closer examination showed that the fish were bleeding from the dermis, below the scales and in association with blood vessels (not in the outer epidermis where blood vessels are not present). Commonly, there was a clear demarcation between healthy and diseased tissue. Many fish had affected fins and necrotic tissue (even if the rest of the fish looked unaffected) and the belly was the most affected part of the fish.

The River Enningdalselva is a border river between Norway and Sweden, but most of the anadromous part of the river is in Norway. The river is quite small. Often less than 2,000 l per sec in the spring. The water is dark brown in colour (similar to an aged, Islay whiskey). The average size of salmon in this river is 5-10kg and grilse are rare. Consequently, Red Skin Disease (RSD) has only been observed in multi-sea-winter salmon in the River Enningdalselva.

A New, Unknown Disease?

What could have been the cause of this salmon disease outbreak? Many possibilities were discussed: were salmon stressed due to low water flow and high water temperature in 2019, or could it be due to pollutants/chemicals in the fjord? The latter was found to be unlikely as the gills were not affected. Could it be linked with a former rainbow trout farm further upstream?

Many samples were taken to test for infectious diseases. No viruses, but many bacteria and parasites were found. However, none of these infectious agents are considered primary pathogens, and none were likely to cause a skin disease.

Atlantic Salmon in Many Rivers Were Affected

In the same year (2019) a similar disease was observed in several rivers in the east Atlantic area:

Rivers in Sweden (west coast), Denmark, UK, Ireland and Norway. It was noted that a similar disease had occurred in Swedish and Finnish fish since 2014, in rivers draining into the Baltic Sea. Numerous studies have been carried out on this disease in Sweden and also some in Finland.

Workshop in Oslo

To discover more about the disease and to exchange knowledge and experience, a workshop was arranged in Oslo in November 2019. Twenty-five managers and scientists from Sweden, Denmark, Finland, England, Scotland, Ireland, Russia and Norway met to discuss possible causes of the new Atlantic salmon disease, with focus on thiamine (vitamin B1) deficiency. It was concluded that Atlantic salmon in all countries were likely affected by the same disease, and it was agreed to name it Red Skin Disease (RSD).

Geographic Occurrence of Red Skin Disease

RSD has occurred yearly since 2014 in rivers draining into the Baltic Sea, but not in the same rivers every year. RSD, but also *Saprolegniosis*, has occurred annually in rivers in Ireland and the UK, while RSD occurred in rivers in Denmark, Norway and the Swedish west coast in 2019 and, to a small extent in 2020, but not in later years. How can we explain this difference if south-eastern Atlantic salmon are feeding and migrating in the same areas of the ocean? Skin disease outbreaks in Atlantic salmon in Russian rivers draining into the Barents Sea have a different appearance to those with RSD and it is likely that they are suffering from a different causative agent(s).

The Cause of RSD is Still Unknown

Apart from Swedish studies of Atlantic salmon in Baltic rivers, the causes of RSD have only to a small extent been studied in other countries. Many possible risk factors remain to be studied. It is not known if the cause(s) are connected with life in freshwater or in the sea. Even if no etiological agent has been found, the disease may be caused by an infectious, undescribed agent.

A great deal of questions remain unanswered, mainly because of our knowledge gaps.

Red Skin Disease – The Search for a Cause and a Potential Breakthrough

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RSD – Did It All Start in the Baltic Sea?

In 2014, fresh run Baltic salmon with skin haemorrhages and fungal infections appeared in Swedish rivers. The disease, since 2019 called Red Skin Disease (RSD), was first seen in River Mörrumsån in southern Sweden, where the salmon run starts in early May. By late June, reports also came from the River Torneälven, a border river between Sweden and Finland. The River Torneälven is the premier Baltic salmon river, producing about 90-95% of all wild smolts. The disease reports declined during late summer and early fall. In October, epizootics of saprolegniosis occurred in both salmon and sea trout in several rivers. The same disease pattern was seen in 2015.

First Round of Investigation

In 2016 governmental funding was provided to the Swedish National Veterinary Institute (SVA) and the Finnish Food Authority (FFA) to investigate if an infection was causing the disease. Sweden sampled 20 fresh-run salmon from each of the Rivers Mörrumsån, Ume-/Vindelälven and Torneälven. A small number of other rivers were sampled during the spawning season. Finland sampled fresh-run salmon from the River Torneälven. Single diseased cases of salmon were also sampled during the autumn, as were broodstock from the River Kemijoki. Skin haemorrhage in various stages (acute, subacute, chronic, healing) and fin lesions were seen, as well as Ulcerative Dermal Necrosis (UDN)-like lesions on the head. Secondary saprolegniosis was seen in several advanced cases. In the River Torneälven, traumatic wounds were the most common finding. Viral culture (BF-2, FHM, ASK) and PCR for infectious salmon anemia virus (ISAV), salmonid alpha virus (SAV) and Onchorhynchus masou virus (OMV) did not identify any virus. Bacteria were identified in some cases (*Vibrio anguillarum*, *Iodobacter limnosediminis*, *Yersinia ruckeri* biotype 1, *Flavobacterium psychrophilum*, *Aeromonas salmonicida* *achromogenes/atypical*, *Aeromonas sobria*, *Enterobacter* sp., *Chryseobacterium* sp.) often in fish with wounds.

Next generation sequencing of internal organs identified potential herpes and iridovirus protein coding sequences. Histopathology of haemorrhaging skin showed a general inflammatory response in the dermis and hypodermis even in acute lesions, indicating an underlying inflammatory process rather than a response to the haemorrhage. Some muscle degeneration, acute or with inflammatory response, was also seen. This histopathological picture is similar to Red Mark Syndrome (RMS), a disease in farmed rainbow trout.

Regarding the UDN-like lesions, the histopathological criteria for a UDN diagnosis was only met in about 50% of the cases. These lesions are not seen in all sampled rivers, and it is unclear whether they are linked to RSD or not. In summary, no easily identifiable infectious disease could be said to cause the issues.

Second Round of Investigation

New funding, approved in 2018, was used to examine: physiological parameters, which can act as biomarkers for environmental pollution in other fish species; thyroid hormones (T3, T4) and vitamin levels. The research was carried in conjunction with Gothenburg University. Fresh run salmon from the Rivers Mörrumsån, Umeälven and Torneälven were sampled. Stale salmon (semi-mature adults) were sampled in September from the River Indalsälven and mature females (ready to spawn) were sampled in the west coast River Lagan in late October. Most of the salmon sampled from the River Umeälven were moribund or severely affected by RSD, whereas the salmon from the other rivers appeared healthy, had mild signs of RSD or mechanical injuries.

Analysis of sampled parameters showed that EROD (ethoxyresorufin-O-deethylase) activity was high in salmon from the River Torneälven, indicating exposure to environmental pollution. In addition, T3 and T4 levels were high in the River Torneälven salmon and T4 in the River Umeälven salmon. Fish from these rivers also had a relatively high level of pro-erythrocytes and in a few cases also erythroblasts in the blood. There were no wounds or signs of internal haemorrhage that could explain the need for an increased production of red blood cells. However, this could perhaps be explained by the high T3/T4 levels, since these hormones can regulate erythropoiesis. There were no significant differences in vitamin levels (α -tocopherol, retinol, astaxanthin, total vitamin A, thiamine (total, TMP and TDP) between the river systems where fresh run salmon were sampled, whereas the spawning fish had low levels of α -tocopherol, retinol and thiamine (total, TMP and TDP). Fish from the River Umeälven had a lower level of free thiamine compared to salmon from the Rivers Mörrumsån and Torneälven. However, total thiamine, TMP and TDP from both samples were at the same level. The River Umeälven salmon also had signs of hemodilution (low Na^+ , Cl^- and Ca^{2+} levels) and high blood glucose. The hemodilution is caused by saprolegniosis and the high blood glucose is caused by inflammation. This can result from stress/exhaustion and a physiological response to the hemodilution, when the fish is attempting to maintain osmotic pressure. Increasing blood glucose demands TDP, which explains the low levels of free thiamine from which the active thiamine metabolites are generated. Multivariate analysis showed that high blood glucose, neutrophils, monocytes/macrophages and low blood Na^+ and Cl^- were associated with severe disease (Weichert et al., 2021). In addition, the Swedish University of Agricultural Sciences (SLU) performed a case control trial, including 116 (62 grilse and 54 MSW) salmon that were pit tagged at the River Umeälven estuary. Thiamine (as recommended: 1 ml/fish of a stock solution with 50 mg thiamine hydrochloride/L distilled water) was injected into 38 grilse and 20 MSW salmon. The effects were measured by the number of fish passing the beacon in the fish ladder, 30 km upstream. There was a positive effect of thiamine injection in grilse (29% passed the ladder compared to 13% non-treated) but no effect in MSW fish (0% passed the ladder compared to 6% non-treated). As RSD is mainly seen in MSW salmon in Sweden, this further indicates that thiamine is not a driving force behind the disease.

Following Up on the Visible Similarities to Red Mark Syndrome

In 2020 SVA started a general wild fish surveillance programme, funded by the Swedish Agency for Marine and Water Management. Part of this program is continuing to research this disease in salmon, including setting up a comprehensive surveillance programme. Additional funding from the joint border fishing licence fund (Sweden/Finland) was received for the River Torneälven work, in cooperation with FFA. This cooperation continues. SVA samples fresh-run salmon per river (Rivers Torneälven, Umeälven, Luleälven, Ätran and Klarälven (land locked salmon), on one or two occasions each summer, whereas FFA can sample diseased fish throughout the season. SVA has measured blood thiamine, glucose and lactate levels without finding any specific deviations. Histopathology of liver, kidney and heart is done on all fish. Skin is investigated in RSD and "UDN" fish showing a similar pattern of infection to that was seen in 2016. SVA has sent samples to external partners for thyroid hormone analysis of fish sampled in 2020-2021 and of the whole metabolism (metabolomics) of fish sampled in 2020 for analyses and we are still awaiting results. In 2020, to follow up on the similarities between RSD to RMS, FFA sent skin samples from RSD fish to the Technical University of Denmark (DTU). It is suggested that RMS may be caused by an intracellular bacteria called "Midichloria-like organism" (MLO).

A real-time PCR run at the DTU produced non-specific amplification (Fig. 1) using the primers from Cafiso et al., 2016. These primers target the 16S of MLO. It has been shown (in silico) that it can cross amplify the 16S of closely related bacteria (personal observation, Argelia Cuenca). Non-specific amplification can mean that something random is causing the amplification. Such an effect may prove insignificant. However, when the melting curves are examined, the melting temperature is the same for all RSD samples (Fig. 2), showing that whatever is causing the amplification has the same DNA sequence. This may indicate that an organism is present and causing the observed effect. The melting temperature is different from MLO, (Fig. 2) and thus we can say that if there is an organism, it is not MLO. More RSD skin samples from 2021 samplings in both Sweden (including samples from the Rivers Umeälven and Luleälven as well as the River Torneälven, and Finland) produced the same results. In 2022, the research continues. More samples are collected on an ongoing basis, including skin from both affected and unaffected (back) areas of RSD fish, and also skin from apparently healthy fish. Samples will be run through histopathology and real-time PCR. In addition, next generation sequencing will be performed to identify the genetic sequence of the potential organism. If an organism can be identified, work remains to show whether it is the causative agent of RSD, including infection trials. However, an intracellular bacterium would explain why regular bacterial cultivation has been unsuccessful.

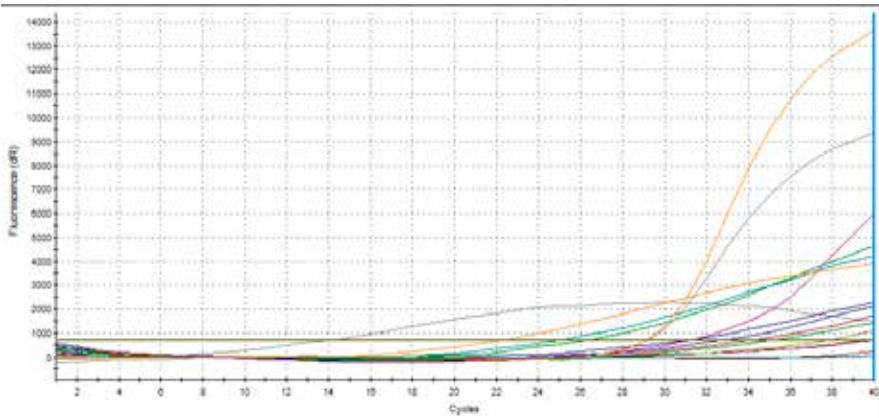


Figure 1. Real-time PCR of RSD skin samples for MLO using the primers by Cafiso et al., 2016. MLO samples included as positive control. Non-specific amplification is seen in most samples, and in one the CT value is only 13.

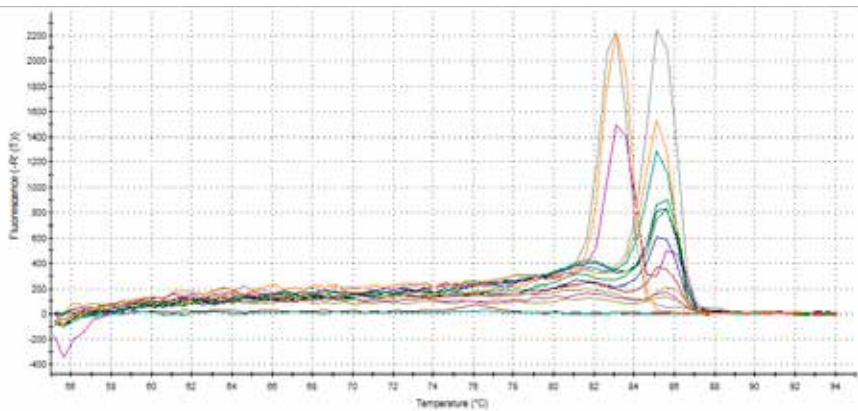


Fig. 2. Melting curves for RSD skin samples and MLO samples, amplified in real-time PCR according to Cafiso et al., 2016. Melting temperatures for RSD samples and MLO samples differ, showing that the RSD samples do not contain MLO, but that the “organism” in all RSD samples has the same genetic sequence.

RT=rainbow trout, BS= Baltic salmon, Tm=melting temperature.

References

Cafiso et al., 2016. Molecular evidence for a bacterium of the family Midichloriaceae (order Rickettsiales) in skin and organs of the rainbow trout *Oncorhynchus mykiss* (Walbaum) affected by red mark syndrome. *J. Fish Dis.* 39, 497–501. <https://doi.org/10.1111/jfd.12371>

Weichert et al., 2021. A multi-biomarker study on Atlantic salmon (*Salmo salar* L.) affected by the emerging Red Skin Disease in the Baltic Sea. *J Fish Dis* 44(4): 429–440. <https://doi.org/10.1111/jfd.13288>

Red Skin Disease – The Situation within Scotland, Reports, and Diagnostic Findings

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Introduction

During 2019 an increase in skin damage including haemorrhaging over the skin surface of wild Atlantic salmon (*Salmo salar*) was reported to Marine Scotland's Fish Health Inspectorate (FHI)¹. Although the cause was unknown, this was not believed to be a new phenomenon, but rather an increase in clinical signs of disease which had been observed previously. Following similar reports in neighbouring countries, a workshop, held towards the end of 2019, agreed to classify the condition as Red Skin Disease (RSD) (*ICES 2020 Working Group*).

This presentation focused upon the situation of RSD within Scotland, between the years 2019 and 2021. It summarised the reports which had been received, the outcomes of diagnostic investigations and referred to ongoing and historical collaboration. The presentation highlighted some of the challenges related to investigating the condition.

For any pathogenic disease to establish a susceptible host species is required together with the pathogen responsible for causing the disease. These must co-exist in environmental conditions which are favourable to pathogen transmission and disease development. At the time of this workshop, a pathogenic involvement in RSD remained uncertain as an aetiological agent had not been identified as a cause of the condition.

Reports Received: 2019 – 2021

Between 2019 and 2021 reports of RSD were received from a total of 32 river systems. Whilst most reports were received in the summer months of June and July the reporting period can stretch from May to September. Environmental conditions are believed to influence the timing and frequency of reports which can increase with specific river conditions, including low water levels and high water temperatures. This is true of other diseases and conditions in wild fish, reflecting the increased chance of observing sick fish under such circumstances which can also exacerbate disease. In some situations, rivers have reported RSD every year (Rivers Alness, Dee, Halladale) or in two from the three years covered by this report (Rivers Annan, Connon, Forss, Naver, North Esk, Spey, Tweed).

¹ Marine Scotland undertakes the role of Scotland's Competent Authority for aquatic animal disease on behalf of Scottish Ministers. The FHI implement a programme of surveillance and diagnostic investigations in line with the current fish health regulations. From a wild fish perspective surveillance is purely passive based relying upon third party notifications involving abnormal mortality or disease suspicion.

The number of reports has fluctuated over the three years analysed:

- 2019 – 32 notifications from 23 river systems (mainly single figure reports)
- 2020 – 105 notifications from 16 river systems (mainly single figure reports, some involving multiple fish)
- 2021 – 35 notifications from 10 river systems (mainly single fish, some with significant mortality)

The data presented above contains reports received by both Fisheries Management Scotland and the FHI. In many cases, fish have often presented with multiple issues including fungal infection, physical damage and secondary bacterial infections. This has added to the complexity of trying to determine not only the cause of RSD and its prevalence, but also the impact the condition has upon wild salmon populations in Scotland.

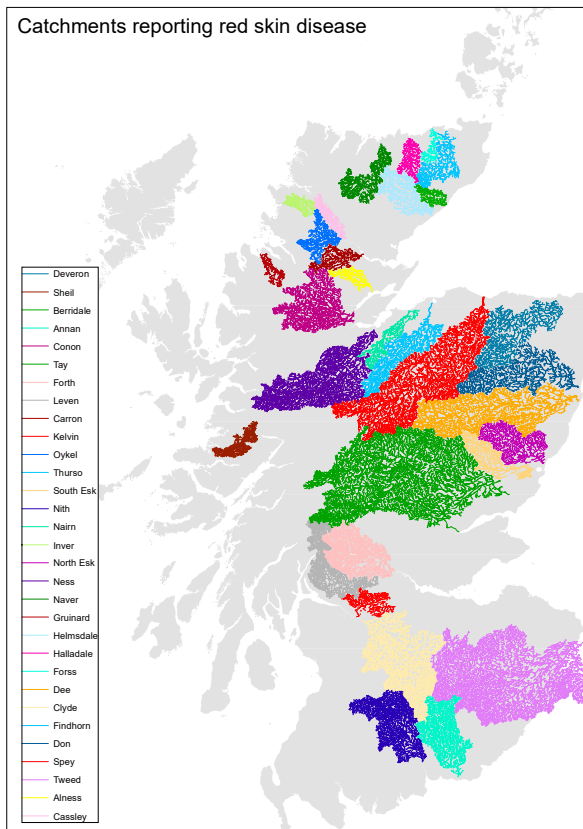


Figure 1. A visual representation of the reported locations (river catchments) of RSD received between 2019 and 2021.

Some caution should be exercised over the data concerning the reports received. These largely relate to third party notifications which, for the majority of cases, have not been verified. Whilst there may be some errors in the data with respect to the number of notifications received it is likely that the locational data presents a more accurate picture in terms of the reports received. It is acknowledged that there are likely to be other river systems which have RSD present but which remain unreported.

Comparison of the small number of years of reports may be problematic. The data held has not been analysed statistically and changes to the notification process and procedures add to the complexity in trying to make year on year comparison.

Diagnostic Findings

A standard diagnostic approach has been applied to 18 cases² between 2019 and 2021 involving fish observed with signs of RSD. Analysis has included histopathology, bacteriological culture, molecular genetics testing (QPCR) and virological cell culture for significant and widely known pathogens affecting Atlantic salmon. Whilst several bacterial species have been identified, along with fungal and parasitic infestation, no specific histopathology has been observed. From the investigations conducted so far, the pathogens isolated are not considered to be a significant factor with respect to RSD and there remains no obvious cause for the condition.

Further diagnostic collaboration between countries experiencing RSD provides an opportunity to pool resources, knowledge, and expertise. This initiative had started following a workshop in 2019 and there is scope for this to resume going forwards.



Figure 2. Images demonstrating clinical signs of RSD

Improving Reporting

Two recent initiatives have been introduced which should help improve the reporting of RSD and other issues relating to wild salmonid fisheries within Scotland.

Firstly, a reporting App developed by Fisheries Management Scotland (FMS) aims to facilitate the ease of reporting issues from specific locations and offer an element of standardisation in terms of the type of information being reported. The FHI have been working in collaboration with FMS concerning this and have agreements in place to use the outputs from the App to complement the passive surveillance programme for aquatic animal disease in wild fish undertaken by Scotland’s Competent Authority.

² Specific case numbers are provided within Annex 1.

Secondly, an initiative, driven by the Environment Agency and supporting partners has led to the development of a severity guide. This is intended to facilitate in identifying the clinical signs associated with RSD and assessing the severity and coverage of haemorrhaging, being either mild, moderate, or severe.

It is hoped that these two initiatives will help improve standardising reporting and allow for the provision of better data which in turn can give a more accurate assessment of the current RSD situation in Scotland and beyond.



Figure 3. Red Skin Disease in wild Atlantic salmon – a severity field guide

Challenges, Questions, and Further Work

Obtaining suitable material for sample analysis is always a challenge when dealing with wild fish populations and there are opportunities for greater collaboration in this area going forwards. The fact that the aetiology of the condition is still unknown and that there is the potential for multiple causes of similar conditions adds to the complexity of the situation and confusion over what is being observed and reported.

Summary Points

- RSD is reported between May and September with the majority of reports being received in June and July.
- It is widespread across numerous river systems within Scotland.
- Some caution needs to be taken over the data relating to reports.
- Health screening has revealed no obvious cause or potential pathogen to date.
- Reporting improvements may be beneficial in learning more about the true extent of RSD and its significance upon wild fish which is not clear.

Acknowledgements

Acknowledgement is given to: Brian Davidson of Fisheries Management Scotland and colleagues Silvia Soares, David Tomlinson and Amanda Walker for their contributions towards this report.

Annex 1. Specific case numbers relevant to diagnostic investigations

Case Number	River system
20190212	Helmsdale
20190287	Halladale
20190288	Naver
20190296	Garry
20190297	Dee
20190348	Little Gruinard
20190186	Conon
20190189	Cassley
20190306	Dee
20190072	Dee
20190322	Forss
20190408	Nith
20200260	Dee
20200271	Dee
20200306	Alness
20210218	Berridale
20210056	Berridale / Langwell
20210217	North Esk

References

FHI published case information - <https://www.gov.scot/collections/publication-of-fish-health-inspectorate-information/>

Fisheries Management Scotland reporting app - <https://fms.scot/fish-health-and-disease/>

ICES. 2020. Working Group on Pathology and Diseases of Marine Organisms (WGPDMO). ICES Scientific Reports. 2:53. 23 pp. <http://doi.org/10.17895/ices.pub.6086>

Red Skin Disease in wild Atlantic salmon – a severity field guide - <https://fms.scot/wp-content/uploads/2022/06/220602-Red-Skin-Disease-Severity-Guide.pdf>

Red Skin Disease, Saprolegniosis and their Potential Impacts on Salmon Populations.

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Red Skin Disease or Saprolegniosis?

We tend to use the term 'red skin' loosely. It is an external physical symptom we can see but the affliction may still be present without external physical signs to the human eye. This could be silently immunosuppressing adult salmonids, which in turn make the fish more susceptible to other diseases (Figure 1). Red skin is a disease we currently know little about. For example, it is not always visibly present, despite appearances of moribund fish and with other fish in the vicinity having red skin. In some instances, we believe that saprolegniosis is the core problem and this in itself is often misdiagnosed as UDN.

Subtle imperceptible changes in environmental stresses on salmon can have far reaching and extreme effects. With increased saprolegniosis (or saprolegniasis) we may be witnessing how climate changes combined with riparian land management manifest themselves biologically. The incidence of *Saprolegnia* infections on wild fish in England and Wales has increased since 2010 (Mathews E .2019) and incidences also appear now more frequently in Scotland. Lower river flows in recent years can cause fish to congregate and this aids in the transmission of *Saprolegnia* zoospores from fish to fish. However, we have found *Saprolegnia* zoospores in rivers and lochs when there are no outbreaks, so we must assume that this pathogen is always present.

It is clear that high levels of mortality can occur from Red Skin Disease, but it is not always clear that Red Skin Disease is the primary or single cause of death. The North Esk, Helmsdale and Forss rivers have been afflicted to varying degrees for several years and in 2022, the Findhorn also suffered high mortalities in the late spring, reportedly from Red Skin Disease. Research on the Welsh Dee has identified fish with "red skin" back into the early 1990s but without mortality necessarily associated with it. These fish were captured at the Chester weir fish trap and the dataset is extensive, so the red skin aspect of adult fish health issues may not be as novel, as we are led to believe. But again, this is all based on basic visual identification. If Red Skin Disease has been around for decades without apparent harm to fish, then it may contribute to vulnerability to other factors which are occurring more frequently, such as saprolegniosis. Anglers talk about red bellied fish as "hard running over the gravel" but is this truly the cause of red bellies?

During 2021, the first author of this paper was commissioned to film sea and freshwater migration of Atlantic salmon for a forthcoming BBC 'Attenborough' wildlife series. It enabled observation of fish daily in their underwater world on several rivers but mainly based on the Rivers Langwell and Berriedale rivers in Caithness. Filming has been done extensively on both these rivers since 2012, so we have a video record of fish health going back a decade of many hundreds, if not thousands of fish. During this period we did not witness anything comparable to what we saw taking place in 2021.

In 2021, the Langwell suffered approximately 80% mortality of the entire adult run and a significant proportion of the fish in the Berriedale also died. On one evening, we removed around 70 fish (*photo appears below*) and up to a dozen were often found dead over subsequent days. Without doubt "red skin" has contributed to mortality in most spring salmon, when the water was cooler and flows higher, but by summer, health issues and mortality were even evident for fish without any signs of red skin. It became apparent that another factor was at play in the form of saprolegniosis which can and did lead to fatalities. This is sometimes misdiagnosed as Red Skin Disease or UDN and we believe is more common than many may have thought previously. In Scottish rivers, we are able to detect many *Saprolegnia* species including *Saprolegnia parasitica*, *Saprolegnia diclina* (Sarowar et al., 2013). These two species are endemic to all fresh water habitats around the world and are known to be partly responsible for declines in natural populations of salmonids and other fresh water fish (van West, 2006 and references contained within the paper). In general, we now know that *S. parasitica* tends to favour fish, whereas *S. diclina* prefers to infect eggs, although we have found both species on all freshwater stages of salmon. Previously *S. parasitica* was thought to be a secondary pathogen, with little economic importance. However, this is far from the truth and it is now well established that it acts as a primary pathogen (van West & Beakes, 2014). In fact, we have shown that *Saprolegnia* is capable of actively suppressing host immunity (Belmonte et al., 2014) and that it produces nucleases that are translocated into fish cells and degrade RNA inside the fish cells thereby actively undermining defence responses in the fish (Trusch et al., 2018).

One of the most difficult issues facing us in studying and diagnosing fish health, is observing timescales and severity of symptoms, in the earlier stages within the river environment. Once the fish are moribund, they are more observable but there is so much wrong with the fish at this point that it is almost impossible to tell what the initial trigger was to this decline in health. In several cases that we are aware of, samples taken by the Fish Health Inspectorate and also by a private fish health veterinary service, have failed to identify *Saprolegnia* as the possible primary pathogen. We know that *Saprolegnia* was present but it is not considered to be the primary pathogen. There is a lot of misdiagnosis because early stage saprolegniosis is very difficult to detect. Once a fish is challenged with saprolegnia spores it takes about 5 days to see the first signs of saprolegniosis and only within a few days later the fish are moribund or will have succumbed to the infection (Apostolakis et al., 2022)

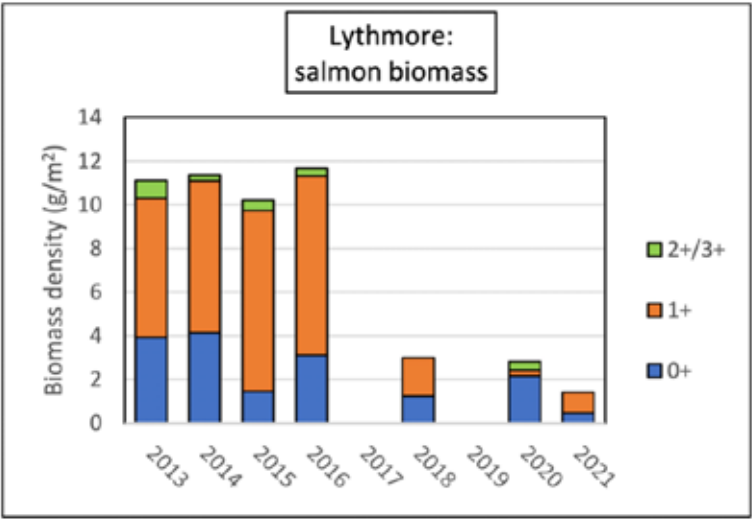
Red Skin Disease has been observed in the spring on both the Langwell and Berriedale since 2016 but it has never before escalated as it did in 2021. Red skin wasn't present in a great many of the dying fish and *S. parasitica* was infecting fish within hours of the fish entering freshwater. But redskin being present in recent years has been a constant and there was never an issue with saprolegniosis before the red skin outbreaks in spring fish. Is it likely the same is happening on the other rivers named above? We know that saprolegniosis tends to escalate in stressed, immunosuppressed fish and also when there are fluctuations in temperature and low river flows, so it could be coincidence and a tragic double whammy of redskin AND unrelated *Saprolegnia* infections that may become the norm. "Further work focussed on the impact of temperature and water flow, in light of future climate change, is necessary to predict how this parasite will impact fish populations and aid the implementation effective fish management schemes." (*Mathews PhD thesis, 2019*)

The Impacts on the River Forss

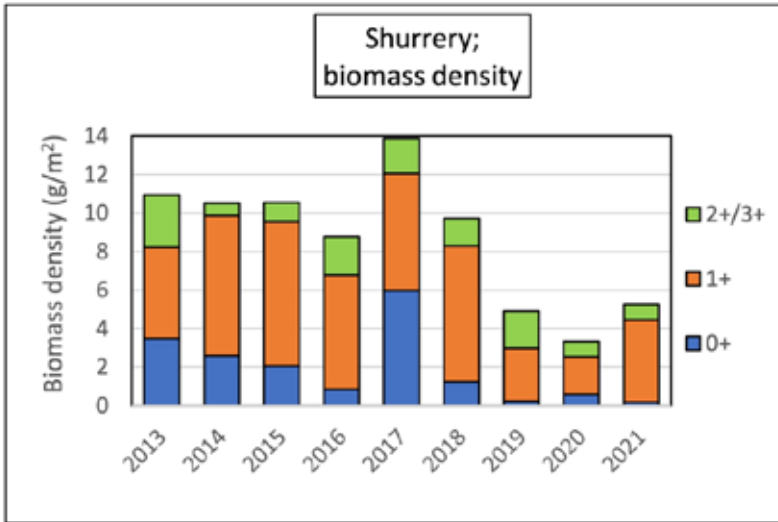
Some liken the impacts of Red Skin Disease (or undiagnosed saprolegniosis) to UDN but there is a big difference in the consequences of the level of mortality of already returned adults in the 1970s and now. With smolt survival to adults at record highs back then, losing 80% of adults was not always a biological disaster. Remove 80% of the mere 2% that survive to adults now and many tributaries become - or indeed are - devoid of spawning fish as a direct consequence (River Forss electrofishing site data - courtesy of Caithness DSFB).

To give a perspective on how severe this issue is for individual populations, here is the electrofishing data for the last 9 years for the Lythmore site on the River Forss.

It tells us the story very clearly. The Forss has been losing significant portions of their adult spawning population to saprolegniosis Red Skin Disease since 2016.



Some protection is afforded to adult fish above Shurrery dam, so the decline here in juvenile biomass is not as stark. However, it is still less than 50% of pre-disease capacity. Will other rivers follow suit?



With climate changes and the low flows in our rivers that we are experiencing more often, it is likely that we will see the occurrences of fish under stress congregated together and vulnerable to disease far more frequently. In short, we strongly believe that we need to put more resources into the causes of salmon declines in our river systems to avoid a potential catastrophe in the coming years.

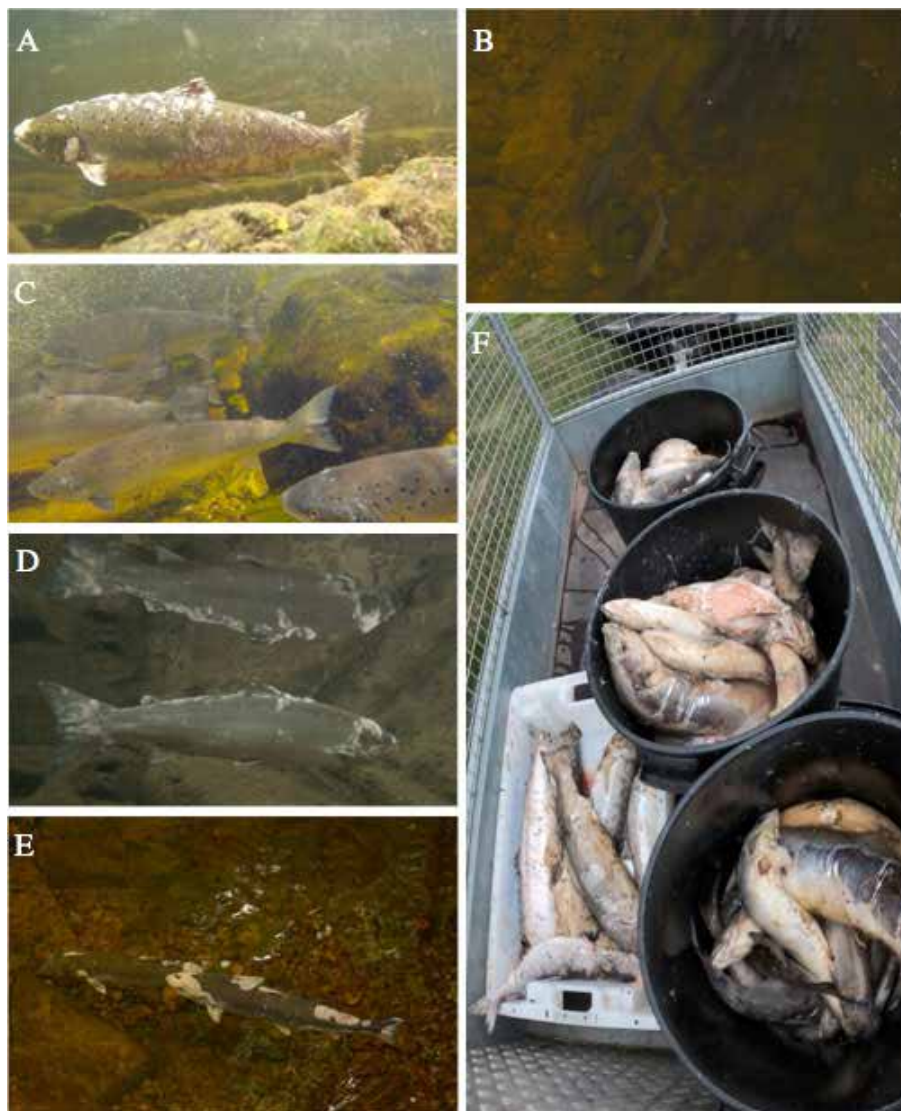


Figure 1 Impact of Red Skin Disease and saprolegniosis

A. This fish could reasonably be described as suffering from red skin disease but clearly has a saprolegnia infection too. **B.** Clean fish in lower Langwell pools after a dry summer in 2018 – photo taken in September. No health issues. **C.** Early stages of saprolegnia infection on otherwise healthy fresh fish ten metres above high tide. July 2021. **D.** Later stage infection with no signs of red skin July 2021. **E.** From the surface, what would these fish be diagnosed as suffering from? **F.** Approximately 70 fish removed from 300 metres of stream in one evening 2021

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Managing Red Skin Disease in Ireland

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Background

In early June 2019, a small number of Atlantic salmon were encountered returning to Irish rivers with signs of bleeding and skin ulceration uncharacteristic of known salmon diseases. This followed reports of salmon also returning to Norway and Scotland which had similar disease signs to those observed in some Irish salmon. By mid-June, salmon with signs of what is now termed Red Skin Disease (RSD), were reported in at least six rivers, both on the east and west coast of Ireland. The affected salmon showed signs of bleeding, ulceration and haemorrhaging mainly along the area of the belly of the fish, and to a much lesser extent on the head and the tail. Secondary fungal infections were also evident where the apparent disease was more advanced and some lethargic and dead salmon were encountered in this condition. Further reports of Atlantic salmon with signs of RSD were received in the following months of 2019 and also have been since reported in small numbers of Irish salmon in subsequent years (2020, 2021 and 2022).

Management Response

In response to the initial reports of salmon having signs of RSD, Inland Fisheries Ireland (IFI) initiated an awareness-raising campaign in the national and regional media amongst stakeholders to facilitate increased reporting in order to better establish the extent of this phenomenon in Irish salmon. A dedicated email (salmon.symptoms@fisheriesireland.ie) was set up by IFI for anglers to report any incidence of such diseased salmon encountered in Irish rivers and provide photographs. Anglers were also advised to contact IFI's 24-hour confidential hotline number on 0818 34 74 24 or 0818 FISH 24 in this regard. It was also advised, that until the cause of the disease was determined and the risk of spreading the disease established, affected salmon should not be removed from the water. Any anglers who captured salmon with signs of RSD were advised to follow normal biosecurity procedures and disinfect tackle, waders and equipment. IFI also initiated surveillance for the disease in two index catchments in the west of Ireland; the National Salmonid Index Catchment (NSIC) River Erriff (where a full upstream trapping facility is available to intercept and monitor returning salmon) and the Galway Fishery on the River Corrib system where there are significant salmon angling catches available for inspection. These initiatives have continued on an annual basis. In 2022, a third surveillance catchment for RSD, the River Moy Fishery in Ballina, was added.

In 2019, a preliminary classification scheme to qualitatively measure the severity of RSD in salmon was developed. This had five categories of severity (minimal, minor, moderate, major and severe). In 2022, a new scheme was adopted to align our severity classification with partners in Britain (Environment Agency, Marine Scotland Science and Natural Resources Wales) which categorises RSD in a simple 3 x 3 matrix of mild, moderate and severe based on both severity of haemorrhage and extent of coverage of RSD on the ventral surface.

Disease Testing

In addition to the above, disease testing of specimen fish with signs of RSD was undertaken principally in collaboration with the Fish Health Unit (FHU) of the Marine Institute to attempt to establish the underlying cause of the disease. In 2019, such analyses were limited due to the varying degrees of degradation of the five specimens secured for testing. As a result, further, more detailed testing of six diseased fish was undertaken in 2020 using fresh specimens captured in the NSIC Erriff to better comply with standard disease testing protocols. Despite the extensive testing (bacteriology, histopathology, molecular analyses and virology) undertaken, no attributable cause was identified and it was concluded that clinical signs associated with RSD were not characteristic of commonly identified diseases associated with salmonid species. As more extensive investigations are underway by the Scandinavian authorities to identify the cause of RSD since then, no further testing has been conducted on Irish salmon.

Extent of Occurrence and Severity

Anecdotal observations suggest that mild RSD-like signs have been observed in Irish salmon for many decades. However, there has been no specific focus in this regard until 2019 when more obviously diseased fish were encountered. Since 2019, Atlantic salmon with signs of RSD have been recorded in all River Basin Districts in Ireland. Apart from our dedicated trapping surveillance in the NSIC Erriff, the majority of these fish have been encountered by anglers either through their catch or direct observation in the river and this clearly highlights the importance of stakeholder awareness in the reporting of such emerging issues of concern. Some additional diseased salmon have been reported from commercial fishers. In 2019, a total of 56 Atlantic salmon were reported as having signs of RSD from a total of 17 river systems; in 2020, this was 113 salmon from a total of 12 river systems; and in 2021, 33 salmon from a total of six river systems. It should be noted that although the majority of recorded cases of RSD in Ireland are observed in one-sea-winter grilse (which predominantly return in the summer months), this is not the case elsewhere in Europe (notably Scandinavia) where RSD is principally observed in multi-sea-winter salmon stocks. This may be a consequence of the Irish stock being predominantly one-sea-winter.

Although potentially an emerging phenomenon, it is important to note that the incidence of RSD observed in Irish Atlantic salmon is thus far very low in terms of the overall Irish catch of salmon (angling and commercial catch). In recent years, the national catch is in the region of 30,000 fish per annum and the vast majority of recorded RSD cases are mild. Indeed, in the NSIC Erriff in 2021, only 3.45% of returning salmon examined had signs of RSD with 93.5% of cases classified as mild and 6.5% as moderate in severity.

Outlook

In coming years, IFI will continue to monitor for the presence of RSD in Irish salmon stocks, promote stakeholder reporting, and liaise with national and international colleagues to exchange relevant information and contribute to advancing knowledge on the underlying cause of this disease.

Acknowledgements

Anglers, commercial fishers, fishery owners and the field staff of IFI are gratefully acknowledged for their general vigilance in response to the appeal to report any salmon encountered with RSD-like signs. IFI staff in the NSIC Erriff, Galway and Moy fisheries are acknowledged for surveillance work in index catchments. Bill Dore, Samantha White, Michelle Geary, David Swords, Evelyn Collins and Bogna Griffin in the FHU of the Marine Institute are acknowledged for disease sampling advice and testing.

Is There a Link Between Red Skin Disease and Red Vent Syndrome?

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Appearance and Occurrence of Red Vent Syndrome

Red Vent Syndrome in Atlantic salmon appeared in the East Atlantic around 2005. Red Vents were particularly observed in salmon in Scottish and Irish rivers but also in several Norwegian rivers along the whole coast (Noguera et al. 2009, Mo et al. 2010). Red vents have rarely been reported from other countries, possibly because the anglers are not aware of the condition. This disease is observed as bleeding in the tissue around the gut and can be mild, moderate or severe.

Red Vent Syndrome is caused by the nematode *Anisakis simplex* – also known as the whale worm. As the causative factor is now known, this condition should be named Red Vent Disease or just Red Vent. Most anglers have likely seen this parasite as it is commonly observed as filamentous spirals in or on the liver and other internal organs of marine fish, including Atlantic salmon. However, this parasite also occurs in the muscles of the salmon. Several studies on the occurrence of Red Vent have been conducted but have mostly included ISW salmon only (Noguera et al. 2015, Kent et al. 2020). *Anisakis* has also been recorded from the gut of post-smolts taken during the SALSEA surveys (2008 – 2010 – Murphy et al., 2010).

Distribution of *A. simplex* in Returning Adult Salmon

In Norway, recent studies have included multi-sea-winter salmon. Ninety salmon, distributed on three size classes, < 3 kg (1SW), 3-7 kg (2SW) and >7 kg (3-4SW), were examined (Mo et al. 2021). The result show that *Anisakis* larvae occurs at 100% prevalence in adult Atlantic salmon while at sea and that larvae are accumulated over the years at sea. In our study, the mean number of larvae decreased in 4SW. This could be explained by increased mortality among the most infected salmon, e.g., by predation. One reason may be that a salmon with numerous *Anisakis* larvae in the musculature has a reduced swimming capacity and thus is an easy prey to a predator, e.g. a whale. About 40 % of *A. simplex* in a salmon is distributed in the two fillets. Of this 40%, more than 90% of the occurrence of the parasite is in the belly parts (Mo et al. 2021).

Increasing Occurrence of *A. simplex* in Atlantic Salmon

According to previous studies, the number of *A. simplex* in 1SW Atlantic salmon was low in the 1960s but also at that time almost every salmon at sea was infected. About 50 years later, all age classes of salmon are infected and the intensity has increased significantly. Scottish salmon have shown an almost fourfold increase from 2009 to 2015 (only six years!) and a significant increase in the number of *Anisakis* in musculature associated with the vent. There does not seem to be a similar increase in Norwegian salmon and could explain why Red Vent is rarely reported in Norway, but it could also be that the anglers are not as aware of the condition. A meta-analysis of published papers concludes that there has been a 283-fold increase in the occurrence of *Anisakis* larvae in marine fish species globally (Fiorenza et al. 2020). This can partly be explained by an increase in the number whales,

the final hosts, especially toothed whales. However, the observed shift in the occurrence of marine crustaceans, the first intermediate host for *A. simplex*, may also be involved.

The seemingly large difference in the distribution of *A. simplex* in the vent versus musculature between Scottish and Norwegian salmon could indicate that they may feed on different prey. It is probably more likely that the fish feed in different areas in the Atlantic Ocean. However, we do not currently have a good explanation as to why so many larvae tend to accumulate or aggregate in the muscles around the end of the gut, especially Scottish salmon.

No Link Between RSD and RV

When an internal examination of Norwegian salmon with RSD is carried out, some *Anisakis simplex* are found, but the fish rarely displays Red Vent. Thus, we have no evidence to claim that there is a link between Red Skin Disease and Red Vent.

In conclusion, we have no results or indications that there is a relationship between RSD and Red Vent. However, a salmon can be affected by both diseases at the same time.

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Red Skin Disease – Unravelling the Mystery and Planning for the Future

Over the past two decades, there have been numerous reports of Atlantic salmon pre-spawners suffering from skin diseases, following river entry. These have occurred in freshwater systems draining into the Atlantic Ocean and adjacent sea areas, such as the Baltic Sea. One of these skin diseases, Ulcerative Dermal Necrosis (UDN) is well known and defined clinically and histologically. The more recently described Red Skin Disease (RSD) is clinically and histologically different from UDN. However, both diseases have an unknown aetiology. Furthermore, pre-spawners may also suffer from other skin anomalies which occur following entry into freshwater or in the period prior to spawning. These skin anomalies, often found on the flanks or associated with the fins of the fish, include small (petechial) or large haemorrhages, ulcers, areas of discoloration, scale loosening or scale loss, areas covered with a thick mucus layer, and small to large areas affected by different species of “fungi” (oomycetes). In the case of UDN and RSD, as mentioned above, the aetiology of these skin diseases is unknown. In addition, they all lack a formal case definition and a disease name.

Parallel to the apparent increase in wild Atlantic salmon skin diseases during the last two decades, there has been a documented increase in skin diseases in farmed salmonids, especially freshwater farmed rainbow trout but also in farmed marine fish (Schmidt et al. 2018). Many of these diseases have a name and defined disease characteristics (Oidtmann et al. 2013, Maddocks et al. 2015). However, as for UDN, RSD and other skin anomalies in wild Atlantic salmon, the aetiology of the farm fish skin diseases are unknown. For some of the skin diseases in farmed fish, treatment with the antibiotic oxytetracycline has proven helpful. This could indicate that bacteria are involved in the development of the disease (Schmidt et al. 2018, 2021).

Recently, Red Mark Syndrome (RMS) in farmed rainbow trout in Europe which is the same disease as Strawberry Disease in farmed rainbow trout in North-America (Metselaar et al. 2022), has been associated with a bacterium which is in many ways similar to the recently described *Midichloria mitochondrii*, within the family Midichloriaceae, in the order Rickettsiales (Cafiso et al. 2016, Orioles et al. 2022). This a group of small, intracellular bacteria that are very difficult to cultivate and diagnosis of their presence is based on genetic analysis. As the bacterium involved in RMS is very similar to *M. mitochondrii*, it is referred to as a *Midichloria*-like organism (MLO). A pattern similar to that of an MLO infection has been found in the skin of diseased wild Atlantic salmon. However, the identification of a clearly defined organism and clarification of its significance in the overall health of the host, requires a great deal of diagnostic work and research.

To fully understand the causes and the significance of the increasing incidence of these skin diseases, governmental diagnostic laboratories will need to significantly increase their efforts to identify and clarify disease outbreaks. This is particularly true in the case of skin diseases in wild Atlantic salmon and other wild fish species. Such laboratories are currently responsible for case definitions and diagnostics of skin diseases in farmed fish and are ideally placed to include similar studies and diagnostics of wild fish. This is particularly true in the case of skin diseases in wild Atlantic salmon, an iconic species that most countries across its distribution have undertaken to preserve and protect. Such research and timely diagnostic services are urgently required.

The occurrence of individual Atlantic salmon suffering from disease and disease outbreaks at a population level, varies during any given year and between years, both within and between rivers. It cannot be expected that specialists from governmental diagnostic laboratories will be present at the start of a disease outbreak and continue to be present during its progression. As discussed during the workshop, tissue sampling can be performed by trained local volunteers associated with the management of the individual river. These locals can provide skin samples from Atlantic salmon at the different stages of disease development, which are necessary for precise diagnosis. Such an approach requires preparation of good protocols for the collection, handling and storage of the samples. The protocols should be richly illustrated with photos or videos that show how the sampling is best done. Necessary equipment for sampling, as well as preservation and fixing agents for the samples, must be made easily available. Ideally, short practical courses should be organised to train those who have volunteered to carry out the sampling. It was recognised during the workshop that such an approach is already under development in some jurisdictions but the scale and distribution of the skin problems affecting Atlantic salmon requires a far wider and more intense regime of sampling and diagnosis.

If a skin disease and possibly a causative infective organism is identified, it will be necessary to understand the causal relationships of the disease outbreaks. Risk assessment studies, involving local fisheries managers will be required, as they will often have access to long historical records and will have a detailed knowledge of their river and the overall behaviour patterns of the adult and juvenile salmon in the system. The managers are ideally placed to collect the additional data required for a thorough risk assessment. As in the case of disease sampling, clear instructions and protocols should be developed by the specialists for these samplers, including a description of the data required, how it is to be obtained and recorded for use in the risk assessment process.

Lastly, there is also a need for risk management studies. These should assess and advise on the handling of individual dead or diseased salmon and how an extensive outbreak of skin disease, involving the entirety of river system or a geographical region, should be assessed and managed.

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Appendix 1

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Emerging skin diseases in Atlantic salmon and the role of Ulcerative Dermal Necrosis

Skin anomalies in adult Atlantic salmon returning to rivers from the ocean have been known for more than 150 years. In the 1860s, 1870s and 1880s a condition named the Salmon Disease caused severe epizootics (equivalent to epidemics in humans) in numerous rivers across the British Isles. During this period thousands of adult salmon died from this skin disease. It seemed that the Salmon Disease was gradually spreading to new rivers, which could, it was thought, have indicated that an infectious aetiology was involved. Some scientists at that time were convinced that a *Saprolegnia* species, commonly seen in moribund and dead salmon, was the causative organism. In each river the epizootic persisted for a few years and then gradually subsided.

About one hundred years later, severe outbreaks of a skin disease hit returning adult salmon again, predominantly in multi-sea winter fish. This time the skin disease affected salmon populations in a larger geographical area in the southern Atlantic Ocean including the Great Britain, Ireland, France, Southeast Norway and the west coast of Sweden, but also the Baltic Sea area. Again, the skin disease seemed to be spreading in a north easterly direction. The disease was most prevalent in the UK and Ireland during the 1960s and into the early 1970's, it appeared in the 1970s in the Baltic area and in the 1980's along the Swedish west coast and in south-eastern Norwegian rivers (Poppe 1989). The skin condition was given the name Ulcerative Dermal Necrosis (UDN) (Carbery 1968). Based on descriptions in earlier publications it was concluded that the Salmon Disease 100 years earlier was most likely also UDN (Roberts 1993).

In the first developmental stages of UDN, which commonly starts before the salmon enter fresh water, the epidermis rather than dermis is affected. In the so-called pre-mycotic stages, there are swellings and necrosis of Malpighian cells, the most common cells in the epidermis. In the basal and supra-basal layers there are areas of complete degeneration of Malpighian cells resulting in small cavities in the epidermis (Roberts 1993). The "roof" or the outer part of the cavities subsequently collapses. In the final stage in the development of the ulcers, which are typically associated with UDN, the epidermal basement membrane breaches and the fungal invasion takes place. Even if fungal infections play an important role in the pathogenesis and pathology of UDN, these infections are likely not the primary cause (Roberts 1993). An infectious agent has so far not been found but it is still believed that an unknown organism is involved. This could be an intra-cellular organism which is triggered by different stressors. Many stressors have been proposed as contributory causes of UDN outbreaks. These include climate change effects such as warmer water, lower water flow / droughts, UV radiation (Henard et al. 2022), heavy metal pollution (Rajkowska-Mysłiwiec et al. 2022) and more.

Interestingly, Roberts (1993) wrote that UDN is likely a cyclical disease which is expected to return before the middle of the 21st century. The UDN outbreaks observed in many rivers the last 3-4 year support this but came earlier than postulated, possibly because

returning Atlantic salmon are increasingly affected by stressors. Roberts (1993) also wrote that the incidence of the UDN epizootics always coincide with very high wild salmon stock levels. Considering the significant decline in wild salmon populations, mainly in the southern Atlantic, it is surprising that the incidence of UDN appears to have risen over recent years. However, the number and intensity of different stressors, currently impacting Atlantic salmon stocks across its geographic range, may be responsible for an increase in the occurrence of various skin diseases. If this pattern continues such outbreaks may prove more frequent and more extensive than before.

UDN was originally described from fresh, early running Atlantic salmon that had recently arrived from the sea into rivers in the UK and Ireland. These MSW fish typically arrived in spring and at low water temperatures. In the surviving fish, UDN levelled out as the water temperatures increased. In other countries, UDN outbreaks were observed in the autumn as water temperatures declined and also during the spawning season. In these countries this pattern continues. Furthermore, sea trout populations and non-anadromous brown trout populations can be severely affected by UDN. Adult salmon and sea trout with saprolegniosis are often claimed to be affected by UDN. However, the oomycete *Saprolegnia parasitica* can aggressively attack the skin of freshwater fish and cause saprolegniosis without the fish having had initial symptoms of UDN or other skin anomalies (see Davies & West in this report).

In 2014 and later, a new skin disease has occurred in Atlantic salmon in many Baltic salmon rivers. Since 2019, the same disease has occurred in rivers draining to the southern Atlantic Ocean, including the Swedish west coast, Norway, Denmark, the UK and Ireland. (Weichert et al. 2021). On this occasion, the new Atlantic salmon skin disease has seemingly spread in a westerly direction. An international workshop, held in Oslo in November 2019, agreed to name the disease Red Skin Disease (RSD). Red Skin Disease is characterised by petechial (a small, red or purple spot caused by bleeding into the skin) to centimetre-sized haemorrhages, especially on the belly of the fish. Additionally, fin damage and scale loss are commonly observed. The skin haemorrhages occur in the dermis, where the outermost blood veins of salmonids are located. Thus, the initial phase of RSD appears different from UDN, and therefore the causal relationships of the two diseases may be quite different.

At the workshop in Edinburgh, June 2022, the speakers presented their knowledge of the incidence of the new disease, diagnostics, fish physiology and the pattern of disease development.

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Summary of Work of the Atlantic Salmon Trust

Since 1967 the Atlantic Salmon Trust has supported research into key aspects of the lives of migratory salmonids. The Trust facilitates, designs and operates research programmes, partners research projects, and organises scientific meetings, workshops and conferences. It communicates its findings to anglers, fishery managers, fishery owners, governments and policymakers, relevant industry bodies and the public.

The role of the Trust is to demonstrate how both species can be conserved and managed in order that their value to society is optimised on a sustainable basis. The abundance of Atlantic salmon, prior to any fisheries exploitation, has declined over the last forty years from 8 – 10 million fish in early 1980s, to 3 – 4 million fish at present. The AST's major concern is the dramatic decline in marine survival in Atlantic stocks, which has fallen from over 20% in the 1980s to, at times, less than 5% over the past 10 years.

The Trust's research work concentrates on improving our scientific knowledge of wild salmon and sea trout, their habitats and their complex and fascinating life histories, and the threats to their survival. Until relatively recently this knowledge was confined mainly to the freshwater aspects of their life cycle. However, through the development of the Likely Suspects Framework, the AST and its partners in the Missing Salmon Alliance, are also focusing on the estuarine, nearshore and marine phases of their lifecycle. In recent years the Trust has embarked on a series of major smolt tracking projects to ensure that risks are significantly reduced for both salmon and sea trout smolts as they journey out into the ocean.

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Summary of Work of the Norwegian Institute for Nature Research

The Norwegian Institute for Nature Research (NINA) is a Norwegian foundation, established in 1988, which researches nature and the interaction between nature and society.

NINA is Norway's leading institution for applied ecological research, with broad-based expertise on the genetic, population, species, ecosystem and landscape level, in terrestrial, freshwater and coastal marine environments. Important areas of work for NINA are: biological diversity, renewable energy, predatory mammals, aquaculture, environmental databases, use and management of natural resources, impact analyses, ecological effects of climate change and economic effects of nature use.

The foundation has almost 300 employees, both biologists and social scientists. Approximately 50 scientists and technicians work with salmonids, primarily Atlantic salmon. The overall focus of NINA's salmonid research group is to generate relevant knowledge and data about human impacts on Atlantic salmonids, as well as development of solutions to mitigate negative impacts. More precisely, the work of the salmonid research group encompasses provision of basic and applied scientific knowledge on salmonids, collection of surveillance data/material and participation in national and international management processes. In addition, outreach aimed at informing the public and relevant stakeholders is also an important activity for the group. Although the group predominantly focuses on individual species or groups of species, its work is also of high value for preservation and restoration of aquatic ecosystems, as salmonids depend on healthy ecosystems to thrive.

<https://www.nina.no/english/Home>

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